SUSTAINABLE PLANT NUTRITION AND SOIL QUALITY MANAGEMENT

EDITORS
PROF. DR. KORKMAZ BELLİTÜRK
PROF. DR. AHMET ÇELİK

EĞİTİM
yayınevi

SUSTAINABLE PLANT NUTRITION AND SOIL QUALITY MANAGEMENT

Editors: Prof. Dr. Korkmaz Bellitürk, Prof. Dr. Ahmet Çelik

Chairman of the Publishing House Group: Yusuf Ziya Aydoğan (yza@egitimyayinevi.com)
Executive Editor: Yusuf Yavuz (yusufyavuz@egitimyayinevi.com)
Interior Designer: Kübra Konca Nam
Cover Designer: Kübra Konca Nam

Republic of Türkiye Ministry of Tourizm and Culture
Publisher Certificate No: 76780

E-ISBN: 978-625-385-750-9
ISBN: 978-625-385-748-6
1. Edition, January 2026

Printing and Binding
Vadi Grafik Tasarım ve Reklamcılık Ltd. Şti.
İvedik Org. San.1420. Cad. No: 58/1 Yenimahalle/ANKARA
Printing House Certificate No: 47479

Library Information Card
SUSTAINABLE PLANT NUTRITION AND SOIL QUALITY MANAGEMENT
Editors: Prof. Dr. Korkmaz Bellitürk, Prof. Dr. Ahmet Çelik
VIII+369, 160x240 mm
Includes references, no index
E-ISBN: 978-625-385-750-9.
ISBN: 978-625-385-748-6

EĞİTİM yayınevi

Publisher Turkey Office: İstanbul: Eğitim Yayınevi Tic. Ltd. Şti., Atakent mah. Yasemen sok. No: 4/B, Ümraniye, İstanbul, Türkiye

Konya: Eğitim Yayınevi Tic. Ltd. Şti., Fevzi Çakmak Mah. 10721 Sok. B Blok, No: 16/B, Safakent, Karatay, Konya, Türkiye
+90 332 351 92 85, +90 533 151 50 42
bilgi@egitimyayinevi.com

Publisher USA Office: New York: Egitim Publishing Group, Inc.
P.O. Box 768/Armonk, New York, 10504-0768, United States of America
americaoffice@egitimyayinevi.com

Logistics and Shipping Center: Kitapmatik Lojistik ve Sevkiyat Merkezi, Fevzi Çakmak Mah. 10721 Sok. B Blok, No: 16/B, Safakent, Karatay, Konya, Türkiye
sevkiyat@egitimyayinevi.com

Bookstore Branch: Eğitim Kitabevi, Şükran mah. Rampalı 121, Meram, Konya, Türkiye
+90 332 499 90 00
bilgi@egitimkitabevi.com

Internet Sales: www.kitapmatik.com.tr
bilgi@kitapmatik.com.tr

EĞİTİM YAYINEVİ GRUBU

TABLE OF CONTENTS

PREFACE

Why Sustainable Plant Nutrition and Soil Quality Management Are Important?

The subjects of sustainable plant nutrition and soil quality management have gained prominence as environmental challenges have intensified. This is due to the fact that ensuring the sustainability of plant nutrition and soil health is imperative for the long-term viability of agricultural production systems. Preserving soil quality and health is imperative for the sustainability of natural resources and ecosystem services, which are undergoing rapid degradation and depletion. The challenges posed by climate change and population growth have further increased the need for fertile and healthy soils to ensure food security.

A prevailing consensus among global strategists posits that future conflicts will predominantly stem from two pivotal natural resources; soil and water. This prompts a critical inquiry: are we providing sufficient protection for these invaluable resources? Soil and water are not easily renewable assets. Soil, as the fundamental basis of agricultural production, also plays a vital role in the proper functioning of ecosystem services. Consequently, sustainable plant nutrition and soil quality management are identified as pivotal strategies, not only for enhancing immediate crop productivity but also for ensuring long-term soil health.

Plant nutrition involves more than supplying essential nutrients to crops. It also supports balanced biological, chemical, and physical processes in the soil. Uncontrolled agricultural practices, particularly improper fertilization and excessive chemical use, can lead to soil salinity, loss of organic matter, and a decline in the diversity and abundance of soil microorganisms. These adverse effects often result in yield losses and contribute to broader environmental problems.

The concept of a sustainable life cycle aims to preserve natural resources and maintain ecosystem services. Widely adopted practices such as using organic fertilizers, practicing crop rotation, mulching, green manuring, restoring soil, and controlling erosion are among the most effective measures for preventing nutrient loss and sustaining soil productivity. Furthermore, balanced plant nutrition enhances crop resistance to pests and diseases, reducing the need for chemical pesticides.

In light of mounting environmental challenges, scientific research has underscored the critical importance of sustainability in agricultural systems. Production models shaped by such evidence-based findings are valuable. While achieving high yields through temporary solutions without taking the necessary precautions to maintain soil fertility may offer short-term economic benefits, it inevitably leads to long-term environmental and economic losses.

In conclusion, sustainable plant nutrition and soil quality management are essential not only for ensuring agricultural productivity and food security but also for safeguarding the integrity of natural resources for future generations.

We extend our sincere appreciation to all the contributing authors who enriched our book project with their valuable chapters and to the publishing team for their dedicated efforts.

Prof. Dr. Korkmaz BELLİTÜRK

Prof. Dr. Ahmet ÇELİK

1 URBAN FARMING DEVELOPMENT BY SOILLESS CULTURE CAN IMPROVE HOUSEHOLD INCOME

Ristina Sıti Sundari[1], Korkmaz Bellitürk[2], Farhan Ahmad[3], Rizky Adi Nugraha Tarigan[4], Rafif Naufal Assadel Tarigan[5], Fatih Büyükfiliz[6]

1. Introduction

In the face of rapid urbanization, limited land availability, and rising food insecurity, urban farming has emerged as a vital strategy for sustainable development. Among its most promising innovations is soilless culture**,** which includes hydroponics, aquaponics, and aeroponics—systems that allow crops to thrive without traditional soil. These methods are not only space-efficient but also resource-conscious, making them ideal for urban environments where land and water are scarce.

Soilless urban farming empowers households to grow high-value crops such as leafy greens, herbs, and even fruiting vegetables on rooftops, balconies, or vertical structures. This localized food production reduces dependency on external supply chains, lowers food costs, and enhances nutritional access. More importantly, it opens up new income-generating opportunities, especially for low- to middle-income urban families. By selling surplus produce to neighbors, local markets, or through digital platforms, households can supplement their earnings and build economic resilience.

Moreover, the integration of soilless systems with renewable energy, organic inputs, and circular economy principles enhances their sustainability and scalability. These systems require less labor and can be managed by women, youth, or the elderly, promoting inclusivity and community engagement. With proper training and support, urban residents can transform underutilized spaces into productive micro-farms, contributing to both environmental stewardship and economic empowerment.

1 Associated Professor. Agribusiness Study Program, Agricultural Faculty, Agribusiness, Universitas Perjuangan Tasikmalaya, -Agricultural Biology, ristinasitisundari@unper.ac.id,Orcid: 0000-0002-5310-8520
2 Professor. Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Tekirdag Namık Kemal University, Tekirdag, Türkiye. kbelliturk@nku.edu.tr, Orcid: 0000-0003-4944-3497
3 Dr. Department of Agronomy, Faculty of Crop Production Sciences, The University of Agriculture Peshawar, Peshawar. Khyber Pakhtunkhwa, PAKISTAN, farhansyk@gmail.com, Orcid: 0000-0002-4248-0714
4 Agrotechnology Study Program, Agricultural Faculty, Universitas Siliwangi, Tasikmalaya, Orcid: 0000-0002-6076-1165
5 Agrotechnology Study Program, Agricultural Faculty, Universitas Siliwangi, Tasikmalaya, rafiftarigan2@gmail.com, Orcid: 0009-0001-7253-6395
6 Dr. Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Tekirdag Namık Kemal University, Tekirdag, Türkiye. fatihbuyukfiliz@hotmail.com, Orcid: 0000-0002-8113-876X

Scientifically, soilless systems enhance nutrient uptake efficiency, reduce pest and disease incidence, and optimize water use through recirculation technologies. This results in higher productivity per unit area compared to conventional soil-based methods. From a socio-economic perspective, these systems lower entry barriers for urban households by requiring minimal land and offering modular scalability. When integrated with renewable inputs and circular economy principles, they become not only environmentally sustainable but also economically viable.

Empirical studies have shown that households engaged in soilless urban farming can generate supplemental income through direct-to-consumer sales, local markets, and digital platforms. Moreover, the cultivation of niche crops—such as microgreens, herbs, and specialty vegetables—can yield premium prices, further enhancing profitability. These systems also foster inclusive participation, particularly among women and youth, by offering manageable labor demands and flexible operation.

In essence, the development of urban farming through soilless culture is more than a technological innovation. it is a socio-economic catalyst. It aligns with global goals for sustainable cities, poverty reduction, and climate resilience. By investing in this approach, policymakers, researchers, and communities can co-create a greener, more equitable urban future one where households are not just consumers of food, but active producers and entrepreneurs.

2. Urbanization and the Emerging Imperative for Sustainable Food Systems

Urbanization is accelerating at an unprecedented pace, particularly across developing nations. The United Nations projects that by 2050, over 68% of the global population will reside in urban areas, intensifying pressure on food systems, infrastructure, and livelihoods (Grauman, 2018)His demographic shift presents both opportunities and formidable challenges, chief among them the strain on land use, food supply chains, and economic resilience, particularly for low-income urban communities. As land becomes increasingly scarce and living costs rise, urban populations face heightened vulnerability to food insecurity and precarious livelihoods.

Urban agriculture has emerged as a localized, participatory strategy to mitigate these pressures. Defined as the cultivation, processing, and distribution of food within and around urban spaces, it enhances food availability while offering supplementary income streams. However, conventional soil-based farming methods often clash with urban land-use priorities and are hindered by contamination, compaction, and spatial constraints. These limitations underscore the growing relevance of soilless culture technologies, hydroponics, aeroponics, and aquaponics, which decouple food production from soil and optimize vertical and rooftop spaces (FAO, 2019).

Soilless culture represents a paradigm shift in urban farming. These systems not only bypass the limitations of degraded urban soils but also enable controlled-environment agriculture (CEA), allowing for year-round production, efficient water use, and reduced pesticide reliance. In Indonesia, initiatives such as Hydroponik Urban Farming Jakarta and cooperatives in West Java have demonstrated tangible socio-economic benefits, with participating households reporting monthly income gains of IDR 1–2 million (Pamuji et al., 2014; Sundari et al., 2025). These outcomes highlight the potential of soilless systems to foster microentrepreneurship and enhance urban resilience.

Aligning with Global Sustainability Goals

Beyond economic benefits, urban soilless farming contributes to environmental sustainability. Many systems integrate closed-loop practices, recycling organic waste, harvesting rainwater, and utilizing solar energy, thereby aligning with the Sustainable Development Goals (SDGs), particularly:

- **Goal 2**: Zero Hunger
- **Goal 11**: Sustainable Cities and Communities
- **Goal 12**: Responsible Consumption and Production (CADFOD, 2015; UN, 2025)

These practices not only reduce the ecological footprint of food production but also promote circular economy principles within urban ecosystems (CADFOD, 2015) (UN, 2025).

Reframing Urban Agriculture as a Core Urban Strategy

Historically marginalized in urban planning, agriculture is now being reimagined as a cornerstone of resilient urban food systems. From household gardens to commercial rooftop farms, urban agriculture contributes to food security, ecosystem services, social cohesion, and local economic development. In rapidly urbanizing countries like Indonesia, where land conversion and pollution threaten traditional agriculture, the adoption of innovative, space-efficient technologies is not merely advantageous—it is essential.

Controlled-environment agriculture, supported by interdisciplinary research and policy frameworks, offers a scalable path forward. By integrating scientific innovation with community engagement and sustainability principles, urban farming—particularly through soilless systems—can transform cities into hubs of food production, economic opportunity, and environmental stewardship

3. Concept and Technological Foundation of Soilless Culture

Soilless systems often outperform traditional methods in terms of water efficiency and yield. Hydroponic setups can achieve water savings up to 90% while delivering 3–10 times higher yields per unit area (Sundari et al., 2022;

Van Os et al., 2019). This makes them ideal for high-density urban settings like those in Java, Indonesia, where arable land is shrinking while urban food demand rises.

The economic impact on households is equally significant. Studies have shown that small-scale hydroponic farming can contribute to 30–50% net profit margins, depending on crop type and market access (Quagrainie et al., 2017). Urban growers may either reduce food expenditures by producing their own vegetables or generate surplus for neighborhood markets, cafes, or online platforms.

Soilless culture encompasses agricultural production systems that do not rely on natural soil as a growth medium. The most common methods include hydroponics (nutrient-enriched water), aquaponics (combining hydroponics with aquaculture), and aeroponics (mist-based nutrient delivery). These systems offer highly controlled environments that optimize plant growth through precise nutrient management, reduced pest exposure, and minimized water usage. Moreover, they can be installed on rooftops, balconies, vertical racks, and indoor settings, making them particularly adaptable to space-constrained urban environments.

Hydroponics systems, for instance, have been shown to increase productivity per square meter by 3 to 10 times compared to soil-based methods. Furthermore, the recirculating nutrient systems used in these methods reduce water consumption by 70–90%, aligning with environmental sustainability goals (Kotler et al., 2021; Sundari & Fitriadi, 2024). Aeroponics, while more technically demanding, offers even higher efficiency in water and nutrient use, and is well-suited for high-value crops like leafy greens, herbs, and strawberries (Sundari et al., 2021, 2022).

Multiple studies confirmed the superior yield and efficiency of soilless methods compared to conventional farming. For example, Al-Kodmany (2018) reported that hydroponic lettuce yields were seven times higher than those from open-field systems on a per square meter basis 3. Furthermore, soilless systems can reduce water consumption by up to 90%, as demonstrated in comparative studies by Resh (2013) 4.

Efficiency in nutrient delivery translates into faster crop cycles, reduced land demand, and minimal pesticide usage. These benefits are particularly crucial in cities where space is at a premium, such as Jakarta or Bandung, and where concerns over pesticide residues influence consumer preferences.

The implementation of soilless culture across selected urban households in West Java demonstrated a consistent improvement in productivity metrics. On average, hydroponic vegetable yields reached 3.5–4.2 kg/m²/month, significantly outperforming the productivity of traditional soil-based home gardens, which ranged between 1.1–1.5 kg/m²/month. Leafy greens such as *kailan* (Brassica oleracea), *pakchoy* (Brassica rapa), and lettuce (*Lactuca sativa*) thrived under nutrient film technique (NFT) systems with minimal pest exposure.

These findings are consistent with global studies indicating that soilless systems can boost urban crop productivity by up to 5–10 times per unit area 1. The stable yields were attributed to controlled nutrient availability, water efficiency, and year-round cropping independent of soil fertility or climate irregularities.

4. Socioeconomic Relevance: Household Income Generation

Soilless Urban Agriculture as an Inclusive Economic Strategy

While technological innovation is a defining feature of soilless agriculture, its transformative potential lies equally in its socio-economic implications. In rapidly urbanizing regions, particularly in the Global South, urban residents increasingly seek flexible, low-barrier, and scalable livelihood opportunities. Soilless systems, especially modular, low-cost hydroponic kits offer a compelling entry point for micro-entrepreneurship. These systems enable households to cultivate vegetables and herbs for self-consumption, thereby reducing household food expenditures, while also producing marketable surpluses for neighbourhood markets, cafés, or digital platforms (Bauw & Suharko, 2015; dos Santos, 2016; Hui, 2011; Poulsen et al., 2017; Sundari et al., 2023). The short crop cycles and year-round cultivation potential support continuous revenue streams.

Empirical studies underscore the economic viability of small-scale hydroponic systems. In some urban communities, especially where traditional food values dominate, soilless produce may be viewed with scepticism. Overcoming this requires consumer education, cultural sensitivity, and potentially incorporating heirloom crops or familiar flavor profiles into cultivation choices. Urban farming is resilient, but its success hinges on smart design, supportive policies, and inclusive innovation. Market access: Consumers may question the freshness or safety of soilless produce. Education and branding are essential to build trust and expand local markets. Despite their technical advantages, soilless systems face cultural and perceptual barriers. In communities where traditional food values dominate, hydroponically grown produce may be met with scepticism regarding its freshness, safety, or authenticity. Addressing these concerns requires a multi-pronged approach:

- Consumer education on nutrient quality and safety
- Culturally sensitive crop selection, including heirloom or locally preferred varieties

- Branding strategies that emphasize transparency, sustainability, and health benefits (Dedi et al., 2023; Ghana, 2014)

Such strategies are essential to build consumer trust and expand market access, particularly in informal economies and community-supported agriculture (CSA) networks (Dedi et al., 2023; Ghana, 2014).

Social Inclusion and Empowerment

The relatively low labour intensity and modularity of soilless systems make them accessible to diverse demographic groups, including women, youth, and the elderly. When coupled with training programs, cooperative models, and digital marketing tools, these systems become platforms for inclusive innovation and social empowerment.

A notable outcome from pilot projects in West Java was the high level of female participation—63% of primary caretakers of soilless units were women. Participants reported increased self-efficacy, enhanced decision-making roles within households, and new opportunities for home-based entrepreneurship. Youth engagement was also significant, particularly through STEM-based school projects and hobby farming initiatives, which fostered both technical skills and environmental awareness

These findings align with global development narratives that position urban agriculture as a tool for inclusive, sustainable livelihoods. Soilless systems, when embedded within supportive policy frameworks and community networks, can catalyze a shift toward more equitable urban food systems. They offer not only a response to spatial and environmental constraints but also a pathway to economic resilience, gender equity, and intergenerational engagement.

5. Sustainability Dimensions and the Circular Economy

Urban soilless agriculture also intersects with sustainability and the circular economy in critical ways. These systems can integrate organic waste recycling, rainwater harvesting, and renewable energy inputs (e.g., solar-powered pumps and grow lights), reducing environmental impact while enhancing cost-efficiency (Abidin et al., 2017; Bihari et al., 2022; Hallett et al., 2016; Mantzanakis & Christofilopoulos, 2023).

Nutrient solutions can be formulated using bio stimulants and secondary metabolites from plant-based inputs, such as *Plectranthus amboinicus*for its antifungal and antioxidative properties. Such integration can improve plant resilience and post-harvest quality, aligning soilless farming with eco-friendly, health-conscious urban food trends.

Additionally, when these systems are designed for multi-use buildings, schools, hospitals, or apartment complexes, they reinforce community food resilience and sustainable resource management, addressing multiple SDGs such as Zero Hunger (Goal 2), Sustainable Cities (Goal 11), and Responsible Consumption and Production (Goal 12) (Sundari & Fitriadi, 2024; World Economic Forum, 2019).

Common growing media (e.g., rockwool, cocopeat) and plastics used in system components raise concerns about waste accumulation and disposal. Innovations in biodegradable materials or circular design are still emerging and often cost-prohibitive for small-scale operators. Rockwool and plastics used in many systems are non-biodegradable, raising concerns about long-term sustainability and disposal (Savvas & Gruda, 2018; Valenzano et al., 2008).

Soilless systems offer significant potential for supplementing household income, particularly in urban settings where formal employment may be scarce or inconsistent. A study by Touliatos et al. (2016) found that small-scale vertical hydroponic farms achieved net profits of up to £180/m² per annum, depending on market proximity and input costs 5.

In the Indonesian context, Cahyaningsih and Ardiansyah (2020) observed monthly income increases of IDR 1–2 million among urban farmers using hydroponic systems in West Java 6. The authors attribute this gain to both fresh produce sales and cost savings on household food expenditures. Other economic benefits include:

1. Short payback periods for low-cost starter kits
2. Low labour intensity, allowing participation by women and the elderly
3. Year-round cultivation, enabling continuous cash flow

However, initial investments and technical training remain barriers for some households as a point echoed in the literature by Bhatt et al. (2021), who call for inclusive financial tools and cooperative business models.

Analysis of economic data from 30 participating households revealed a mean income increment of IDR 1.35 million/month, equivalent to 12–15% of their baseline earnings. This figure includes both direct produce sales and estimated savings from home consumption. Urban farmers selling to local markets and digital platforms (via WhatsApp groups and e-commerce apps) realized faster returns on investment, particularly in communities with active cooperative networks. Break-even analysis indicated that small-scale hydroponic units (≤10 m²) required 2.5 to 4 months to recover initial setup costs ranging from IDR 500,000 to 1.2 million. Households that diversified their offerings, such as producing seedlings, selling nutrient solutions, or creating pre-packaged salad kits, reported faster income stabilization.

These results reinforce previous research from Cahyaningsih and Ardiansyah (2020) on hydroponic income generation among urban households in West Java.

Table 1. Yield and Economic Impact of Soilless vs. Soil-Based Systems

Parameter	Soilless (Hydroponic)	Traditional Soil-Based
Average Yield (kg/m²/month)	3.5 – 4.2	1.1 – 1.5
Household Income Gain (IDR/month)	1.35 million	~450,000 (est.)
Crop Cycle Duration (days)	30 – 35	40 – 50
Pest Incidence (reported cases/month)	0.3	2.1
Payback Period	2.5 – 4 months	10 – 12 months
Average Yield (kg/m²/month)	3.5 – 4.2	1.1 – 1.5

Comparative performance metrics between hydroponic and conventional home gardening systems in urban households of West Java.

6. Barriers and Strategic Considerations

Despite its benefits, several barriers limit the widespread adoption of soilless systems:

a. Initial investment costs: Systems and infrastructure may require upfront capital ranging from IDR 500,000 to several million, depending on complexity.
b. Technical skills and maintenance: Effective management of pH, EC (electrical conductivity), and nutrient formulations requires training.
c. Market integration: Without cooperative models or digital access, farmers may face difficulty in marketing and distributing produce efficiently
d. Policy support: While urban farming is often promoted in city development plans, regulatory support for rooftop agriculture and microenterprise funding remains limited.

This model integrates government, academia, industry, media, communities, and financial institutions to co-develop supportive ecosystems for urban agribusiness. For instance, training programs by universities, microloans by financial institutions, and promotional campaigns via media channels can jointly reduce barriers to adoption.

Effective operation of hydroponic and aeroponic systems requires continuous monitoring of nutrient concentrations, pH, EC, and microbial control. Without ongoing education and adaptive management tools, urban farmers, especially household-scale or first-time adopters—might face crop failure or inefficient yields. There's a need for more accessible tech, user-friendly design, and localized extension services. Managing nutrient concentrations, pH, and EC requires baseline agronomic training. Inadequate knowledge can result in crop loss or nutrient inefficiency (Safitri et al., 2021; Van Os et al., 2019).

Despite its benefits, soilless agriculture still faces several barriers:

1. High start-up costs: Initial investment in structure, nutrients, and monitoring equipment remains a hurdle for many households, especially in informal settlements.

2. Regulatory ambiguity: Lack of clear zoning laws for rooftop or balcony farming can discourage uptake 11.
3. Information asymmetry: Limited access to training and technical resources hinders proper implementation and maintenance.
4. Waste management: Non-biodegradable media like rockwool can accumulate as urban solid waste unless recycled or substituted.

Bhattarai et al. (2021) stress the role of policy frameworks, public-private partnerships, and extension education in resolving these bottlenecks, particularly in the Global South (Maschio, 2017).

7. Case Applications and Indonesia's Context

In the Indonesian context, particularly in urban and peri-urban areas of Java Island, soilless agriculture is gaining traction. Municipalities like Bandung and Jakarta have initiated pilot projects in low-income housing complexes, providing residents with basic hydroponic kits and training modules (Savvas & Gruda, 2018; Sundari et al., 2021). These initiatives reflect a growing institutional recognition of urban farming not merely as a subsistence activity, but as a scalable livelihood strategy.

In West Java's Tawang district, where population density is rising and arable land is increasingly fragmented, soilless farming presents a strategic opportunity to buffer household income, particularly during periods of seasonal employment volatility. Empirical observations suggest that integrating hydroponic systems into household routines can generate consistent yields of high-demand crops such as pakchoy, lettuce, and kale. These crops align with shifting consumer preferences toward pesticide-free, locally grown produce, creating branding and value-adding opportunities for MSMEs (Guo, 2021; Pertanian, 2021)

However, the transition to controlled-environment agriculture (CEA) is not without challenges. Contrary to assumptions of biosecurity, indoor systems remain susceptible to pest and pathogen outbreaks. In closed-loop environments, infestations can spread rapidly, and the use of synthetic pesticides is often restricted due to urban health regulations. This necessitates the adoption of integrated pest management (IPM) strategies, including biological controls, habitat manipulation, and microbial inoculants—requiring both technical expertise and financial investment. For researchers and practitioners, this presents an opportunity to combine biochemical insights, consumer behaviour analysis, and economic modelling into localized innovation systems.

Ultimately, Indonesia's urban farming trajectory, anchored in soilless culture, offers a replicable model for other rapidly urbanizing nations. It demonstrates how scientific innovation, when embedded in socio-economic realities and supported by inclusive governance, can transform urban households into resilient, productive agents within the food system.

8. Future Outlook and Research Gaps

Advancing Soilless Urban Agriculture through Interdisciplinary Inquiry

As urban agriculture evolves from a grassroots movement into a strategic pillar of resilient food systems, soilless culture technologies demand rigorous, interdisciplinary research to unlock their full potential. While pilot projects and community-based initiatives have demonstrated promising outcomes, significant knowledge gaps remain in understanding the long-term economic, nutritional, and ecological implications of these systems—particularly in tropical urban contexts like Indonesia.

To ensure scalability, inclusivity, and sustainability, future research must address the following priority areas:

a. Quantifying household-level ROI (Return on Investment) across different system types and scales.

There is a critical need to develop robust financial models that assess ROI for various soilless systems, ranging from low-cost NFT setups to commercial-scale vertical farms. These models should incorporate capital expenditure, operational costs, yield variability, and market dynamics to inform household decision-making and MSME investment strategies.

b. Characterizing nutrient-use efficiency across crop types in tropical urban climates

Tropical microclimates introduce unique challenges in nutrient solubility, evapotranspiration, and plant metabolism. Research should focus on optimizing nutrient formulations and delivery protocols for key urban crops, while also exploring the role of bio stimulants and microbial consortia in enhancing NUE and crop quality.

c. Developing user-friendly monitoring technologies for non-expert growers

To democratize access to soilless farming, especially among non-expert growers, there is a need for affordable, user-friendly monitoring tools. Innovations in IoT-based sensors, mobile diagnostics, and AI-driven nutrient management systems can reduce technical barriers and improve system reliability.

d. Modelling urban food systems to simulate household income effects under different policy scenarios.

Systems modelling can simulate the socio-economic impacts of urban farming under various policy interventions—such as subsidies, zoning reforms, or carbon credits. These models should integrate household income effects, food access metrics, and environmental externalities to guide evidence-based policymaking.

By addressing these research gaps through transdisciplinary collaboration—linking agronomy, economics, behavioural science, and data analytics—soilless urban agriculture can evolve into a scientifically grounded, socially inclusive, and economically viable solution for future cities.

9. Energy Dependence and Climate Variability

While soilless agriculture offers a promising solution to urban food insecurity and land scarcity, its scalability is intrinsically linked to energy availability and climate stability. Most hydroponic, aeroponic, and aquaponic systems are energy-intensive, relying on continuous electricity to power pumps, nutrient delivery systems, artificial lighting, and climate control technologies. In tropical urban environments—where temperature and humidity fluctuations are pronounced—energy demands for ventilation, cooling, and lighting can significantly increase operational costs (Sustainability, 2020).

This energy dependence introduces two critical vulnerabilities. First, as global energy prices fluctuate and fossil fuel subsidies are phased out, urban farms may face rising input costs that erode profitability, particularly for low-income households and MSMEs operating on thin margins. Second, climate variability, including heatwaves and erratic rainfall patterns, can disrupt system performance, especially in setups lacking adaptive climate control mechanisms.

Integrating renewable energy sources, particularly solar photovoltaics, presents a viable mitigation strategy. Solar-powered hydroponic systems have demonstrated potential in reducing long-term operational costs and enhancing system autonomy. However, affordability and scalability remain significant barriers in many urban contexts. Initial capital investment for solar infrastructure, coupled with limited access to financing and technical expertise, constrains adoption especially among marginalized communities.

To address these challenges, future research and policy must focus on:

- Techno-economic modelling of energy use across system types and urban microclimates.
- Life-cycle assessments (LCA) to evaluate the carbon footprint and energy return on investment (EROI) of renewable-integrated systems.
- Design of modular, low-energy systems tailored to tropical urban settings.
- Policy incentives such as green energy subsidies, carbon credits, or feed-in tariffs to support the adoption of clean energy in urban agriculture.

The resilience of soilless urban farming hinges not only on agronomic efficiency but also on energy sovereignty. Embedding renewable energy solutions into system design is essential to ensure that urban agriculture remains economically viable, environmentally sustainable, and climate-resilient in the decades ahead.

10. Limited Policy Support and Regulatory Uncertainty

Urban farming often operates in gray zones of land use, water regulation, and food safety. Many cities still lack formal policies that define zoning rights, rooftop access, or guidelines for selling produce grown in non-traditional settings. Without a regulatory framework, investment and public-private partnerships may stagnate. Urban farms often operate outside established regulatory frameworks. Without a clear policy inclusion, investment and community adoption may stall (*OECD-FAO Agricultural Outlook 2022-2031*, 2022; OECD, 2024)

While urban farming is acknowledged in regional planning documents, participating households reported a lack of access to financial support, rooftop permits, or structured technical assistance. Without institutional backing, scaling these initiatives may be uneven or short-lived. Adoption of collaborative frameworks such as the Hexahelix model, which engages government, academia, industry, media, civil society, and finance, could address institutional inertia.

Policy ambiguity presents an additional hurdle. In many jurisdictions, urban farming is not formally embedded in land-use policy or business licensing frameworks. This creates legal uncertainty for rooftop cultivation or community farming initiatives, inhibiting investment and long-term planning. Integrating urban agriculture into spatial planning regulations and food system strategies is crucial to ensure stability and institutional support.

11. Economic Viability and Market Integration

While promising as a source of household income, the soilless urban farms may face challenges scaling up profitably. Issues include:

a. Price competition with conventional produce

b. Consumer perception of quality or safety

Inconsistent market access without cooperative marketing systems. In the long run, business models need to adapt with branding, subscription models, or integration with health-focused food services. Despite the positive outcomes, some households reported operational challenges. These included:

1. Fluctuating pH and EC levels in nutrient solutions
2. Occasional pump failures due to irregular power supply
3. Algal growth and mosquito larvae in neglected reservoirs

Such issues suggest a learning curve and a need for simplified training materials, automated systems, or community-based technical support. Households with prior agricultural experience showed higher system resilience and better adaptation over time.

12. Anticipating Future Challenges of Urban Soilless Farming

While soilless urban farming offers a compelling response to urban food insecurity and income inequality, several emerging challenges could hinder its long-term viability. As cities grow more complex, these systems must evolve amid economic, environmental, and social constraints. One major challenge lies in energy dependency. Hydroponic and aeroponic systems depend heavily on electricity for pumps, lighting, and temperature regulation. In regions with unstable power grids or rising energy costs, this dependence may undermine affordability and scalability. Integrating renewable energy—like solar-powered systems—has shown promise, but remains cost-prohibitive for smallholder adoption without external support.

Another issue is the technical learning curve. Managing nutrient solutions, monitoring pH and EC levels, and controlling humidity and temperature demand a level of agronomic knowledge unfamiliar to many first-time urban farmers. Without adequate extension services or user-friendly tools, improper management can lead to crop failure, nutrient waste, and economic losses.

Economic challenges persist in market integration and consumer perception. While demand for local, pesticide-free produce is growing, urban farmers must still compete with conventional supply chains on price and distribution efficiency. Additionally, some consumers may remain skeptical about soilless products, associating them with artificial cultivation. Addressing this requires branding, education, and perhaps sensory quality research—a domain in which your own expertise in metabolite profiling and consumer preference analysis could be highly impactful.

To overcome these barriers, collaborative frameworks such as the Hexahelix model—involving government, academia, industry, media, civil society, and finance—can catalyse holistic innovation. This is especially relevant to HP's interdisciplinary approach, which fuses agronomic science with consumer insights and branding strategies to empower urban micro-enterprises. Together, these challenges demand interdisciplinary collaboration, innovation, and inclusive governance to ensure that urban soilless farming realizes its full potential, not just as a food source, but as a driver of urban resilience and inclusive economic opportunity.

Finally, there are environmental and material sustainability issues to consider. Widely used substrates like rockwool are non-biodegradable, and single-use plastics are common in system infrastructure. This poses a long-term waste management concern unless biodegradable materials and circular design principles are more widely adopted.

13. Implication

The findings of this study affirm that soilless urban farming—particularly hydroponics—can serve as a viable strategy for enhancing household income, especially in densely populated, low-to-middle-income urban areas. The economic, ecological, and educational dimensions of such systems suggest a multidimensional impact on urban resilience:

1. Economically, households benefit through both direct revenue and savings on food expenses.
2. Socially, inclusive participation (notably among women and youth) fosters local entrepreneurship and community cohesion.
3. Ecologically, water-saving and pesticide-free practices align with sustainable development and resource conservation.

This research also highlights that urban soilless farming can act as a gateway for circular economy integration and localized food sovereignty, strengthening the role of cities in achieving SDGs 2, 11, and 12. Moreover, the interdisciplinary nature of the approach, bridging agronomy, consumer behaviour, and socio-economic planning, makes it adaptable across various urban typologies.

14. Conclusion

Urban farming with soilless culture has proven to be more than a technological innovation; it is an actionable pathway toward food security and economic empowerment for urban households. The observed increase in household income, system adaptability, and high consumer acceptance illustrate the transformative potential of this model in modern urban planning and livelihood strategies.

While barriers remain, such as technical complexity, capital requirements, and regulatory gaps, the benefits far outweigh the limitations, particularly when embedded within cooperative, policy-supported ecosystems. The study underscores that sustainable urban food systems are not limited to large-scale interventions but can also flourish at the household level through smart, scalable solutions like hydroponics and aquaponics.

Suggestion

1. Policy and Institutional Support Local governments should integrate urban soilless farming into spatial and economic development plans. This includes simplifying rooftop access regulations, offering start-up grants, and supporting micro-cooperatives.
2. Capacity Building and Technical Literacy Educational institutions and NGOs should collaborate to deliver hands-on training, focusing on affordable, low-tech systems and maintenance routines suitable for non-specialist users.

3. Inclusive Innovation Models the Hexahelix framework should be applied to foster multi-stakeholder innovation, linking government, academia, industry, media, communities, and finance to co-develop tools, funding pathways, and knowledge exchange platforms.
4. Digital Integration and Branding Urban farmers should be encouraged to use mobile platforms for marketing, logistics, and consumer education. Branding strategies that highlight freshness, safety, and sustainability (e.g., “locally grown hydroponics”) can enhance market value.
5. Future Research Direction: Additional longitudinal studies are needed to assess long-term profitability, environmental footprint, and nutrient profile optimization. Integrating metabolomic and sensory science into urban agribusiness planning—like your work with value-added products—can create tailored crop designs for niche urban markets.

REFERENCES

Abidin, S. Z., Nasihien, R. D., & Budiyanto, H. (2017). Air Inflated Greenhouse as Urban Farming Facilities: Architectural Overview. *IJTI (International Journal Of Transportation And Infrastructure)*, *1*(1), 1. https://doi.org/10.29138/ijti.v1i1.326

Bauw, I. Z., & Suharko. (2015). *Gerakan Urban Farming: Studi Atas Mobilisasi Sumber Daya Oleh Komunitas Bandung Berkebun* [UGM]. file:///C:/Users/HP/AppData/Local/Mendeley Ltd/Mendeley Desktop/Downloaded/Zainab Bauw, Suharko - 2015 - Gerakan Urban Farming Studi Atas Mobilisasi Sumber Daya Oleh Komunitas Bandung Berkebun.html

Bihari, C., Ahamad, S., & Saha, S. (2022). *Rooftop Vegetable Farming in Urban Areas*. *04*(06), 226–228.

CADFOD. (2015). Sustainable Development Goals: Action towards 2030. *Www.Cadfod.Org.Uk*, 11. www.cadfod.org.uk

Dedi, D., Sundari, R. S., & Heryadi, D. Y. (2023). Perilaku Konsumen terhadap Level Penggunaan Gula Aren (Arenga piñnata). *Mimbar Aagribisnis: Jurnal Pemikiran Masyarakat Ilmiah Berwawasan Agribisnis*, *9*(1), 1312–1322. https://doi.org/10.25157/ma.v9i1.9542

dos Santos, M. J. P. L. (2016). Smart cities and urban areas—Aquaponics as innovative urban agriculture. *Urban Forestry and Urban Greening*. https://doi.org/10.1016/j.ufug.2016.10.004

FAO. (2019). *Enhancing National and Regional Capacities to Deal with Tilapia Lake Virus* (Issue June). https://www.fao.org/3/CA5225EN/CA5225EN.pdf

Ghana, A. K. (2014). Peranan Urban Farming dalam Menarik Minat Beli Konsumen pada Real Estate Perubamah di Surabaya. In *Const. Comment.*

Grauman, J. V. (2018). The speed of urbanization around the world. In *Population bulletin of the United Nations* (Vol. 1, Issue 8). https://population.un.org/wup/assets/WUP2018-PopFacts_2018-1.pdf

Guo, M. (2021). Soil Health Assessment and Management : Recent Development in Science and Practices. *Soil System*, *61*, 1–20.

Hallett, S., Hoagland, L., & Toner, E. (2016). Urban agriculture: Environmental, economic, and social perspectives. In *Horticultural Reviews* (Vol. 44, Issue November). https://doi.org/10.1002/9781119281269.ch2

Hui, S. C. M. (2011). Green roof urban farming for buildings in high-density urban cities. *World Green Roof Conference*.

Kotler, P., Kartajaya, H., & Setiawan, I. (2021). Marketing 5.0 Technology for Humanity. In *News.Ge* (10th ed.). John Wiley & Sons, Inc.

Mantzanakis, S., & Christofilopoulos, E. (2023). *Urban Farming*. *April*. https://doi.org/10.13140/RG.2.2.36119.24488

Maschio, B. M. (2017). *Urban Agriculture to develop Food Sovereignty Lessons from and to Havana*.

OECD-FAO Agricultural Outlook 2022-2031. (2022). OECD. https://doi.org/10.1787/f1b0b29c-en

OECD. (2023). Urban agriculture: Enhancing food systems in cities. https://www.oecd.org/publications/urban-agriculture-7ec0c158-en.htm

OECD. (2024). *Recommendation of the Council on OECD Legal Instruments Guiding Principles concerning International Economic Aspects of Environmental Policies 8*. http://legalinstruments.oecd.org

Pamuji, A. Z. K., Al-Baihaqi, M. S., & Kinasih, I. D. (2014). *Akuaponik sebagai jawaban kemandirian pertanian dan perikanan kota surabaya* (Vol. 0030).

Pertanian, P. I. (2021). *Soilless-based Agriculture* (pp. 1–47).

Poulsen, M. N., Neff, R. A., & Winch, P. J. (2017). The multifunctionality of urban farming: perceived benefits for neighbourhood improvement. *Local Environment*. https://doi.org/10.1080/13549839.2017.1357686

Quagrainie, K. K., Manolio, R., Flores, V., Kim, H., Mcclain, V., Quagrainie, K. K., Manolio, R., Flores, V., & Kim, H. (2017). Economic analysis of aquaponics and hydroponics production in the U . S . Midwest. *Journal of Applied Aquaculture*, *00*(00), 1–14. https://doi.org/10.1080/10454438.2017.1414009

Safitri, K. I., Abdoellah, O. S., & Gunawan, B. (2021). Urban Farming as Women Empowerment: Case Study Sa'uyunan Sarijadi Women's Farmer Group in Bandung City. *E3S Web of Conferences*, *249*. https://doi.org/10.1051/e3sconf/202124901007

Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry - A review. *European Journal of Horticultural Science*, *83*(5), 280–293. https://doi.org/10.17660/eJHS.2018/83.5.2

Sundari, R. S., & Fitriadi, B. W. (2024). Groundwork for Understanding the Principles and Importance of sustainable Agriculture. In K. Bellitürk (Ed.), *Fundamental of Sustainable Agriculture* (1st ed., Issue 1, pp. 29–66). IKSAD Publishing House. https://iksadyayinevi.com/home/fundamentals-of-sustainable-agriculture/

Sundari, R. S., Heryadi, D. Y., & Nursamsi, R. (2025). Kelayakan Usaha Tani Sawi dan Selada Hijau Sistem Hidroponik di Kelompok Tani Tunas Harapan Feasibility of Mustard and Green Lettuce Farming Business Using Hydroponic Systems in Farmer Groups Tunas Harapan. *Mimbar Aagribisnis: Jurnal Pemikiran Masyarakat Ilmiah Berwawasan Agribisnis*, *11*(1), 1173–1182. https://doi.org/http://dx.doi.org/10.25157/ma.v11i1.16877

Sundari, R. S., Sulistyowati, L., & Noor, T. I. (2021). Soilless Culture in Urban Farming. *International Conference on Biodiversity, Microbiology to Multiple Industrial and Environmental Application to Support Sustainable Development and Improve Human Welfare, 18 December 2021At: Surakarta, Center of Java, Indonesia*, *8*(2), 29–59. https://doi.org/DOI: 10.13057/asnmbi/m080202

Sundari, R. S., Sulistyowati, L., Noor, T. I., & Setiawan, I. (2022). Soilless Culture for Agribusiness throughout Urban Farming in Indonesia. In M. Turan, S. Argin, Güneş, & E. Y. Adem (Eds.), *Soilless Culture* (pp. 1–10). Intechopen. https://doi.org/10.5772/intechopen.101757

Sundari, R. S., Sulistyowati, L., Noor, T. I., & Setiawan, I. (2023). Break Barriers: The Woman Roles in Urban Farming Development in Indonesia. *Baltica Journal*, *36*(4), 48–67. https://www.researchgate.net/publication/370410867_BREAK_BARRIERS_THE_WOMAN_ROLES_IN_URBAN_FARMING_DEVELOPMENT_IN_INDONESIA

Touliatos, D., Dodd, I. C., & McAinsh, M. R. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food and Energy Security, 5*(3), 184–191. https://www.researchgate.net/publication/301294868

UN. (2025). Progress towards the Sustainable Development Goals. In *United Nations General Assembly Economic and Social Council* (Vol. 64782, Issue May).

Valenzano, V., Parente, A., Serio, F., & Santamaria, P. (2008). Effect of growing system and cultivar on yield and water-use efficiency of greenhouse-grown tomato. *Journal of Horticultural Science and Biotechnology*, *83*(1), 71–75. https://doi.org/10.1080/14620316.2008.11512349

Van Os, E. A., Gieling, T. H., & Heinrich Lieth, J. (2019). Technical equipment in soilless production systems. In *Soilless Culture: Theory and Practice Theory and Practice*. Elsevier B.V. https://doi.org/10.1016/B978-0-444-63696-6.00013-X

World Economic Forum. (2019). *The Global Risks Report*. 1–114. http://wef.ch/risks2019

2 INTEGRATING SOIL HEALTH METRICS INTO AGRIBUSINESS INVESTMENT DECISIONS

Ristina Sıti Sundari[1], Budhi Wahyu Fitriadi[2]

1. Introduction

The economic invisibility of soil health

Though fundamental to agricultural productivity and ecosystem resilience, soil health remains excluded mainly from economic valuation and investment frameworks. This “economic invisibility” arises from its complex, multidimensional nature and the slow pace at which soil properties change, factors that resist short-term financial quantification. Conventional agribusiness metrics prioritize immediate outputs such as yield per hectare and input costs, often neglecting the long-term consequences of soil degradation or the benefits of regenerative practices.

Moreover, soil health contributes to public goods like carbon sequestration and water purification, yet farmers typically bear the costs of maintaining it without adequate compensation, an example of market failure. The absence of standardized soil health indicators in financial reporting and sustainability disclosures further obscures its economic relevance. As the Berkeley Food Institute notes, integrating soil health into economic and policy frameworks remains a critical yet unresolved challenge for sustainable agriculture.

Economic invisibility arises from several factors, such as:

Multidimensional and Slow-Changing: Soil properties change is making quantification difficult	**Traditional Agribusiness:** Focus on yield, input cost, and market prices, overlooking long-term soil impacts.
Market Failure Exists: Farmers bear the costs of stewardship, while many benefits are public goods	**Lack of Standardized Metrics:** No standardized soil indicators in financial reporting and sustainability disclosures

Soil health is vital in agricultural productivity, environmental resiliency, and ecosystem sustainability.

Why investors and agribusinesses should care?

Investors and agribusinesses increasingly recognize that soil is not just a production input but a long-term asset. The reason Why Soil Health Matters Economically:

1 Associated Professor. Agribusiness Study Program, Agricultural Faculty, Agribusiness, Universitas Perjuangan Tasikmalaya, -Agricultural Biology, Orcid: 0000-0002-5310-8520, ristinasitisundari@unper.ac.id
2 Assistant Professor. Agribusiness Study Program, Agricultural Faculty, Agribusiness, Universitas Perjuangan Tasikmalaya, -Development Economics, budhiwahyu@unper.ac.id

- Improved ROI: Healthy soils reduce input costs (e.g., fertilizers, irrigation) and increase yield stability. Healthy soils enhance nutrient cycling and water retention, reducing reliance on costly inputs like synthetic fertilizers and irrigation. This lowers operational expenses while stabilizing yields, improving return on investment (ROI).
- Climate resilience: Soils with high organic matter buffer against droughts and floods, reducing financial risk. Soils rich in organic matter act as natural buffers against climate extremes. They retain moisture during droughts and improve infiltration during heavy rains, mitigating crop losses and reducing financial risk from weather volatility.
- Carbon markets: Soils can sequester carbon, opening revenue streams through carbon credits. Soils are significant carbon sinks. Practices that build soil organic carbon, like cover cropping or reduced tillage, can qualify for carbon credits, creating new revenue streams through voluntary or compliance-based carbon markets.
- Supply chain security: Degraded soils threaten long-term raw material availability, increasing volatility. Soil degradation undermines long-term productivity and raw material availability. Maintaining soil health ensures a consistent supply for agribusinesses, reducing volatility and safeguarding supply chain continuity
- Consumer demand: Markets increasingly reward sustainable practices, and soil health is central to regenerative branding. As consumer awareness grows, markets increasingly favor sustainably produced goods. Soil health is a cornerstone of regenerative agriculture, enhancing brand value and market access through eco-labels and sustainability certifications.

"Healthy soil is gold for businesses. Investing in climate-smart agriculture could generate up to $10 trillion in net financial return over 30 years." Forbes Business Council, "An investment in soil health delivers private and public benefits. It supports productivity, climate mitigation, and long-term profitability." IUCN Report. Based on the insights from the Soil Health Institute's 100-farm study, USDA economic analyses (Thorsen & Woodbridge, 2011), and corporate reporting frameworks, here is a visual framework for integrating soil health metrics into agribusiness investment decisions:

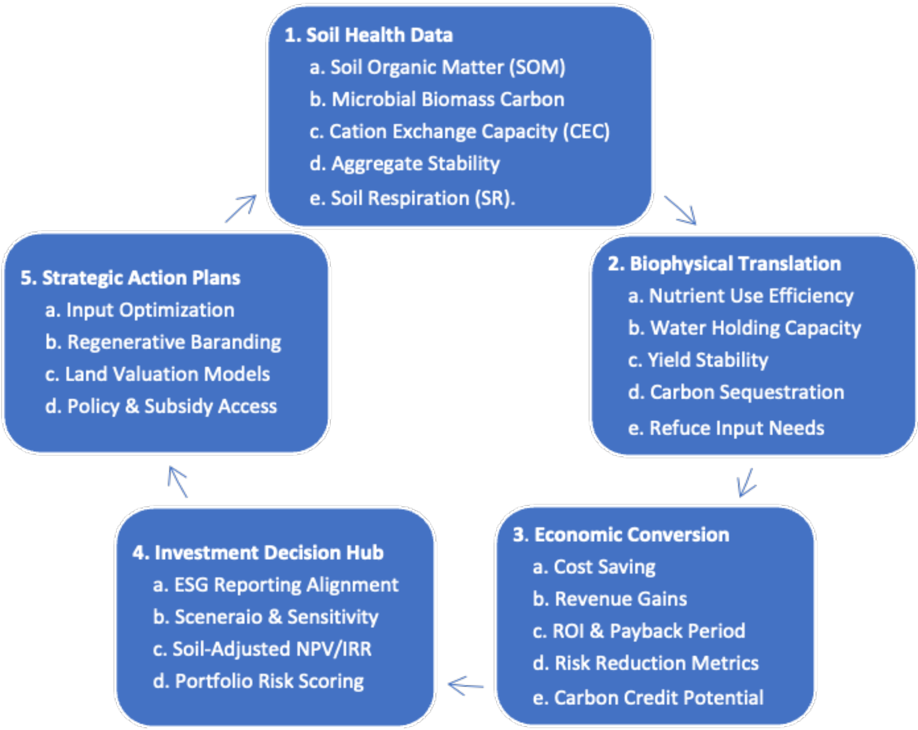


Figure 1. Soil Health–Integrated Agribusiness Investment Model

The insights from the Sources involved in:

- Economic Benefits: Adopting soil health systems, such as cover cropping, reduced tillage, and organic amendments, has lowered corn production costs by $24 per acre while boosting net income by $51.60 per acre. These gains stem from reduced input dependency and improved soil productivity.
- Yield Stability: Approximately 67% of farmers practicing soil health management report increased yields. This reflects healthy soils' enhanced resilience and biological activity, which support consistent crop performance across variable conditions.
- Carbon & ESG: Soil carbon sequestration is gaining traction in carbon markets and Environmental, Social, and Governance (ESG) frameworks. By quantifying and monetizing carbon stored in soils, farmers and agribusinesses can access new income streams while aligning with sustainability mandates (Rejesus et al., 2021).
- Investor Relevance: Agribusiness investors are beginning to view soil as a financial asset, but need simplified, standardized metrics (e.g., traffic-light systems). Investors are beginning to recognize soil as a long-term financial asset. However, to integrate soil health into investment

decisions, they require simplified, standardized metrics, such as traffic-light systems or soil health indices, that translate complex biophysical data into actionable financial insights.

2. Soil Health Metrics: Scientific Foundations

Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. To integrate soil health into agribusiness investment decisions, we must first understand the key metrics that quantify it. These metrics fall into three broad categories: biological, chemical, and physical indicators (Table 1, Table 2, and Table 3).

Table 1. Biological Indicators

Metric	Description	Economic Relevance
Soil Organic Matter (SOM)	Carbon-rich material from decomposed plant and animal residues	Enhances nutrient retention, water holding, and microbial activity; linked to yield stability
Microbial Biomass Carbon (MBC)	Living microbial content in soil	Indicator of biological activity and nutrient cycling; higher MBC improves nitrogen use efficiency
Soil Respiration	CO_2 release from microbial metabolism	Reflects microbial activity and organic matter turnover; linked to soil fertility and carbon sequestration.

Table 2. Chemical Indicators

Metric	Description	Economic Relevance
Cation Exchange Capacity (CEC)	Soil's ability to hold and exchange nutrients	High CEC improves fertilizer efficiency and reduces leaching losses
pH and Electrical Conductivity (EC)	Acidity/alkalinity and salt concentration	Affects nutrient availability and crop tolerance; optimal pH reduces input costs.

Table 3. Physical Indicators

Metric	Description	Economic Relevance
Aggregate Stability	Resistance of soil structure to erosion and compaction	Improves infiltration, reduces runoff, and supports root development
Bulk Density	Mass of soil per unit volume	Lower bulk density indicates better porosity and root penetration, which is linked to reduced tillage costs.
Water Holding Capacity	Soil's ability to retain moisture	Enhances drought resilience and reduces irrigation needs

Why these metrics matter for investment

- Yield Stability: 67% of farmers using soil health systems reported increased yields. With 67% of farmers reporting increased yields from soil health practices, investors gain confidence in agricultural assets' long-term productivity and resilience. Stable yields reduce revenue volatility and enhance portfolio performance.

- Cost Reduction: Soil health systems reduced corn production costs by $24/acre and soybean by $16.57/acre. Soil health systems lower input costs by $24/acre for corn and $16.57/acre for soybeans through reduced fertilizer, irrigation, and pest control needs. This improves profit margins and operational efficiency, key indicators for investment viability (Soil Health Institute, 2021; Stevens, 2015; USDA, 2025).
- Carbon Sequestration: SOM increases can be monetized through carbon markets. Increases in soil organic matter (SOM) can be monetized via carbon markets, offering new revenue streams. This aligns with ESG investment criteria and enhances the financial attractiveness of regenerative farming systems.
- Risk Mitigation: Improved soil structure and biology buffer against climate extremes. Improved soil structure and biological activity enhance water retention and nutrient cycling, buffering crops against droughts, floods, and other climate extremes. This reduces climate-related financial risk and strengthens long-term asset resilience (Rejesus et al., 2021).

3. Economic Translation of Soil Metrics

Soil health metrics are not just ecological indicators; they can be translated into tangible economic outcomes that matter to farmers, investors, and agribusinesses. This section explains how soil health improvements affect profitability, risk, and long-term asset value.

Cost savings from soil health practices

Soil health practices, such as no-till farming, cover cropping, and nutrient management, enhance the efficiency of agricultural inputs by improving soil structure, nutrient cycling, and water retention. These improvements translate into measurable cost savings: Corn: Farmers saved an average of $24.00/acre in production costs. Soybean: Savings averaged $16.57/acre, even without yield increases (Lichtenberg, 2024; Soil Health Institute, 2021; Stevens, 2015; USDA, 2025).

These savings came from reduced fertilizer, pesticide, fuel, and labor expenses. These reductions stem from decreased reliance on fertilizers, pesticides, fuel, and labor. As the Soil Health Institute emphasizes, “Even if yield did not change, the soil health management system was still more profitable due to reduced expenses (Soil Health Institute, 2021).” This highlights the financial resilience and operational efficiency of soil health systems, making them a compelling strategy for farmers and investors. 67% of farmers reported yield increases after adopting soil health systems. The average yield gains are that corn reached +7.73 bu/acre, and Soybeans reached +2.91 bu/acre. Net income increased by $51.60/acre for corn and $44.89/acre for soybeans. These gains are attributed to improved nutrient cycling, water retention, and resilience to weather extremes.

Risk reduction and climate resilience

It was noted that 97% of farmers reported increased resilience to extreme weather (drought, heavy rain) and 93% reported improved field access during wet conditions. These benefits reduce volatility in yield and income, making farms more attractive to investors. (Bellitürk & Sundari, 2024; Sundari & Fitriadi, 2024). Soil health practices reduce variability in yields and revenues over time, a key factor in investment risk analysis. (Rejesus et al., 2021).

Carbon sequestration and ecosystem services

Soil organic matter comprises decomposed plant and animal residues, microbes, and humus. It is critical for soil fertility, structure, and water retention. SOM acts as a carbon sink by locking atmospheric carbon dioxide (CO_2) into stable organic compounds in the soil. This process is called carbon sequestration.

Soil organic matter (SOM) increases carbon storage, which can be monetized through:

- Carbon credit markets: Landowners or farmers who adopt carbon-sequestering practices can earn carbon credits. These credits represent a specific amount of CO_2 removed from the atmosphere; They can be sold to companies or governments seeking to offset their emissions.
- Ecosystem service payments: Landowners or farmers who adopt carbon-sequestering practices can earn carbon credits. These credits represent a specific amount of CO_2 removed from the atmosphere. They can be sold to companies or governments seeking to offset their emissions.

Natural climate solutions are agricultural practices that enhance carbon sequestration and ecosystem health, like Cover Cropping and No-Till Farming.

- Cover cropping involves planting crops (like legumes or grasses) during off-seasons. The benefit is to add organic matter to the soil, reduce erosion and nutrient runoff, enhance microbial activity, and increase carbon storage.
- No-Till Farming can avoid disturbing the soil through plowing. The benefit is that it preserves soil structure and microbial life, and reduces CO_2 emissions from soil disturbance, increasing long-term carbon retention.

It matters for climate mitigation, soil health, economic incentives, and policy.

Long-term asset value

- Healthy soils retain land value and reduce depreciation due to erosion or nutrient depletion.

Healthy soils function as a natural capital asset, preserving land productivity and buffering against depreciation. By maintaining organic matter, microbial diversity, and structural integrity, soils reduce vulnerability to erosion, salinization, and nutrient depletion—key drivers of land degradation. This resilience translates into sustained agronomic performance, which underpins land valuation in both agricultural and ecological markets. According to the Natural Resources Conservation Service, practices like cover cropping and conservation tillage enhance soil structure and nutrient cycling, thereby protecting long-term land value (NRCS Healthy Soils).

- Soil degradation can reduce land rental rates and resale value.

Soil degradation through erosion, compaction, acidification, or nutrient loss directly impacts land rental rates and resale value. Degraded soils exhibit reduced crop yields, increased input costs, and diminished ecological services, making them less attractive to tenants and buyers. Studies show that land degradation can reduce ecosystem service provisioning by up to 60%, with cascading effects on economic productivity and asset valuation (Lal, 2015) .

- Investors are beginning to treat soil health as a financial asset in ESG-aligned portfolios.

Investors are increasingly recognizing soil health as a strategic ESG asset, integrating it into sustainability-linked portfolios. Healthy soils contribute to carbon sequestration, climate resilience, and biodiversity, key metrics in environmental risk assessment. ESG-aligned funds now target regenerative agriculture and soil restoration as long-term value drivers, with soil health linked to stable returns and reduced climate exposure. For instance, BetterSoil and WBCSD highlight how soil stewardship aligns with ESG principles, offering both environmental and financial dividends (General & Share, 2021; Hub, 2024).

4. Framework for Investment Decision-Making

To bridge the gap between soil science and agribusiness finance, this section presents a structured framework that integrates soil health metrics into investment models.

Soil-integrated ROI models

Traditional ROI:

$$ROI = \frac{Net\ Profit}{Total\ Investment}\ x\ 100$$

Soil-adjusted ROI:

$$\text{Soil adjusted ROI} = \text{Net Profit} + \text{Soil Health Gains Total Investment} \times 100$$

Where Soil Health Gains include: Reduced input costs; Yield stability premiums, Carbon credit income; Avoided land degradation costs

Table 4. Decision Support Tools

Tool	Function	Example
Soil Dashboards	Real-time monitoring of pH, EC, and SOM	USDA's Soil Health Card
Remote Sensing & AI	Detect degradation, predict yield	Sentinel-2, CropX, Regrow
Scenario Analysis	Compare outcomes under different soil conditions	Monte Carlo simulations
Sensitivity Analysis	Test how ROI changes with SOM or CEC	Elasticity modeling

ESG and sustainability reporting

Soil health is increasingly recognized as a foundational component of sustainable agriculture and climate resilience, making it a critical metric within Environmental, Social, and Governance (ESG) frameworks. By embedding soil health indicators into ESG reporting, organizations can demonstrate tangible commitments to regenerative practices, biodiversity conservation, and ethical land stewardship.

Environmental Dimension: Soil acts as a major carbon sink, second only to oceans, and plays a pivotal role in carbon sequestration, erosion control, and climate mitigation. Metrics such as soil organic matter, pH levels, and erosion risk can quantify ecological impact and regenerative potential (Hub, 2024). Additionally, soil health influences water management, nutrient cycling, and supports diverse microbial and macrobiotic life, contributing to overall biodiversity (Tracex, 2023).

Social Dimension: Healthy soils underpin food security by enhancing crop productivity and nutritional quality. They also support community resilience through sustainable livelihoods, especially in smallholder systems. ESG-aligned social metrics may include equitable access to land, fair labor practices, and inclusive participation in sustainable farming initiatives (Tracex, 2023). Soil stewardship also intersects with human rights, particularly in regions vulnerable to land degradation and displacement.

Governance Dimension: Transparent reporting on land stewardship, including soil conservation strategies, cover cropping, and reduced tillage, reflects ethical governance and long-term risk management. ESG governance indicators can encompass board structure, executive accountability, and shareholder rights, especially when linked to sustainability goals and climate disclosures. Integrating soil health into governance reporting ensures that environmental integrity is embedded in corporate decision-making.

By aligning soil health metrics with ESG standards, companies not only meet compliance and certification requirements but also build resilience, trust, and market differentiation in an increasingly sustainability-driven economy.

Purpose of the ESG framework: A strategic lens for sustainable value

The Environmental, Social, and Governance (ESG) framework serves as a multidimensional tool for assessing corporate sustainability, ethical governance, and long-term resilience. It enables organizations to navigate complex socio-environmental challenges while aligning with stakeholder expectations and regulatory mandates (Esgthereport, 2024).

Risk Management: ESG frameworks help identify and mitigate non-financial risks—such as climate volatility, labor disputes, and reputational damage—that can materially affect long-term performance. By incorporating double materiality assessments, companies evaluate both financial exposure and societal impact (Esgthereport, 2024).

Transparency: ESG reporting promotes disclosure of sustainability practices, enabling comparability and accountability across industries. Frameworks like GRI, SASB, and TCFD provide structured methodologies for reporting environmental metrics, social equity indicators, and governance protocols (Esgthereport, 2024).

.Investment Decisions: ESG data is increasingly used by investors to assess whether companies align with their values and risk profiles. ESG scores and sustainability ratings influence capital allocation, with ESG-aligned firms often enjoying lower cost of capital and higher valuation premiums (Esgthereport, 2024).

Regulatory Compliance: ESG reporting is becoming mandatory in many jurisdictions, tied to stock exchange listings and government directives. For example, the EU's Corporate Sustainability Reporting Directive (CSRD) expands ESG disclosure requirements to over 50,000 companies (Deloitte, 2022).

ESG is important regarding Investor Demand: ESG-aligned companies often attract more capital and enjoy lower cost of capital; Consumer Expectations: Modern consumers prefer brands that align with ethical and sustainable values; Operational Resilience: ESG practices often lead to better risk management and long-term profitability; Global Goals: ESG aligns with broader agendas like the UN Sustainable Development Goals (SDGs). Investors increasingly demand soil-related disclosures in Sustainability reports, Green bond frameworks, and Impact investment portfolios.

Portfolio risk scoring: soil health as a financial risk indicator

Soil degradation is not only an ecological concern; it is a **material financial risk** that directly impacts farm productivity, asset valuation, and investment decisions. Integrating soil health metrics into portfolio risk scoring enables financial institutions to assess exposure to nature-related risks and enhance resilience across agricultural value chains.

a. Degraded soils and financial vulnerability

Farms operating on degraded soils often experience higher input costs due to increased fertilizer and irrigation needs, greater yield volatility from reduced buffering capacity against climate extremes, and lower land valuation stemming from diminished productivity and long-term ecological liabilities. A study by the University of Cambridge and Robeco found that farms on degraded land saw a 13% decline in market value, while those on healthy soils experienced a 6% increase following extreme weather events (Robeco, 2022).

b. Risk mitigation applications

- Loan Underwriting: Soil health indicators such as organic matter content, erosion risk, and biological activity can inform creditworthiness by predicting long-term farm viability and repayment capacity.
- Insurance Pricing: Insurers can use soil degradation profiles to adjust premiums based on exposure to yield loss, flood risk, or drought sensitivity.
- Land Acquisition Decisions: Investors and agribusinesses can incorporate soil health scores into due diligence to avoid stranded assets and prioritize regenerative land portfolios.

Table 5. Risk Exposure on Farms on Degraded Soils

Impact Area	Description
Input Costs	Increased fertilizer, irrigation, and pest control expenses
Yield Volatility	Greater sensitivity to droughts, floods, and pests
Asset Depreciation	Lower land value due to declining productivity and erosion liabilities

Farms with degraded soils showed a 13% decline in asset value post-extreme weather, while those with healthy soils rose by 6% (Deloitte, 2022).

Table 6. Risk Mitigation Channels

Financial Decision Area	Role of Soil Health Metrics
Loan Underwriting	Predicts farm viability through organic matter %, erosion scores, and soil biology
Insurance Pricing	Adjusts premiums based on susceptibility to yield loss or climate extremes
Land Acquisition	Assesses long-term land productivity and resilience against stranded assets

Investors can prioritize regenerative land assets, reducing exposure to environmental degradation and financial volatility.

This approach aligns with emerging nature-related financial disclosure frameworks, such as the Taskforce on Nature-related Financial Disclosures (TNFD), which advocate for integrating ecosystem dependencies and impacts into financial decision-making(Esgthereport, 2024).

•

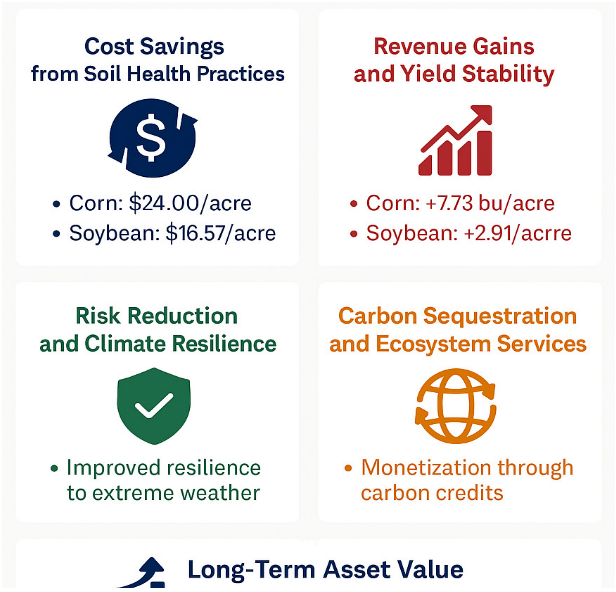


Figure 2. Economic Translation of Soil Metrics

5. Case Studies: Soil Health in Action

Urban Farming with Compost-Based Systems in Indonesia Urban microgreen producers in West Java have adopted composted organic waste as a growing medium within rooftop farming systems, showcasing a circular approach to urban agriculture. This substrate enhances soil organic matter (SOM) levels and stimulates microbial activity, contributing to nutrient cycling and plant vigor in soilless environments. The system demonstrates substantial agronomic and economic efficacy, reducing input costs by 30% through the reutilization of local organic residues. Moreover, consistent yields and adopting “eco-label” branding have elevated consumer trust and market differentiation, positioning urban farms as nodes of sustainability and innovation within densely populated landscapes.

MSME-Led Regenerative Agriculture in the Philippines Micro-, small-, and medium-sized enterprises (MSMEs) in Philippine rural zones are driving regenerative practices, notably by integrating cover cropping and using EM4 biofertilizers. These approaches enrich SOM content, which increased by 0.8%

over two years, while enhancing cation exchange capacity (CEC) by 15%, indicating improved nutrient retention and soil fertility. The biological inputs reduce reliance on synthetic fertilizers, resulting in an 18% rise in net income. Additionally, improved crop resilience under variable climatic conditions affirms the long-term viability of MSME-led regenerative frameworks, fostering ecological integrity and rural livelihoods.

Carbon Farming in the U.S. Midwest. In the American Midwest, large-scale carbon farming initiatives have embraced no-till practices and cover cropping over expansive acreages exceeding 1,000 hectares. These interventions yielded a 1.2% rise in SOM and facilitated annual carbon sequestration rates of 2.5 tons CO_2e per hectare. Quantified through soil sampling and remote sensing verification, the associated environmental services translated into tangible economic returns via carbon credit schemes, with participating farmers earning between $15 and $30 per acre per year. Such outcomes underscore the compatibility of climate-smart agriculture with market-based incentive structures, anchoring carbon farming within the broader discourse on sustainable land stewardship**.**

These examples illustrate how soil health metrics can directly link to profitability, resilience, and new revenue streams.

6. Policy and Institutional Support

Farmers often bear the full cost of adopting soil health practices, while many benefits, such as improved water quality or carbon sequestration, are public goods. This creates a market failure where soil health is underprovided. Public subsidies can help internalize these externalities by reducing the cost burden on farmers. Such as Cost-share programs like EQIP (Environmental Quality Incentives Program) and CSP (Conservation Stewardship Program) in the U.S. State-level programs in Maryland and Delaware have shown strong "

"Subsidy payments can align private incentives with public environmental goals by encouraging adoption of soil health practices." (Rejesus et al., 2021), USDA Journal of Soil and Water Conservation Read PDF. Cost-share programs (e.g., EQIP, CSP in the U.S.) reduce adoption barriers. Indonesia's KUR Kredit Usaha Rakyat can be aligned with soil health benchmarks for MSMEs.

Carbon markets and payments for ecosystem services (PES)

Carbon markets offer a financial mechanism to incentivize sustainable agricultural practices, particularly those that enhance soil organic matter (SOM) and reduce tillage intensity (Aslam et al., 2021). These practices sequester atmospheric carbon and improve soil structure and microbial function, yielding long-term agronomic and ecological benefits. Land stewards receive tradable credits proportional to verified carbon sequestration through carbon credit schemes, integrating soil health improvements into global climate mitigation frameworks. Similarly, Payments for Ecosystem Services (PES) monetize ecological functions such as enhanced water infiltration, erosion control, and biodiversity conservation. PES schemes recognize and quantify the economic value of ecosystem services, offering performance-based compensation that aligns farmer incentives with watershed management and climate resilience goals.

Soil health cards and digital extension tools

India's Soil Health Card Scheme exemplifies a targeted approach to empowering smallholder farmers through site-specific nutrient and pH diagnostics. Coupling traditional soil analysis with actionable recommendations enables precise input use, mitigating nutrient imbalances and fostering long-term soil fertility. (Sundari, 2024; Sundari et al., 2019, 2021, 2022). Integrating digital platforms such as Regrow and SoilGrids further enhances decision-making by visualizing geospatial soil properties, historical trends, and predictive agronomic outcomes. (Indarto et al., 2019). These tools democratize access to soil data and promote knowledge transfer via user-friendly dashboards and algorithm-driven insights, fostering adaptive management across diverse agroecological zones. Collectively, such innovations strengthen the nexus (Choy et al., 2025) between soil science, precision agriculture, and inclusive extension strategies.

7. Socio-Economic Impacts of Biofertilizer Adoption in Resource-Limited Communities

Adoption barriers

Despite the agroecological promise of microbial inoculants like EM4 that enhance nutrient uptake, suppress pathogens, and restore soil biota, their adoption within marginalized smallholder settings remains suboptimal due to intersecting socio-technical and institutional barriers. Knowledge asymmetry constitutes a primary bottleneck; small-scale producers often lack exposure to participatory agronomic training or locally adapted inoculant protocols, limiting their confidence in biological inputs (Andersson et al., 2023). Cultural norms favor conventional fertilizers due to long-standing perceptions of instant efficacy and yield reliability, a mindset reinforced by aggressive agrochemical marketing and limited demonstrations of EM4 performance across varied agroecologies (Choy et al., 2025). Structural issues such as fragmented supply chains and the absence of community-scale fermentation hubs hamper availability and affordability, particularly in low-access regions. Although EM4 presents long-term cost benefits, initial outlays for training, equipment, or transition trials act as psychological and economic deterrents for resource-constrained farmers (Andersson et al., 2023). Furthermore, policy blind spots such as limited integration of microbial amendments into extension curricula or input subsidies curtail their institutional legitimacy, impeding systemic uptake across farming communities (Andersson et al., 2023). Bridging these gaps requires a holistic strategy combining adaptive trials, community co-production models, and policy realignments that incorporate microbial inputs into national sustainability agendas.

Labor dynamics: how biofertilizers reshape agricultural workforce structures

The transition from synthetic inputs to biofertilizers such as **Effective Microorganisms (EM4)** is not merely a technical shift; it reconfigures labor allocation, skill requirements, and generational engagement in farming systems. These dynamics are especially relevant for ESG-aligned agribusinesses seeking to foster inclusive, resilient, and knowledge-driven rural economies.

Labor redistribution

- EM4 application typically involves more frequent but less intensive labor compared to synthetic fertilizers.
- Tasks such as fermentation monitoring, dilution preparation, and soil inoculation require precision but are less physically demanding.
- This shift enables redistribution of labor across age groups and gender, promoting equitable participation in farm operations.

Skill development

- Farmers must acquire technical competencies in microbial fermentation, dilution ratios, and timing of application to optimize efficacy.
- This creates demand for local extension services, vocational training, and farmer field schools focused on regenerative inputs.
- Studies show that biofertilizer adoption correlates with increased knowledge intensity per hectare, enhancing long-term productivity and ecological literacy.

Youth engagement

- EM4-based practices align with sustainability values and innovation, making them attractive to younger farmers.
- The emphasis on biological inputs, digital monitoring, and circular resource use resonates with youth-led agroecological movements.
- Programs integrating EM4 into urban farming and school-based agriculture have shown increased youth participation in regenerative farming models (Zhang et al., 2022).

Income effects: economic implications of EM4 biofertilizer adoption

a. Input cost reduction

- EM4 reduces dependence on synthetic fertilizers, lowering recurring input costs.
- Locally sourced or self-fermented EM4 formulations further decrease external procurement expenses.
- Studies show biofertilizer use can reduce fertilizer costs by 15–40%, depending on crop type and formulation method.

b. Yield stability

- EM4 enhances soil microbiota diversity, improving nutrient cycling and root health.
- This leads to greater resilience against abiotic stressors (e.g., drought, salinity), stabilizing yields across seasons.
- Yield consistency supports predictable income streams, crucial for smallholder financial planning.

c. Market differentiation

- EM4-grown produce can be labeled as organic, eco-friendly, or regenerative, appealing to conscious consumers.
- Such differentiation enables access to premium markets, including farm-to-table, export-grade, and ESG-certified supply chains.
- Branding strategies that highlight microbial soil health and chemical-free cultivation enhance consumer trust and price realization.

d. Microenterprise opportunities

- EM4 production fosters community-based agribusinesses, especially in fermentation, packaging, and distribution.
- Youth and women-led cooperatives can engage in value-added EM4 formulations, creating local employment.
- These enterprises align with inclusive ESG goals, promoting circular economies and rural innovation.

The adoption of Effective Microorganisms (EM4) biofertilizers introduces a multidimensional shift in farm economics, particularly for MSMEs and regenerative agribusiness models. These effects span input efficiency, market positioning, and community enterprise development.

Feedback loops and community resilience

Biofertilizer initiatives, particularly those involving EM4 production, serve as catalytic platforms for circular economy integration and community resilience-building. By utilizing locally sourced organic waste for microbial cultivation, these practices reinforce circular flows and reduce dependency on synthetic inputs, an approach aligned with climate–ecosystem resilience frameworks (Choy et al., 2025). Community-based training and participatory production further cultivate social capital, strengthening household collaboration, peer learning, and intergenerational knowledge transfer (Springer, 2020). These feedback loops, between ecological practices and social cohesion, enable adaptive capacity and enhance collective agency. Such models illustrate how community-driven circularity fosters long-term food sovereignty and economic autonomy, especially in resource-limited settings (Andersson et al., 2023; Choudhury et al., 2024). As agribusiness models increasingly embrace regenerative inputs, EM4 systems exemplify how circular integration and resilient networks coalesce into sustainable micro-ecosystems primed for inclusive development.

8. Conclusions

Integrating soil health metrics into agribusiness investment decisions represents a paradigm shift, transforming how stakeholders value, manage, and capitalize on agricultural systems. By bridging the scientific underpinnings of soil vitality with economic translation tools, this framework empowers decision-makers to align ecological resilience with financial performance. Key takeaways from the case studies underscore that soil health is not merely an agronomic concern but a strategic asset. Incorporating biologically informed indicators such as microbial activity, nutrient cycling, and soil structure into investment assessments unlocks long-term productivity, risk mitigation, and sustainability insights. Moreover, enabling policy instruments and institutional frameworks are vital in mainstreaming soil health considerations. Incentives tied to regenerative practices, transparent metric standards, and multi-sectoral coordination create fertile ground for inclusive agribusiness growth. The socio-economic uplift from biofertilizer adoption in resource-limited communities further illustrates soil health as a lever for equity and empowerment. Biofertilizers catalyze systemic benefits that ripple beyond the farm gate by lowering input costs, enhancing crop resilience, and fostering circular economies. Investing in soil health is not just environmentally prudent—it is economically strategic and socially transformative. Future agribusiness models must embed soil metrics at their core to unlock scalable, climate-smart, and inclusive outcomes.

References

Andersson, J., François-Ferrière, M., & Hoskova, K. (2023). Circular Solutions, Community Revolutions: The Social Impact of Circularity. In *World Economic Forum*.

Aslam, Z., Bellitürk, K., & Ahmad, A. (2021). Innovative Waste Management Technologies for Sustainable Agriculture: Tha Case of Vermicomposting. In *Fertilizer and Their Efficient Use in Sustainable Agrculture* (pp. 9–46).

Bellitürk, K., & Sundari, R. S. (2024). The Power of Earthworm: Vermicompost Drives to Sustainable Agriculture. In K. HUANG, S. A. BHAT, F. LI, & V. KUMAR (Eds.), *Earthworm Technology in Organic Waste Management* (Issue 1, pp. 307–321). Sciencedirect, Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-443-16050-9.00018-9

Choudhury, M., Wu, H., & Shahidullah, A. K. M. (2024). Improving the feedback loop between community- and policy-level learning: Building resilience of coastal communities in Bangladesh. *Sustainable Development*, *32*(2), 1508–1524. https://doi.org/10.1002/sd.2686

Choy, Y. K., Onuma, A., & Lee, K. E. (2025). The Nexus of Industrial–Urban Sustainability, the Circular Economy, and Climate–Ecosystem Resilience: A Synthesis. *Sustainability (Switzerland)*, *17*(6). https://doi.org/10.3390/su17062620

Deloitte. (2022). *What is ESG ? Why is ESG here to stay ?* https://www.deloitte.com/ce/en/services/consulting/perspectives/esg-explained-1-what-is-esg.html

Esgthereport. (2024). *Top Sustainability Frameworks: A Comprehensive Comparison*. https://esgthereport.com/the-top-sustainability-frameworks-for-organizations/

General, H. N., & Share, T. G. (2021). *Investing in soil health to help transform food and agriculture systems*. WBCSD.

Hub, S. S. (2024). *The Important Connection of Healthy Soil and ESG & Sustainability Investing | betterSoils*. InvestSEG.

Indarto, I., Novita, E., Wahyuningsih, S., Herlinda, N. D., & Hidayah, E. (2019). Application of recursive digital filter (RDF) methods for baseflow separation: study at Brantas watershed. *Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan (Journal of Natural Resources and Environmental Management)*, *9*(3), 626–640. https://doi.org/10.29244/jpsl.9.3.626-640

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability (Switzerland)*, *7*(5), 5875–5895. https://doi.org/10.3390/su7055875

Lichtenberg, E. (2024). Thinking about soil health: A conceptual framework. *Soil Security*, *14*(100130), 1–7. https://doi.org/10.1016/j.soisec.2024.100130

Rejesus, R. M., Aglasan, S., Knight, L. G., Cavigelli, M. A., Dell, C. J., Lane, E. D., & Hollinger, D. Y. (2021). Economic dimensions of soil health practices that sequester carbon: Promising research directions. *Journal of Soil and Water Conservation*, *76*(3), 55A-60A. https://doi.org/10.2489/jswc.2021.0324A

Robeco. (2022). *Nature-related financial risk: use case. How soil degradation amplifies the financial vulnerability of listed companies in the agricultural value chain* (1st ed.). University of Cambridge Institute for Sustainability Leadership. https://www.cisl.cam.ac.uk/files/robeco-cisl_nature-related_financial_risk_use_case_-_land_degradation_vfinal2.pdf

Soil Health Institute. (2021). *Economics of Soil Health Systems on 100 farms, A Comprehensive Evaluation Across Nine States*.

Stevens, A. (2015). *The Economics of Soil Health: Current Knowledge, Open Questions, and Policy Implications*. 31.

Sundari, R. S. (2024). *Setaman Cinta Pertanian Kota Jilid 1* (1st ed.). https://books.google.com/books?hl=en&lr=&id=Q0wZEQAAQBAJ&oi=fnd&pg=PA1&dq=smart+farming+dalam+pendidikan&ots=jJoFaGjikS&sig=szq4ljIfJ67p9FqKc8c9YZ_pftk

Sundari, R. S., & Fitriadi, B. W. (2024). Groundwork for Understanding the Principles and Importance of Sustainable Agriculture. In K. Bellitürk (Ed.), *Fundamentals of Sustainable Agriculture* (1st ed., Issue 1, pp. 29–66). IKSAD Publishing House. https://iksadyayinevi.com/home/fundamentals-of-sustainable-agriculture/

Sundari, R. S., Sulistyowati, L., & Noor, T. I. (2021). Soilless Culture in Urban Farming. *International Conference on Biodiversity, Microbiology to Multiple Industrial and Environmental Applications to Support Sustainable Development and Improve Human Welfare, 18 December 2021, Surakarta, Central Java, Indonesia*, *8*(2), 29–59. https://doi.org/DOI: 10.13057/asnmbi/m080202

Sundari, R. S., Sulistyowati, L., Noor, T. I., & Setiawan, I. (2022). Soilless Culture for Agribusiness throughout Urban Farming in Indonesia. In M. Turan, S. Argin, Güneş, & E. Y. Adem (Eds.), *Soilless Culture* (pp. 1–10). Intechopen. https://doi.org/10.5772/intechopen.101757

Sundari, R. S., Umbara, D. S., Fitriadi, B. W., & Sulaeman, M. (2019). Consumer Preference on Catfishes (Patin and Lele) Sweetmeat Product. *Journal of Physics: Conference Series*, *1179*(1). https://doi.org/10.1088/1742-6596/1179/1/012166

Thorsen, S., & Woodbridge, D. (2011). The business case for investing in safety. *Offshore*, *71*(1).

Tracex. (2023). *Measuring Farm Sustainability Metrics for Better Agriculture*. https://tracextech.com/farm-sustainability-metrics/

USDA. (2025). *Soil Health Economics* (Issue May).

Zhang, R., Luo, L., Liu, Y., & Fu, X. (2022). Impact of Labor Migration on Chemical Fertilizer Application of Citrus Growers: Empirical Evidence from China. *Sustainability (Switzerland)*, *14*(13), 1–14. https://doi.org/10.3390/su14137526

3

THE IMPACT OF ANIMAL MANURE AND BIOCHAR APPLICATION ON SOIL HEALTH AND PLANT NUTRITIONAL COMPOSITION

Mohammad H. Dawood[1], George F. Antonious[2], Kayahan Yılmaz[3], Ahmet Refik Önal[4]

1: UNDERSTANDING SOIL HEALTH AND HOW IT SHAPES PLANT NUTRITION

Soil health lies at the heart of sustainable agriculture. It's the foundation that supports productive, resilient, and environmentally responsible farming. Healthy soils aren't just about dirt, they're complex systems with physical, chemical, and biological properties that influence everything from crop growth to water retention and nutrient cycling. One of the most promising ways to enhance soil health naturally is through the use of organic amendments like animal manure and biochar. These materials, often viewed as agricultural byproducts or waste, are now recognized for their powerful role in enriching soil and reducing dependence on synthetic inputs (Lehmann & Joseph, 2015).

Animal manure, long used in traditional farming, is rich in organic matter and essential nutrients. Its application has been shown to improve soil structure, increase soil organic carbon (SOC), and stimulate microbial activity—all of which support healthy plant growth. For example, studies in apple orchards found that incorporating compost before planting improved tree growth and yield for years afterward (Safaei Khorram et al., 2019).

Biochar, a carbon-rich product created through the pyrolysis of organic material, adds a unique dimension to soil management. Its porous structure helps retain water and nutrients and offers a long-lasting source of organic carbon. Biochar not only improves soil fertility but also plays a role in mitigating climate change by sequestering carbon in the soil.

What's even more exciting is how these two amendments—manure and biochar—can work together. When applied in combination, they create a powerful synergy. Research shows that this duo can enhance soil nutrient content, lower soil bulk density, and even reduce greenhouse gas emissions

1 Department of Crop Science, College of Agriculture, University of Telafer, Ninevah 54003, Iraq., ORCID ID: 0000-0003-2145-3335, E-mail: mohammadh.dawood@uotelafer.edu.iq
2 Division of Environmental Studies, College of Agriculture, Heath and Natural Resource, Kentucky State University, Frankfort, KY 40601, USA, ORCID ID: 0000-0003-1109-4076 E-mail: george.antonious@kysu.edu
3 Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Animal Science, Tekirdağ, Türkiye. ORCID ID: 0000-0001-6899-5663, E-mail: kyilmaz@nku.edu.tr
4 Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Animal Science, Tekirdağ, Türkiye. ORCID ID: 0000-0002-9125-7412, E-mail: aronal@nku.edu.tr

in certain contexts (Agegnehu et al., 2016; Verheijen et al., 2009). In tropical farming systems, for instance, combining compost with biochar led to higher maize yields while lowering environmental impact.

These improvements in soil health directly translate to better plant nutrition and growth. Biochar has been shown to improve the uptake of key nutrients like nitrogen, phosphorus, and potassium, making plants more robust and resilient. While some studies, such as those in apple orchards, found that biochar didn't always improve fruit yield or quality, it consistently promoted stronger vegetative growth and healthier plants (Safaei Khorram et al., 2019).

As shown in Figure 1, both the type and amount of nutrient inputs play a crucial role in shaping soil pH throughout the various stages of rice growth. This highlights the importance of selecting the right combination of organic amendments to foster a soil environment that supports healthy crop development. The combined use of animal manure and biochar has proven especially beneficial—not only improving nutrient availability but also boosting microbial diversity and activity, both essential for maintaining soil health (Haque et al., 2021). t 28 days after transplanting (DAT), the highest pH value (6.55) was observed with the treatment of 25% recommended fertilizer (RF) plus 6 t ha^{-1} biosolid, while the lowest (6.27) was recorded with 75% RF and 2 t ha^{-1} biosolid. This trend continued at 60 DAT, with the same treatments producing the highest (6.66) and lowest pH levels. By 84 DAT, pH values ranged between 6.65 and 6.75, with the 75% RF + 2 t ha^{-1} biosolid treatment (T3) again showing the lowest reading, while the 25% RF + 6 t ha^{-1} biosolid matched the effect of biosolid combined with farmyard manure (FYM) for the highest. Overall, pH levels increased across all treatments as the season progressed, though the rise was smallest in T3 (Haque et al., 2021).

In essence, integrating animal manure and biochar into soil management is more than just a fertility boost—it's a step toward more sustainable and regenerative agriculture. By improving soil health, supporting plant nutrition, and reducing reliance on synthetic fertilizers, this approach helps create farming systems that are productive, resilient, and better for the planet.

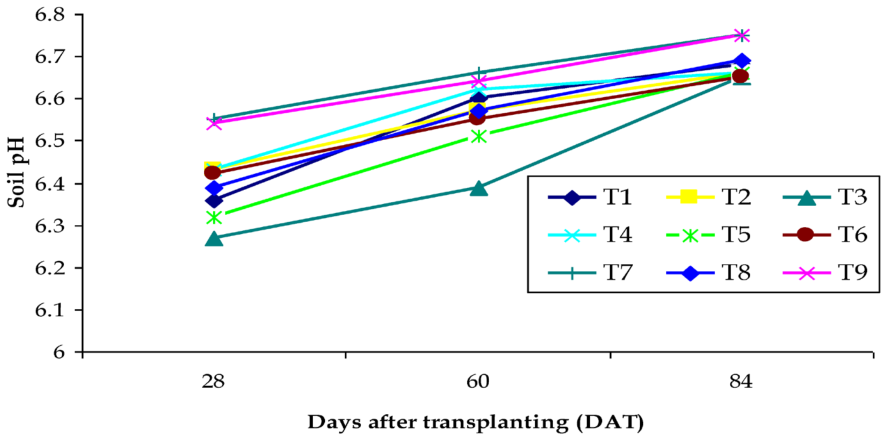


Figure 1 Effect of various nutrient sources and application rates on soil pH during different growth stages of Aman rice. Source: https://www.mdpi.com/2071-1050/13/6/3103/htm#f1.

2: THE ROLE OF ANIMAL MANURE IN SOIL HEALTH

For generations, farmers have turned to animal manure as a natural way to enrich their soils—and for good reason. More than just waste, animal manure is a nutrient-rich organic material that plays a crucial role in maintaining soil fertility and supporting sustainable agriculture. Packed with essential elements like nitrogen, phosphorus, and organic matter, manure helps build healthier, more productive soils over time. One of the most important benefits of animal manure is its ability to boost organic soil carbon (SOC), a key factor in improving soil structure and long-term fertility. By increasing SOC, manure improves the soil's ability to hold water, supports better root development, and enhances microbial life soil. For instance, long-term studies in apple orchards have shown that applying compost before planting led to improved tree growth and yield for up to seven years (Antonious, 2024; Safaei Khorram et al., 2019). That's powerful proof to manure's lasting impact on soil and plant health.

But the benefits go far beyond just providing nutrients. Manure helps balance soil pH, making acidic soils more neutral and alkaline soils more manageable (Hoffmann et al., 2001).

Perhaps one of the most exciting effects of animal manure is how it stimulates life in the soil. Manure provides food for beneficial microbes, boosting microbial biomass and activity. These tiny organisms are essential for breaking down organic material and releasing nutrients to plants. In fact, research shows that manure can increase microbial respiration and biomass by up to 25%, supporting a vibrant, living soil ecosystem (Graham et al., 2009; Tubeileh & Goss, 2022). It also encourages beneficial soil organisms like earthworms, which improve aeration, nutrient cycling, and soil structure (Altieri & Nicholls, 2003).

Speaking of structure, manure contributes significantly to improving the physical health of the soil. It strengthens soil aggregates—clusters of soil particles that stick together—making the soil more resistant to erosion and better able to retain moisture. As shown in Figure 2, manure application leads to the formation of larger, more stable aggregates. These structures improve water infiltration, reduce runoff, and help plants cope better with drought. Manure also increases porosity and reduces bulk density, making it easier for plant roots to grow and access nutrients (Lupwayi et al., 2000).

From a sustainability perspective, one of manure's greatest strengths is its role in natural nutrient management. Unlike synthetic fertilizers, which can lead to nutrient runoff and pollution, manure releases nutrients slowly as it decomposes. This slow-release process provides a steady nutrient supply to crops while minimizing the risk of leaching into waterways (Campbell et al., 1986). However, it's important to manage manure carefully—too much, or poorly timed applications can create environmental risks. Responsible use, guided by soil testing and best practices, ensures that manure remains a sustainable asset, not a liability (Shapiro et al., 2021).

Overall, animal manure is much more than a traditional farming input—it's a powerful tool for building soil health and achieving sustainability in agriculture. Its ability to improve soil structure, boost microbial life, and provide a balanced, slow-releasing source of nutrients makes it cornerstone of eco-friendly farming. When used wisely, manure helps farmers grow healthier crops while protecting the land for future generations.

Figure 2. Manure enhances soil physical properties, including the formation of soil aggregates. Photo courtesy of the USDA NRCS Soil Health Flickr collection. Source: Manure Impact on Soil Aggregation – Soil Health Nexus

3: BIOCHAR: A SUSTAINABLE SOLUTION FOR HEALTHIER SOILS AND A HEALTHIER PLANET

In recent years, biochar has emerged as a powerful tool in the push for more sustainable farming. Made from organic materials like crop residues or wood through a process called pyrolysis (heating without oxygen), biochar offers a range of benefits—not just for improving soil health but also for fighting climate change.

One of the most notable properties of biochar is its capacity to enhance soil structure. Thanks to its highly porous architecture, biochar improves the soil's ability to retain water and air—both essential for healthy root development and plant growth. Additionally, this improved environment supports greater microbial activity and stimulates soil enzyme production, which plays a vital role in nutrient cycling and organic matter decomposition, further contributing to soil fertility and plant health (Antonious et al., 2020). In regions facing erratic rainfall or water shortages, this means crops can stay hydrated for longer, which can reduce the stress on both plants and farmers. It also helps prevent nutrients from being washed away, ensuring that valuable fertilizers actually stay in the root zone where plants can use them. For example, a study by Yu et al. (2017) found that adding biochar made from hemlock or switchgrass to loamy sand soil helped the soil hold more water.

Studies back this up. Lehmann and Joseph (2015) pointed out that biochar can encourage a more active and diverse microbial community, which helps keep soil healthy and productive. Later, Zhou and colleagues (2019) found that using biochar and biochar-based fertilizers improved the makeup of soil microbes in the karst mountain regions—proof that biochar offers real support to beneficial soil life. More recently, Wang et al. (2023) showed that a phosphate fertilizer mixed with biochar enhanced both microbial activity and phosphorus availability, while also promoting the growth of citrus seedlings. In another study, Antonious (2024) examined how manure-amended soils influence nitrate and phosphate runoff, as well as how biochar and organic fertilizers impact sweet potato yield and nutrition. Supporting these findings, Nepal et al. (2024) analyzed heavy metal buildup in cabbage grown with different soil treatments, further proving that phytoremediation can work in polluted soils.

Another benefit of biochar is that it reduces soil compaction. By lowering soil bulk density, it becomes easier for roots to grow deep and strong. This improved root access means plants can reach more water and nutrients, which often results in better yields. (Atkinson et al., 2010) showed that adding biochar to soil significantly improved water retention and aggregation, two properties that are vital for healthy plant development, especially under the stresses of climate change.

Beyond improving soil, biochar is also gaining attention for its role in tackling climate change. According to He et al. (2024), biochar can increase carbon storage in soils and lower greenhouse gas emissions on farmland—making it a powerful tool for both farming and the environment. Meanwhile, Sultan et al. (2024) offered a wide-ranging review that highlights how both traditional and nano-biochar can boost a plant's resistance to salt stress, all while cutting emissions. Together, these findings underline the many ways biochar can support sustainable agriculture from the ground up.

On the chemical side, biochar helps unlock nutrients in the soil. Studies have shown that it improves the availability of critical elements like nitrogen, phosphorus, and potassium—nutrients that plants need to grow strong and produce food. For example, Alkharabsheh et al. (2021) found that biochar-amended soils had greater nutrient availability, contributing to better crop performance.

Biochar's impact even extends to improving environmental safety.

As illustrated in Figure 3, the application of biochar offers several interconnected benefits: improved soil structure, increased water retention, reduced compaction, and enhanced nutrient availability. All these contribute to healthier soils, stronger crops, and more sustainable farming systems.

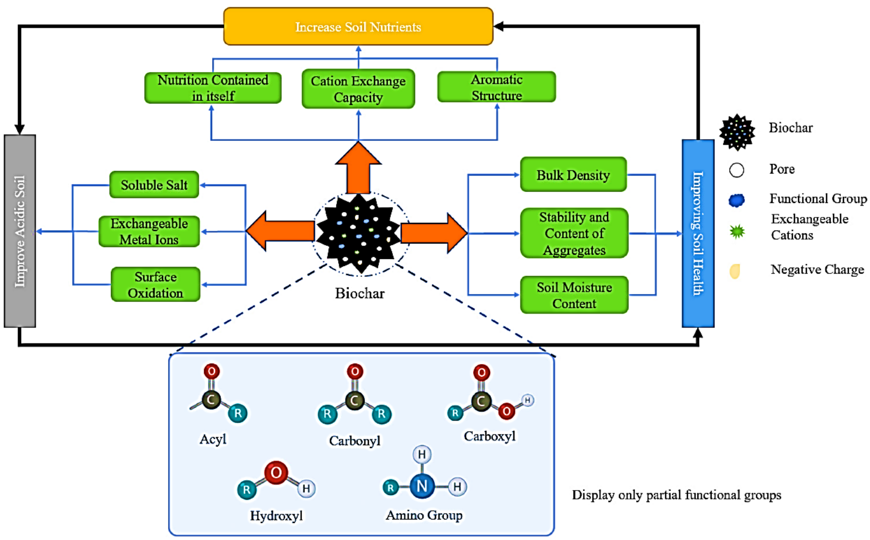


Figure 3 Mechanisms by which biochar improves soil's physical properties. This figure illustrates the key benefits of biochar, including improved soil structure, increased water retention, reduced bulk density, and enhanced nutrient availability. source: https://doi.org/10.3390/su17052214

Biochar's sponge-like structure—clearly visible in the figure—does a lot more than just improve how soil holds together. Those tiny pores actually create cozy, stable spaces for helpful soil microbes to settle and flourish. These microorganisms are the behind-the-scenes workers of the soil, helping to recycle nutrients and make them more accessible to plants.

Lehmann and Joseph (2015) found that adding biochar to soil boosts both the activity and diversity of these microbes, which are vital for keeping soils productive and balanced ecosystems. More recently, Li et al. (2023) showed that biochar helps build healthier soil by offering a supportive environment where these microbes can thrive—leading to better fertility and stronger plant growth. Similarly, Moreno-Barriga et al. (2017) discovered that biochar can increase the organic matter in soil, which in turn encourages even more microbial growth and activity.

In addition to supporting microbial life, biochar helps improve the physical condition of the soil. As shown in the figure, This means plant roots can grow more easily and reach essential nutrients and water deeper in the soil profile—a key factor in supporting strong, healthy crops (Atkinson et al., 2010).

Perhaps one of the most exciting benefits of biochar is its contribution to long-term carbon storage. The figure also highlights the biochar's role in enhancing soil organic carbon (SOC) sequestration, which is a crucial mechanism for mitigating climate change. A global meta-analysis by (Gross et al., 2021)found that biochar significantly increases SOC levels across a wide range of soil types, highlighting its potential as a natural climate solution.

Accordingly, biochar offers a suite of interrelated benefits that align perfectly with the goals of sustainable agriculture. From improving soil structure and boosting microbial life to enhancing nutrient availability and storing carbon, biochar is a powerful, nature-based tool for building resilient farming systems and addressing environmental challenges at the same time (Zandvakili et al., 2025).

4: SYNERGISTIC POWER OF ANIMAL MANURE AND BIOCHAR FOR SUSTAINABLE SOIL HEALTH

As agriculture continues to evolve in the face of climate pressures and growing food demands, many farmers and scientists are turning back to nature for smarter, more sustainable solutions. One approach gaining serious traction is the combination of animal manure and biochar. While both have long been used on their own, recent evidence shows that using them together delivers far greater benefits than either could offer alone. For example, a 2024 study reported that mixing biochar with animal manure not only boosted soil fertility and microbial activity but also helped cut down on carbon dioxide emissions typically associated with manure use (Lebrun et al., 2024). It's a win-win for both soil health and the climate. Building on that, another study from 2024 found that this same combination led to notable improvements in crop growth and yield—even under water-limited conditions (Amanullah & Khalid, 2016).

These findings point to a promising path forward: using natural amendments in synergy to build more resilient, productive, and environmentally friendly farming systems.

When applied together, animal manure and biochar create a synergistic effect that can dramatically improve soil health and plant growth. Studies have consistently shown that this combination increases the nutrient content of soil, improves its physical structure, and reduces soil compaction (Verheijen et al., 2009). These improvements help crops grow stronger and more efficiently, while reducing reliance on synthetic fertilizers, an important step for more eco-friendly farming.

For instance, research in tropical farming systems found that using biochar alongside compost led to higher maize yields and lower greenhouse gas emissions (Franzluebbers et al., 2014). Similarly, a study in the USA, Kentucky demonstrated that mixing biochar with poultry manure not only boosted soil fertility and crop performance but also improved the overall soil structure (Fouad Antonious et al., 2022).

The benefits aren't just about quantity; they're also about quality. In the USA, researchers found that combining cow manure and biochar enhanced microbial activity and nutrient availability—two essential ingredients for healthy soils and robust plant growth (Antonious, 2018; Fouad Antonious et al., 2022). These microbial communities play a vital role in nutrient cycling, breaking down organic matter and making nutrients more accessible to plants.

One of the most compelling findings comes from research showing that this combination doesn't just help crops grow it helps them grow better. A study in degraded tropical soils showed that the joint application of poultry manure and biochar significantly increased the nutritional value of sweet potato leaves and roots (Agbede & Oyewumi, 2022). This points to biochar's potential to enhance food quality, not just quantity—a key priority in sustainable food systems.

Even more encouraging, studies continue to show that these organic amendments can help regenerate soil ecosystems. For example, biochar provides a stable, porous habitat for beneficial soil microbes, while manure offers the organic matter they need to thrive. Together, they foster a vibrant soil microbiome that supports long-term fertility and resilience (Uzoma et al., 2011).

That said, it's important to recognize that these benefits aren't uniform across all conditions. The effectiveness of biochar and manure depends on factors such as soil type, climate, and how the materials are applied. Research from the Loess Plateau in China showed that biochar's impact on nutrient levels was more noticeable in certain grassland soils, emphasizing the need to tailor practices to local conditions (Han et al., 2016).

When used thoughtfully, this combination can bring wide-reaching sustainability benefits. Biochar, in particular, has been shown to significantly improve soil physical properties, such as water retention and structure (Atkinson et al., 2010). Its low bulk density allows roots to grow more freely and absorb nutrients more effectively, while its porous nature increases aeration and helps the soil hold moisture.

Biochar can also enhance soil chemical properties, making nutrients like nitrogen, phosphorus, and potassium more available to plant nutrients that are vital for strong, healthy crops (Alkharabsheh et al., 2021). Even more impressively, it helps reduce the risk of contamination by binding potentially toxic metals, making it a valuable tool not just for farming but also for soil remediation.

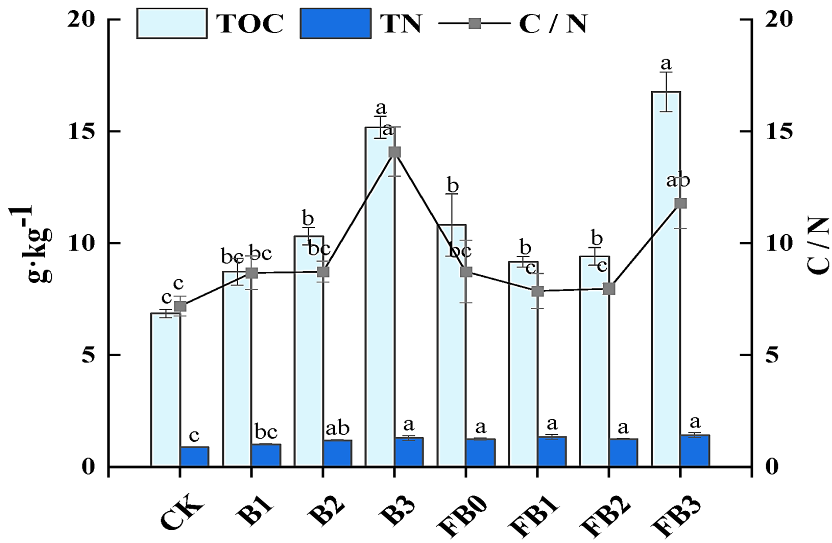


Figure 4 Soil TOC and TN under varying biochar and manure treatments (Adapted from: https://www.mdpi.com/2073-4395/15/6/1384)

The combined application of biochar and animal manure has been shown to have significant positive effects on soil health and plant growth, as illustrated in Figure 4. The figure highlights the increase in total organic carbon (TOC) and total nitrogen (TN) in soil when biochar and manure are applied together, compared to individual treatments. This synergistic effect is crucial for enhancing soil fertility and supporting sustainable agricultural practices.

The study by Sun et al. (2025) demonstrated that the dual application of biochar (2.0%) and manure (0.5%) resulted in a 10.4% increase in TOC and a 10.19% increase in TN compared to biochar alone, and a 54.94% increase in TOC and a 14.68% increase in TN compared to manure alone. This indicates that the combined treatment not only improves soil nutrient content but also enhances soil structure and water retention capacity, leading to better plant growth and reduced greenhouse gas emissions. The study found that the combined treatment significantly increased bacterial diversity and catalase activity while reducing the dominance of *Acidobacteria*, indicating improved metabolic adaptation. This highlights the potential of combined treatments to improve soil health through enhanced microbial activity (Sun et al., 2025).

The combined use of biochar and animal manure can be an effective strategy for sustainable agriculture, as it enhances soil fertility, improves plant nutritional quality, and reduces environmental risks. Future research should focus on optimizing application rates and methods to maximize the benefits of combined treatments in different soil and environmental conditions.

5: PLANT NUTRITIONAL COMPOSITION AND GROWTH

The use of animal manure and biochar doesn't just improve soil—it can also enhance how well plants grow and absorb nutrients. For instance, biochar has been shown to boost the uptake of essential nutrients like nitrogen, phosphorus, and potassium across a variety of crops (Lehmann & Joseph, 2015). In apple orchards, adding biochar and compost helped increase trunk thickness and the number of shoots, though it didn't lead to a noticeable improvement in fruit yield or quality (Safaei Khorram et al., 2019). Still, the overall boost in soil health and nutrient availability often translates to stronger, more resilient plants that are better able to resist pests and diseases.

Recent research has continued to highlight the benefits of combining biochar and animal manure. One study on *Lithocarpus litseifolius*, for example, found that pairing biochar with nitrogen, phosphorus, and potassium fertilizers significantly increased both biomass and the concentration of active compounds, all while reducing the need for chemical fertilizers (Ye et al., 2024). Similarly, studies on wheat have shown that organic soil amendments like biochar can improve nutrient uptake and increase dry matter production (Adnan et al., 2003). Biochar also appears to enhance the availability of both macro- and micronutrients. In urban settings, for instance, researchers found that applying biochar with biofertilizers significantly improved the growth and nutrient uptake of silver maple saplings (Sifton et al., 2023). In Guava Orchards, biochar improved soil fertility and helped plants absorb nutrients more effectively, leading to better overall growth (Mota et al., 2020).

Interestingly, biochar doesn't just affect the soil—it can also influence how plant roots develop. One study showed that biochar helped reshape root systems in a way that allowed plants to use nitrogen more efficiently, meaning less fertilizer was needed (Zhuang et al., 2023). In apple trees, this improved root development was also linked to better fruit quality, thanks to changes in sugar metabolism (Li et al., 2024).

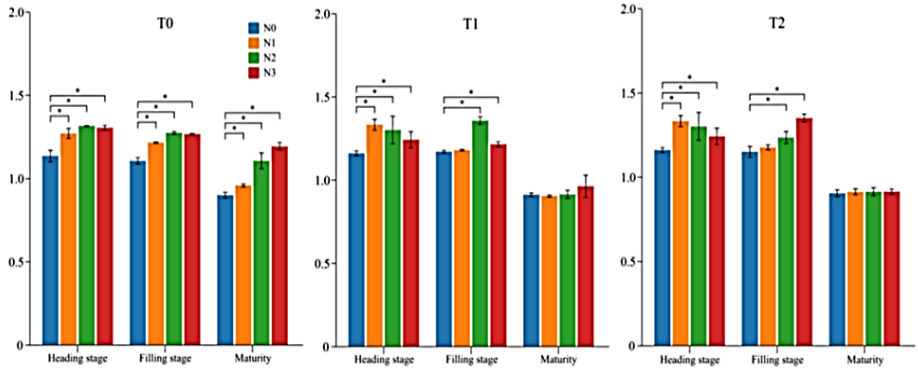


Figure 5 Nitrogen uptake in rice stems under varying nitrogen and biochar rates (Adapted from: https://www.aloki.hu/pdf/2303_48594876.pdf)

Adding biochar to soil has emerged as an effective strategy for enhancing nutrient absorption in crops, as demonstrated in Figure 5. The graph compares varying application rates of biochar and nitrogen fertilizer, tracking their influence on nitrogen levels in rice stems throughout different growth phases.

A clear pattern emerges from the data—treatments with higher biochar concentrations (T1 and T2) consistently result in elevated nitrogen content during critical developmental stages, including tillering, heading, grain filling, and maturity (Ding, 2025). This reinforces biochar's ability to optimize nutrient availability and uptake, supporting stronger plant growth and ultimately contributing to better crop yields (Ding, 2025).

But how exactly does biochar do this? Part of the answer lies in its ability to improve the physical and biological properties of soil. Biochar doesn't just enrich soil—it transforms it. By improving soil structure and boosting water retention, it creates the perfect habitat for beneficial microbes. These tiny but mighty organisms play a crucial role in decomposing organic matter, releasing essential nutrients that plants need to thrive. Research supports this, showing that soils treated with biochar often have higher microbial activity and greater diversity, making them more fertile and resilient (Lehmann & Joseph, 2015). The porous structure also reduces soil compaction, which means roots can grow more freely and access nutrients more easily (Atkinson et al., 2010).

In short, biochar brings multiple benefits. From improving nutrient uptake and soil health to boosting plant growth and resilience, it's a promising tool for making agriculture more sustainable and climate friendly. Its wide-ranging effects make it a valuable addition to efforts aimed at increasing productivity while protecting natural resources.

CONCLUSION

A good soil is the backbone of farming when it comes to keeping soil healthy, animal manure and biochar are like nature's own power duo. Manure packs in the nutrient's plants crave—nitrogen, phosphorus, potassium—while biochar works behind the scenes, locking in moisture, cutting down nutrient waste, and giving soil microbes a cozy home to do their thing. Together, they're a game-changer for sustainable farming.

But here's the catch: not all soils or farms are the same. What works miracles in one field might barely make a dent in another. The type of biochar (wood-based? crop leftovers? manure-derived?), how much manure gets applied, the local climate, even the crops being grown—all of it plays a role. That's why there's no magic formula. Farmers have to tweak things based on their land's quirks.

We've still got a lot to figure out, though. How do these amendments hold up over decades? Can we fine-tune how they're used to cut costs and environmental impact? And how do we make them practical for everyday farming? Research needs to dig deeper into these questions.

At the end of the day, manure and biochar aren't just about bigger harvests, they're about farming smarter. They help keep soil alive, reduce agriculture's carbon footprint, and make sure we're not sacrificing tomorrow's fertility for today's yields. It's a step toward growing food in a way that actually *works* with nature, not against it.

REFERENCES

Adnan, A., Mavinic, D. S., & Koch, F. A. (2003). Pilot-scale study of phosphorus recovery through struvite crystallization examining the process feasibility. *Journal of Environmental Engineering and Science*, *2*(5), 315–324. https://doi.org/10.1021/es802886k

Agbede, T. M., & Oyewumi, A. (2022). Effects of Biochar, Poultry Manure and Their Mixture on Essential Nutrients of Sweet Potato Leaves and Storage Roots in Degraded Tropical Alfisols of Southwest Nigeria. *Communications in Soil Science and Plant Analysis*, *53*(15), 1903–1916. https://doi.org/10.1080/00103624.2022.2069799

Agegnehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2016). Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment*, *543*, 295–306. https://doi.org/10.1016/j.scitotenv.2015.11.004

Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., Almutairi, K. F., & Al-Saif, A. M. (2021). Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy*, *11*(5), 993. https://doi.org/10.3390/agronomy11050993

Altieri, M. A., & Nicholls, C. I. (2003). Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems. *Soil and Tillage Research*, *72*(2), 203–211. https://doi.org/10.1016/s0167-1987(03)00089-8

Amanullah, K., & Khalid, S. (2016). Integrated Use of Phosphorus, Animal Manures and Biofertilizers Improve Maize Productivity under Semiarid Condition. *Organic Fertilizers - From Basic Concepts to Applied Outcomes*, 137–155. https://doi.org/10.5772/62388

Antonious, G. F. (2018). Biochar and Animal Manure Impact on Soil, Crop Yield and Quality. In *Agricultural Waste and Residues*: InTech.

Antonious, G. F. (2024). Impact of biochar and organic fertilizers on sweet potato yield, quality, ascorbic acid, β-carotene, sugars, and phenols contents. *International Journal of Environmental Health Research*, *34*(11), 3708–3719. https://doi.org/10.1080/09603123.2024.2318368

Antonious, G. F., Turley, E. T., & Dawood, M. H. (2020). Monitoring soil enzymes activity before and after animal manure application. *Agriculture*, *10*(5), 166. https://doi.org/10.3390/agriculture10050166

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and soil*, *337*, 1–18. https://doi.org/10.1007/s11104-010-0464-5

Campbell, C., Biederbeck, V., Selles, F., Schnitzer, M., & Stewart, J. (1986). Effect of manure and P fertilizer on properties of a Black Chernozem in southern Saskatchewan. *Canadian journal of soil science*, *66*(4), 601–614. https://doi.org/10.4141/cjss86-060

Ding, J. N. (2025). EFFECTS OF BIOCHAR APPLICATION AND NITROGEN FERTILIZER REDUCTION ON NUTRIENT UPTAKE AND YIELD OF RICE IN COLD REGIONS. *Applied Ecology and Environmental Research*, *23*(3), 4859–4876. https://doi.org/10.15666/aeer/2303_48594876

Fouad Antonious, G., Hasan Dawood, M., Todd Turley, E., & Bradley Paxton, R. (2022). Biochar and Animal Manures Increased Yield of Three Varieties of Turnips. *International Journal of Applied Agricultural Sciences*, *8*(1), 50. https://doi.org/10.11648/j.ijaas.20220801.16

Franzluebbers, A. J., Sawchik, J., & Taboada, M. A. (2014). Agronomic and environmental impacts of pasture–crop rotations in temperate North and South America. *Agriculture, Ecosystems & Environment*, *190*, 18–26. https://doi.org/10.1016/j.agee.2013.09.017

Graham, E., Grandy, S., & Thelen, M. (2009). Manure effects on soil organisms and soil quality. *Emerging Issues in Animal Agriculture. Michigan State University Extension*, 1–6. www.canr.msu.edu/uploads/files/AABI/Manure%20effects%20on%20soil%20organisms.pdf

Gross, A., Bromm, T., & Glaser, B. (2021). Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis. *Agronomy*, *11*(12), 2474. https://doi.org/10.3390/agronomy11122474

Han, F., Ren, L., & Zhang, X.-C. (2016). Effect of biochar on the soil nutrients about different grasslands in the Loess Plateau. *CATENA*, *137*, 554–562. https://doi.org/10.1016/j.catena.2015.11.002

Haque, M. M., Datta, J., Ahmed, T., Ehsanullah, M., Karim, M. N., Akter, M. S., Iqbal, M. A., Baazeem, A., Hadifa, A., & Ahmed, S. (2021). Organic amendments boost soil fertility and rice productivity and reduce methane emissions from paddy fields under sub-tropical conditions. *Sustainability*, *13*(6), 3103. https://doi.org/10.3390/su13063103

He, D., Ma, H., Hu, D., Wang, X., Dong, Z., & Zhu, B. (2024). Biochar for sustainable agriculture: Improved soil carbon storage and reduced emissions on cropland. *Journal of Environmental Management*, *371*, 123147. https://doi.org/10.1016/j.jenvman.2024.123147

Hoffmann, I., Gerling, D., Kyiogwom, U. B., & Mané-Bielfeldt, A. (2001). Farmers' management strategies to maintain soil fertility in a remote area in northwest Nigeria. *Agriculture, Ecosystems & Environment*, *86*(3), 263–275. https://doi.org/10.1016/S0167-8809(00)00288-7

Lebrun, M., Zahid, Z., Bednik, M., Medynska-Juraszek, A., Száková, J., Brtnický, M., Holátko, J., Bourgerie, S., Beesley, L., & Pohořelý, M. (2024). Combined biochar and manure addition to an agricultural soil benefits fertility, microbial activity, and mitigates manure-induced CO2 emissions. *Soil Use and Management*, *40*(1), e12997. https://doi.org/10.1111/sum.12997

Lehmann, J., & Joseph, S. (2015). *Biochar for environmental management: science, technology and implementation*. Routledge, Taylor & Francis Group, London. https://doi.org/10.4324/9780203762264

Li, H., Yang, L., Mao, Q., Zhou, H., Guo, P., Agathokleous, E., & Wang, S. (2023). Modified biochar enhances soil fertility and nutrient uptake and yield of rice in mercury-contaminated soil. *Environmental Technology & Innovation*, *32*, 103435. https://doi.org/10.1016/j.eti.2023.103435

Li, W., Gao, J., Zhou, S., & Zhou, F. (2024). Effect of Biochar on Apple Yield and Quality in Aged Apple Orchards on the Loess Plateau (China). *Agronomy*, *14*(6), 1125. https://doi.org/10.3390/agronomy14061125

Lupwayi, N., Girma, M., & Haque, I. (2000). Plant nutrient contents of cattle manures from small-scale farms and experimental stations in the Ethiopian highlands. *Agriculture, Ecosystems & Environment*, *78*(1), 57–63. https://doi.org/10.1016/S0167-8809(99)00113-9

Moreno-Barriga, F., Díaz, V., Acosta, J. A., Muñoz, M. Á., Faz, Á., & Zornoza, R. (2017). Organic matter dynamics, soil aggregation and microbial biomass and activity in Technosols created with metalliferous mine residues, biochar and marble waste. *Geoderma*, *301*, 19–29. https://doi.org/10.1016/j.geoderma.2017.04.017

Mota, P. K., Silva, B. M., Borghi, E., Viana, J. H. M., Resende, Á. V. d., & Moura, M. S. d. (2020). Soil physical quality in response to intensification of grain production systems. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *24*(10), 647–655. https://doi.org/10.1590/1807-1929/agriambi.v24n10p647-655

Nepal, A., Antonious, G. F., Gyawali, B. R., Webster, T. C., & Bebe, F. (2024). Assessing the bioaccumulation of heavy metals in cabbage grown under five soil amendments. *Pollutants*, *4*(1), 58–71. https://doi.org/10.3390/pollutants4010005

Safaei Khorram, M., Zhang, G., Fatemi, A., Kiefer, R., Maddah, K., Baqar, M., Zakaria, M. P., & Li, G. (2019). Impact of biochar and compost amendment on soil quality, growth and yield of a replanted apple orchard in a 4-year field study. *Journal of the Science of Food and Agriculture*, *99*(4), 1862–1869. https://doi.org/10.1002/jsfa.9380

Shapiro, C., Johnson, L. J., Schmidt, A., & Koelsch, R. (2021). Determining crop available nutrients from manure. *University of Nebraska–Lincoln Extension*, *(NebGuide G1335)*.https://extensionpubs.unl.edu/publication/g1335/2021/html/view

Sifton, M. A., Smith, S. M., & Thomas, S. C. (2023). Biochar-biofertilizer combinations enhance growth and nutrient uptake in silver maple grown in an urban soil. *PloS one*, *18*(7), e0288291–e0288291. https://doi.org/10.1371/journal.pone.0288291

Sultan, H., Li, Y., Ahmed, W., Shah, A., Faizan, M., Ahmad, A., Abbas, H. M. M., Nie, L., & Khan, M. N. (2024). Biochar and nano biochar: Enhancing salt resilience in plants and soil while mitigating greenhouse gas emissions: A comprehensive review. *Journal of Environmental Management*, *355*, 120448. https://doi.org/10.1016/j.jenvman.2024.120448

Sun, J., Tu, S., Lu, X., & Li, X. (2025). Coupling of Biochar and Manure Improves Soil Carbon Pool Stability, Pore Structure, and Microbial Diversity. *Agronomy*, *15*(6), 1384. https://doi.org/10.3390/agronomy15061384

Tubeileh, A. M., & Goss, M. J. (2022). Assessing the effects of using animal manure on soil health. In *Burleigh Dodds Series in Agricultural Science* (pp. 281–308): Burleigh Dodds Science Publishing.

Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., & Nishihara, E. (2011). Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use and Management*, *27*(2), 205–212. https://doi.org/10.1111/j.1475-2743.2011.00340.x

Verheijen, F., Jeffery, S., Bastos, A., Van Der Velde, M., Diafas, I., & Parsons, C. (2009). Biochar application to soils: a critical scientific review of effects on soil properties, processes and functions. Joint Research Centre. *Institute for Environment and Sustainability, Ispra, Italy*. https://doi.org/10.2779/978-92-79-12298-7

Ye, Z., Zhang, H., Lin, X., Huang, S., Zou, S., & Zou, X. (2024). Effect of Biochar Using N, P, and K Fertilisers on Growth and Quality of Lithocarpus litseifolius. *Agronomy*, *14*(4), 728.

Yu, O. Y., Harper, M., Hoepfl, M., & Domermuth, D. (2017). Characterization of biochar and its effects on the water holding capacity of loamy sand soil: Comparison of hemlock biochar and switchblade grass biochar characteristics. *Environmental Progress & Sustainable Energy*, *36*(5), 1474–1479. https://doi.org/10.1002/ep.12592

Zandvakili, O. R., Barker, A. V., Hashemi, M., Xing, B., Spokas, K. A., Herbert, S. J., Ribbe, A. E., Clemente, R., & Parikh, S. J. (2025). Physicochemical evolution of sugar maple biochar: Insights from a long-term field trial. *Journal of environmental quality*. https://doi.org/10.1002/jeq2.70053

Zhuang, X., Wan, H., Wang, H., Qin, S., He, J., & Lyu, D. (2023). Characteristics of cadmium accumulation and tolerance in apple plants grown in different soils. *Frontiers in plant science*, *14*, 1188241–1188241. https://doi.org/10.3389/fpls.2023.1188241

4

THE USE OF *AZOTOBACTER* IN ORGANIC FARMING

Yusuf Solmaz[1], Someyyeh Razzaghi[2], Sude Kartal[3], Ahmet Çelik[4], Korkmaz Bellitürk[5]

Abstract

Azotobacter is a genus of bacteria that lives freely and can fix nitrogen naturally, and it is used as an important biological fertilizer in organic farming. This bacterium enriches the soil by converting atmospheric nitrogen into a form that plants can use. Additionally, it produces growth hormones that support root development and increase the solubility of nutrients like phosphorus, enhancing the nutrient uptake of plants. Another significant benefit of *Azotobacter* is its ability to improve the resilience of plants against environmental stresses. It strengthens plant resistance to abiotic stress conditions such as drought and salinity. This feature offers a major advantage, particularly in agriculture, in facing the challenges of climate change. The use of *Azotobacter* in organic farming reduces the environmental impacts of chemical fertilizers, improves soil health, and supports sustainable agriculture. The excessive use of chemical fertilizers degrades soil structure and leads to water pollution; however, biological fertilizers like *Azotobacter* minimize these negative effects. In conclusion, *Azotobacter* offers an environmentally friendly alternative in organic farming, enhancing productivity and preserving ecosystems.

Keywords: *Azotobacter*, organic farming, microbial fertilizer, plant.

1. Introduction

The utilization of chemical fertilizers and amendments in global agriculture has significantly improved production and productivity. But over time, it has been noted that chemical substances disrupt the natural equilibrium and negatively impact human health. As a result, organic farming has arisen as a preeminent agricultural method that protects human health. Organic farming is an approach aimed at restoring the ecological balance damaged by incorrect practices by establishing a system advantageous to both humans and the environment. It primarily promotes the utilization of organic and eco-friendly fertilizers instead

1 Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Tekirdağ, Türkiye, ORCID:0000-0003-2170-0375, e-mail: ysolmaz@nku.edu.tr
2 Erciyes University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Kayseri, Türkiye, ORCID:0000-0002-8028-452X, e-mail: srazzaghi@erciyes.edu.tr
3 Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Tekirdağ, Türkiye, ORCID: 0009-0004-8679-9243, e-mail: 1220322022@nku.edu.tr
4 Adıyaman University, Agriculture Faculty, Department of Soil Science and Plant Nutrition, Adıyaman, Türkiye. ORCID: 0000-0001-8958-4978, e-mail: ahmetcelik@adiyaman.edu.tr
5 Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Tekirdağ, Türkiye, ORCID: 0000-0003-4944-3497, e-mail: kbelliturk@nku.edu.tr

of synthetic chemicals, crop rotation, soil conservation, enhancement of plant resistance, and the employment of natural predators to emphasize enhancing product quality over production quantity (Rehber and Turhan, 2001). Organic farming is an agricultural methodology that prohibits chemical inputs and governs all stages from production to consumption (Kırımhan, 2005). Organic farming aims to augment genetic diversity, advocate for the use of natural pesticides, guarantee timely soil management, preserve and enhance soil structure and fertility, and control diseases, weeds, and vegetation. Its numerous advantages encompass safeguarding future generations, mitigating soil erosion, preserving soil water quality, conserving energy, reducing chemical residues from the soil, protecting agricultural laborers, enhancing the income of economically disadvantaged farmers, optimizing economic output, ensuring soil biological diversity, and enhancing the aroma of soil-derived products (Mandal, 2020; Öner, 2020).

2. Microbial Fertilizer

Microorganisms and biofertilizers derived from microbial products, or microbial fertilizers, have proven pivotal in promoting sustainable managed organic farming in recent years (Okumuş and Alçınkaya, 2019). Microbial fertilizers, designed for agricultural production, comprise microorganisms that facilitate nutrient absorption and essential nutrients for plant growth and development (Şahin, 2010). Microbial fertilizers are created by directly incorporating laboratory-cultivated mycorrhizal fungi, connected with either bacteria or roots, into the soil. Bacterial inoculants, microbial cultures, bioinoculants, and bacterial fertilizers are all other names for microbial fertilizers (Parlak and Güner, 2017). Microbial fertilizers, essential for sustainable agriculture, improve plant health by mitigating diseases and promoting development through the provision of diverse nutrients and phytohormones. Microbial fertilizers augment soil fertility and elevate productivity. Microbial fertilizers confer multiple advantages, including enhancements in photosynthesis, amino acid production, pest management, biofortification, and mitigation of abiotic stress (Baran et al., 2023). Studies have demonstrated that the microbial community and activity in the soil are enhanced after the application of formulations to the host plant (Arora et al., 2011). Microbial fertilizers can be classified into various types based on their benefits. They are categorized as nitrogen fixers, phosphate and potassium solubilizers, sulfur oxidizers, silicate solubilizers, and decomposing cultures based on their functions (Parlak and Güner, 2017). Plant growth-promoting rhizobacteria (PGPR) are free-living microorganisms that enhance plant development, function as biological control agents, or serve as microbial fertilizers (Çakmakçı, 2005). Genera of bacteria currently utilized and evaluated in microbial fertilization include *Acinetobacter*, *Agrobacterium*, *Alcaligenes*, *Arthrobacter*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Bradyrhizobium*, *Frankia*, *Pantoea*, *Pseudomonas*, *Rhizobium*, *Serratia*, *Stenotrophomonas*, *Streptomyces*, and *Thiobacillus* (Arora et al., 2011).

3. *Azotobacter*

Azotobacter was identified in 1901 by Beijerinck, a Dutch microbiologist and botanist. Subsequently, more species, including *A. vinelandii*, *A. chroococcum*, *A. armeniacus*, *A. beijerinckii*, *A. nigricans*, *A. paspali*, *A. salinestris*, and *A. tropicalis*, were discovered (Jimenez et al., 2011; Özen and Ussery, 2012; Chen et al., 2018). The predominant species is *A. chroococcum*. *Azotobacter* is a gram-negative, aerobic bacterium that exists freely in the soil, producing thick-walled cysts, and is characterized by an oval or spherical morphology. It is a heterotrophic, free-living nitrogen-fixing bacterium that flourishes in neutral and alkaline soils. *Azotobacter* species belong to the category of rhizobacteria that enhance plant growth extracellularly (Bicek, 2021). *Azotobacter* species possess the distinctive capability to produce cysts in response to adverse and stressful conditions, including severe temperatures, freezing, salinity, and drought (Sadoff, 1975). These cysts safeguard *Azotobacter* species from environmental stresses and soil predators (Aasfar et al., 2021). *Azotobacter* spp. exhibit considerable sensitivity to acidic pH, elevated salinity, and temperature extremes (Jnawali et al., 2015). Azotobacter exhibits optimal growth within a pH range of 4.8–8.5 and effectively fixes nitrogen at a pH range of 7.0–7.5. The ideal temperature range for *Azotobacter* growth is 28–32°C, with a maximum temperature of approximately 38°C and a minimum temperature of 22°C (Tolangı, 2022). Azotobacter are frequently found in soil, water, and sediments (Apriliya and Mulyawan, 2022). The abundance of *Azotobacter* species in the soil can fluctuate based on various factors, including the physicochemical and microbiological characteristics of the soil (Kizilkaya, 2009). The density of *Azotobacter* in the soil varies with the depth of the soil profile (Bicek, 2021). The dimensions of these microorganisms range from 2-10 x 1-2.5 µm (Apriliya and Mulyawan, 2022). These bacteria are recognized for their capacity to fix N_2 in a free (non-symbiotic) way. *Azotobacter* are bacteria capable of synthesizing vitamins, amino acids, growth hormones, antifungal agents, hydrogen cyanide, and siderophores, which can promote plant growth and protect plants against pathogen attacks (Gurikar et al., 2016).

4. Activities of *Azotobacter* in Promoting Plant Growth

Despite numerous studies on the use of *Azotobacter* in promoting plant growth, the exact mechanism behind the growth-promoting effect of these bacteria has not yet been fully elucidated (Ansari et al., 2017).

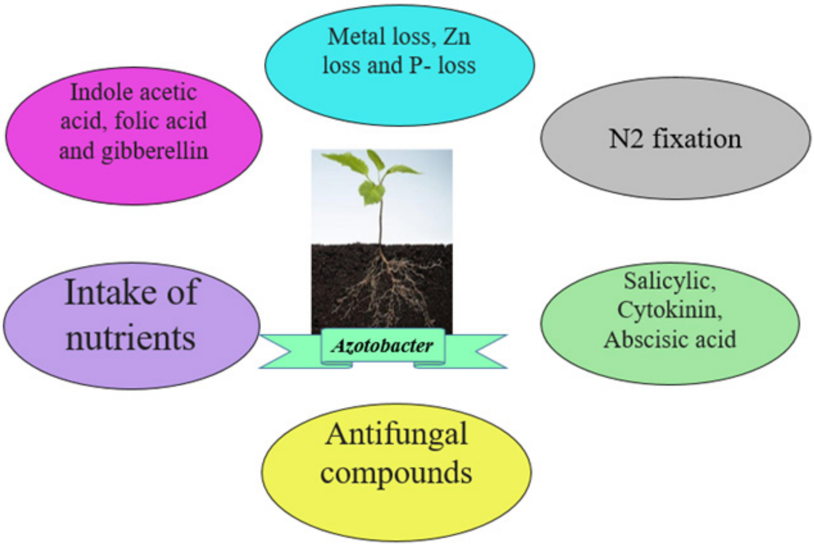


Figure 1. Effective Mechanisms of *Azotobacter* in Plant Development

4.1. The Contribution of *Azotobacter* to Plant Growth through Nitrogen Fixation

Nitrogen is a component of proteins, nucleic acids, and chlorophyll (Bolat and Kara, 2017). Therefore, the amount of nitrogen provided to the plant affects the formation of proteins, amino acids, protoplasm, and chlorophyll. Thus, sufficient nitrogen supply is necessary to achieve high yields in agriculture (Jnawali et al., 2015). Nitrogen deficiency is one of the limiting factors in agricultural production; it negatively affects many characteristics of the plant, such as its growth rate, vegetative development, flowering, and fruit set (Bolat and Kara, 2017). The atmosphere contains approximately 78% inert, unusable nitrogen (Jnawali et al., 2015). It has been reported that the air mass over one decare of land contains 8,642 tons of elemental nitrogen (Kovancı, 1975). Plants cannot directly utilize this nitrogen. If the plants want to benefit from it in this form, this nitrogen must be converted into an inorganic form. The conversion of atmospheric nitrogen, which is abundant but not usable by plants in its molecular form, into an organic form through fixation is called biological nitrogen fixation (Müftüoğlu and Demirer, 1998). Nitrogen fixation is one of the most important microbial activities and biological processes occurring on Earth after photosynthesis (Nongthombam et al., 2021). *Azotobacter* exhibits rapid growth and has a high level of nitrogen fixation. Therefore, it can be used for both nitrogen fixation studies and plant inoculation (Prajapati et al., 2008; Shokri and Emtiazi, 2010). *Azotobacter* converts nitrogen into ammonia, allowing plants to later benefit from this ammonia (Nongthombam et al., 2021). *Azotobacter* requires an optimum level of calcium for its growth and nitrogen-fixing ability (Sumbul et al., 2020). Increased nitrogen levels negatively affect the efficiency of *Azotobacter* (Soleimanzadeh and Gooshchi, 2013). *Azotobacter* species have the ability to fix 20 kg of nitrogen per hectare per year; this amount can be used in agricultural production (Kizilkaya, 2009). All *Azotobacter* species do not have the ability to fix atmospheric nitrogen. The nitrogen-fixing capacity of *Azotobacter* species can vary from species to species (Bicek, 2021). Various studies have shown that the need for nitrogen fertilizers decreases in agricultural plants inoculated with *Azotobacter* (Sumbul et al., 2020). Romero-Perdomo et al. (2017) reported that the application of mixed cultures of *Azotobacter* strains could reduce the need for nitrogen fertilizers by up to 50%. Some *Azotobacter* species can convert phosphorus, which is the least mobile and least accessible nutrient for plants in most soils, into easily absorbable soluble forms for plants. Low phosphorus availability limits biological nitrogen fixation (Aasfar et al., 2021).

4.2. The Ability of *Azotobacter* to Produce Plant Growth-Promoting Hormones

Growth substances, or plant hormones, are naturally produced by both microorganisms and plants; these substances have stimulatory and inhibitory effects on certain physiological and biochemical processes in microorganisms and plants (Sumbul et al., 2020). *Azotobacter*, in addition to fixing nitrogen, produces physiologically active substances such as vitamin B12, auxins (IAA), thiamin, riboflavin, nicotinic acid, folic acid, pantothenic acid, and biotin. Additionally, *Azotobacter* can produce substances such as indole acetic acid, folic acid, and gibberellin that positively affect plant physiology (Tolangı, 2022). These hormones, which are produced by *Azotobacter*, are provided from the rhizosphere or root surface, positively affecting the growth of the upper plants growing in the environment (Sumbul et al., 2020). When *Azotobacter* is applied to seeds, seed germination significantly increases (Jnawali et al., 2015). In addition to producing plant growth hormones, some *Azotobacter* strains are characterized by their ability to synthesize antifungal substances that limit the development of phytopathogenic species (Bjelic et al., 2015). In a study conducted by El_Komy et al. (2020), it was found that the use of a mixture of *Azotobacter*, *Azospirillum*, and *Klebsiella* significantly reduced the mycelium development of some pathogenic fungi such as *Macrophomina phaseolina*, *Rhizoctonia solani*, and *Fusarium solani*. The solubility of potassium (K) and zinc (Zn) elements is an important component of *Azotobacter*'s potential to promote plant growth. *Azotobacter* has the ability to produce organic acids by chelating zinc cations in the soil and lowering the pH around the soil (Aasfar et al., 2021). As a result of zinc solubilization, siderophore substances such as vibrioferrin, amphibactins, and croseilins are produced by *A. chroococcum*, and these substances also contribute to the control of plant pathogens in the soil (Saravanan et al., 2011; Baars et al., 2018). Studies have shown that *Azotobacter* is not only effective in potassium solubilization but also plays significant roles in enhancing potassium assimilation in plants (Wu et al., 2005; Singh et al., 2010).

In the study conducted by Ordookhani et al. (2011), the effect of inoculating the roots of sweet basil (*Ocimum basilicum L.*) with PGPR (*Pseudomonas putida* strain 41, *Azotobacter chroococcum*, and *Azosprillum lipoferum*) on plant growth and essential oil yield was investigated. Sweet basil (*Ocimum basilicum L.*) seeds were sown in pots containing 7 kg of mixed soil. Before sowing, 7 different PGPR (*Pseudomonas putida*, *Azotobacter chroococcum*, *A. lipoferum*, *P. putida* + *A. chroococcum*, *P. putida* + *A. lipoferum*, *A. chroococcum* + *A. lipoferum*, *P. putida* + *A. chroococcum* + *A. lipoferum*) applications were made to the seeds. As a result of the study, the maximum root fresh weight, stem fresh weight, stem dry weight, root dry weight content, and essential oil yield were observed with the application of *Pseudomonas* + *Azotobacter* + *Azosprillum*. Furthermore, in a study conducted by Tolangı (2022), the nitrogen fixation and PGPR effects of *Azotobacter chroococcum* on tomato plants were examined, and it was reported that *A. chroococcum* had a significant impact on the growth of tomato plants. Additionally, it has been noted that *A. chroococcum* could be a good option as a plant growth promoter for the sustainable growth of various crops in the fields.

Alsalim (2020) evaluated the nitrogen fixation (nitrogenase enzyme activity), inorganic phosphate solubilization, siderophore, and IAA production capacities of *A. chroococcum* and *R. leguminosarum* inoculants. Furthermore, the effects of their application alone or in combination on the length and weight of the faba bean plant and roots were examined. Additionally, the survival rates of the inoculants in the soil during the experiment were evaluated. At the end of the experiment, the combined application of *A. chroococcum* and *R. leguminosarum* inoculations resulted in the highest percentage of increase in the length of the vegetative part of the plant, the weight of the vegetative part, the root length, and the root weight. Kızıloğlu and Bilen (2004), were investigated the effects of nitrogen fertilization applied to the soil and leaves, and inoculation with *Azotobacter* sp. isolates on the dry matter content and total nitrogen content of wheat plants. They found that the inoculation of plants with *Azotobacter* sp. showed higher dry matter content and total nitrogen content compared to the non-inoculated ones. In a study conducted by Baral and Adhikary (2013), the effect of *Azotobacter* on the growth and yield of corn was investigated, and it was reported that where *Azotobacter* was applied, the plant height, ear height, number of ears per m^2, ear length, number of grains per row, 1000-grain weight, grain yield, and stover yield of corn significantly increased.

5. The Potential of *Azotobacter* in Bioremediation

The process of reducing soil pollution through methods such as activating the native soil microbiota that reduces the pollution or introducing efficient microorganism isolations into the contaminated soil is called bioremediation. *Azotobacter* species constitute a significant portion of the soil biota (Gradova et al., 2003).

Azotobacter species produce active compounds as a form of biodiversity that promotes the proliferation of rhizosphere microorganisms by utilizing organic substrates such as mannitol, various organic acids, and benzoic acid as sources of carbon and energy (Onwurah and Nwuke, 2004). Therefore, *Azotobacter* species can be used in the bioremediation of oil-contaminated soils (Sumbul et al., 2020).

5.1. Pesticide Degradation

Pesticides are chemical substances or mixtures of substances used to prevent or control the effects of insects, weeds, microorganisms, and other pests that can cause damage during the production, harvesting, storage, or transportation of agricultural and livestock products (Akdoğan et al., 2012). During the application of pesticides, a portion evaporates or disperses into the environment and is lost, while the remaining part remains on the plant surface and in the soil. Pesticides that enter the atmosphere can be carried to different areas by the wind and can return to the soil with rainfall. In this way, pesticides that reach non-target plants and organisms can lead to residue formation and toxic effects on these species (Kiziewicz and Czeczuga, 2002). Therefore, soil contaminated with pesticides loses its fertility and poses serious environmental problems due to toxic effects. Pesticides applied to the soil can be utilized as substrates by *Azotobacter* and can undergo degradation (Abo-Amer, 2011).

5.2. Heavy Metal Tolerance

In a study conducted by Abo-Amer (2014), it was reported that among *Azotobacter* isolates obtained from soil contaminated with wastewater, heavy metals such as Co^{2+}, Ni^{2+}, Zn^{2+}, and Cu^{2+} exhibited significant resistance. This study highlights the potential use of these *Azotobacter* isolates in the bioremediation of metal-contaminated systems. Furthermore, Joshi and Juwarkar (2009), reported that a heavy metal-resistant strain of *Azotobacter* spp. has a strong binding ability with Cd and Cr, and this is effective in controlling the uptake of these metals by wheat plants grown in heavy metal-contaminated soils. *Azotobacter* bacteria encounter heavy metals before they enter the cell, with these bacteria producing extracellular polymeric substances in large quantities (Gorin and Spencer, 1961). These extracellular polymeric substances play an important role by chelating metal ions and preventing their entry into bacterial cells (Sumbul et al., 2020).

5.3. Salty Environment

Salinity is the most significant stress factor threatening plant health among abiotic stresses (Yang et al., 2009). Salinity causes disruptions in the movement of water and ions in plant cells, negatively affecting plant growth, morphology, physiology, and other vital activities, ultimately leading to plant death (Maggio et al., 2007). These microorganisms affect plant growth and biochemical processes and also accelerate the production of certain organic molecules that help plants gain immunity against various abiotic stresses. In addition, it has been found that beneficial bacteria (PGPR) that promote plant growth have a positive effect on improving plant health by eliminating various biotic and abiotic stresses (Sumbul et al., 2020).

6. The Role of *Azotobacter* in the Management of Plant Diseases

Azotobacter, besides promoting plant growth, also plays a role in suppressing plant diseases. Maheshwari et al. (2012), in their study, found that the *A. chroococcum* TRA2 strain isolated from the wheat rhizosphere exhibited strong antagonistic activity against the root rot pathogens *Macrophomina phaseolina* and *Fusarium oxysporum*, and in addition, improved the growth of wheat plants. In a study conducted by Akram et al. (2016), it was reported that the application of *A. chroococcum* to chickpea plants significantly reduced the disease incidence caused by the root-knot nematode *Meloidogyne incognita*.

There are many mechanisms behind the various management strategies that *Azotobacter* uses to control plant diseases. Among these are the production of siderophores, antimicrobial substances, toxins, and growth hormones such as auxins, gibberellins, and cytokinins. Although multiple properties may be active depending on the bacterial strain used, environmental conditions, the relevant pathogen, and the target (Sumbul et al., 2020).

Azotobacter can produce antifungal compounds in various forms, such as azotobactin, azotochelin, aminochelin, HCN, testin, viscosinamide, zwittermycin A, etc. *Azotobacter* has a wide antibiotic potential that can be used as a biological control agent as an alternative to chemical substances in agricultural production and various food industry applications (Tarana et al., 2024). Some pathogens that can be controlled by using *Azotobacter* as a bio-inoculant include *Alternaria*, *Fusarium*, *Rhizoctonia*, *Macrophomina*, *Curvularia*, *Helminthosporium*, and *Aspergillus* (Jnawali et al., 2015).

7. Conclusion and Recommendations

Azotobacter has great potential as a natural and environmentally friendly biofertilizer source in organic farming. Its advantages, such as nitrogen fixation, production of growth hormones, enhancement of nutrient solubility, and increased tolerance to environmental stresses, indicate that this microorganism offers an effective solution for improving productivity in organic farming. Additionally, the use of *Azotobacter* improves soil health and supports sustainable agricultural practices by minimizing the environmental impacts of chemical fertilizers. With these characteristics, the widespread use of *Azotobacter* in organic farming would be an important step toward both environmental and economic sustainability.

8. References

Aasfar, A., Bargaz, A., Yaakoubi, K., Hilali, A., Bennis, I., Zeroual, Y., Meftah Kadmiri, I., 2021. Nitrogen Fixing *Azotobacter* Species as Potential Soil Biological Enhancers for Crop Nutrition and Yield Stability. Frontiers in Microbiology, 12: 628379. doi: 10.3389/fmicb.2021.628379.

Abo-Amer, A.E., Abu-Gharbia, M.A., Soltan, E.S.M., Abd El-Raheem, W.M., 2014. Isolation and Molecular Characterization of Heavy Metal-Resistant *Azotobacter chroococcum* From Agricultural Soil and Their Potential Application in Bioremediation. Geomicrobiology Journal, 31 (7): 551-561.

Abo-Amer, A.E., 2011. Biodegradation of Diazinon by Serratia Marcescens DI101 and Its Use in Bioremediation of Contaminated Environment. Journal of Microbiology and Biotechnology, 21 (1): 71–80.

Akdoğan, A., Divrikli, Ü., Elçi, L., 2012. Pestisitlerin Önemi ve Ekosisteme Etkileri. Akademik Gıda, 10 (1): 125-132.

Akram, M., Rizvi, R., Sumbul, A., Ansari, R.A., Mahmood, I., 2016. Potential Role of Bioinoculants and Organic Matter for the Management of Root-Knot Nematode Infesting Chickpea. Cogent Food and Agriculture, 2 (1): 1183457.

Alsalim, H.A., 2020. *Azotobacter chroococcum* and *Rhizobium leguminosarum* Inoculums Survival in Soil and Efficiency in Enhancing Plant Growth. Plant Archives, (09725210), 20 (2).

Ansari, R.A., Rizvi, R., Sumbul, A., Mahmood, I., 2017. PGPR: Current Vogue in Sustainable Crop Production. In Probiotics and Plant Health, 455-472.

Apriliya, I., Mulyawan, R., 2022. Utilization of *Azotobacter* as Bio-Fertilizer to Support Sustainable Agriculture. International Journal of Chemical and Biochemical Sciences, 197-206.

Arora, N.K., Khare, E., Maheshwari, D.K., 2011. Plant Growth Promoting Rhizobacteria: Constraints, in Bioformulation, Commercialization, and Future Strategies. Plant Growth and Health Promoting Bacteria, 97-116.

Baars, O., Zhang, X., Gibson, M.I., Stone, A.T., Morel, F.M., Seyedsayamdost, M.R., 2018. Crochelins: Siderophores with an Unprecedented Iron-Chelating Moiety from The Nitrogen-Fixing Bacterium *Azotobacter chroococcum.* Angewandte Chemie, 130 (2): 545-550.

Baral, B.R., Adhikari, P., 2013. Effect of *Azotobacter* on Growth and Yield of Maize. *SAARC* Journal of Agriculture, 11 (2): 141-147.

Baran, M., Erbaş Köse, Ö.D., 2023. Mikrobiyal Gübreler ve Kullanım Alanları. Türk Tarım-Gıda Bilim ve Teknoloji Dergisi Uluslararası Kongresi. TURSTEP.

Bicek, S., 2021. Azotu Fikse Eden *Azotobacter* Türlerinin Buğday Rizosferlerinden İzolasyonu ve Moleküler Karakterizasyonu, Doktora Tezi.

Bjelić, D.Đ., Marinković, J.B., Tintor, B.B., Tančić, S.L., Nastasić, A.M., Mrkovački, N.B., 2015. Screening of *Azotobacter* Isolates for PGP Properties and Antifungal Activity. Zbornik Matice Srpske Za Prirodne Nauke, (129): 65-72.

Bolat, İ., Kara, Ö., 2017. Bitki Besin Elementleri: Kaynakları, İşlevleri, Eksik ve Fazlalıkları. Bartın Orman Fakültesi Dergisi, 19 (1): 218-228.

Gurikar, C., Naik M.K., Sreenivasa, M.Y., 2016. *Azotobacter*: PGPR Activities with Special Reference to Effect of Pesticides and Biodegradation. Microbial Inoculants in Sustainable Agricultural Productivity, Vol, 1: 229-244. DOI 10.1007/978-81-322-2647-5_13.

Chen, S.L., Tsai, M.K., Huang, Y.M., Huang, C.H., 2018. Diversity and Characterization of *Azotobacter* Isolates Obtained from Rice Rhizosphere Soils in Taiwan. Annals of Microbiology, 68: 17-26.

El_Komy, M.H., Hassouna, M.G., Abou-Taleb, E.M., Al-Sarar, A.S., Abobakr, Y., 2020. A Mixture of *Azotobacter, Azospirillum*, and *Klebsiella* Strains Improves Root-Rot Disease Complex Management and Promotes Growth in Sunflowers in Calcareous Soil. European Journal of Plant Pathology, 156 (3): 713-726.

Gorin, P.A.J., Spencer, J.F.T., Tulloch, A.P., 1961. Hydroxy Fatty Acid Glycosides of Sophorose from Torulopsis Magnoliae. Canadian Journal of Chemistry, 39 (4): 846-855.

Gradova, N.B., Gornova, I.B., Eddaudi, R., Salina, R.N., 2003. Use of Bacteria of the Genus *Azotobacter* for Bioremediation of Oil-Contaminated Soils. Appl. Biochem. Micro., 39 (3): 279-281.

Jimenez, D.J., Montana, J.S., Martinez, M.M., 2011. Characterization of Free Nitrogen Fixing Bacteria of the Genus *Azotobacter* in Organic Vegetable Grown Colombian Soils. Brazilian Journal of Microbiology, 42: 846-858.

Jnawali, A.D., Ojha, R.B., Marahatta, S., 2015. Role of *Azotobacter* in Soil Fertility and Sustainability–A Review. Adv. Plants Agric. Res, 2 (6): 1-5.

Joshi, P.M., Juwarkar, A.A., 2009. In Vivo Studies to Elucidate the Role of Extracellular Polymeric Substances from *Azotobacter* in Immobilization of Heavy Metals. Environ. Sci. Technol., 43 (15): 5884-5889.

Kırımhan, S., 2005. Organik Tarım Sistemleri ve Çevre. Çevre Yönetimi Dizisi, No:2, Ankara.

Kızıloğlu, F.T., Bilen S., 2004. Topraktan ve Yapraktan Uygulanan Azotlu Gübrelemenin ve *Azotobacter* sp. İzolatı İle Aşılamanın Buğday Bitkisinin Kuru Madde Miktarı ve Toplam Azot İçeriği Üzerine Etkisi. Konferans: 3. Ulusal Gübre Kongresi, Tarım Sanayi Çevre. 11-13 Ekim, Biyogübreler, s: 945-952. Tokat.

Kiziewicz, B., Czeczuga, B., 2002. Bioaccumulation of Organochlorine Pesticides in the Trophic Chain Alga-Freshwater Fish. Acta Ichthyologica et Piscatoria 32(1): 41-51.

Kizilkaya R., 2009. Nitrogen Fixation Capacity of *Azotobacter* Spp. Strains Isolated from Soils in Different Ecosystems and Relationship Between Them and the Microbiological Properties of Soils. J Environ Biol, 30 (1): 73–82.

Kovancı, Y., 1975. Bitki Besleme ve Gübreleme İlmi. Ege Üniv., Ziraat Fak., Bornova – İzmir.

Maggio, A., Raimondi, G., Martino, A., De Pascale, S., 2007. Salt Stress Response in Tomato Beyond the Salinity Tolerance Threshold. Environ. Exp. Bot., 59:276–282.

Maheshwari, D.K., Dubey, R.C., Aeron, A., Kumar, B., Kumar, S., Tewari, S., Arora, N.K., 2012. Integrated Approach for Disease Management and Growth Enhancement of *Sesamum indicum* L. Utilizing *Azotobacter chroococcum* Tra2 And Chemical Fertilizer. World J. Microb. Biot., 28 (10): 3015-3024.

Mandal, S., 2020. Organic Farming. Erişim Adresi: https://www.surendranathcollege.ac.in/wp-content/uploads/2022/05/ORGANIC-FARMING.pdf, Erişim Tarihi:27.02.2025

Müftüoğlu, N.M., Demirer, T., 1998. Toprakta Azot Bilançosu. Atatürk Üniversitesi Ziraat Fakültesi Dergisi, 29 (1).

Nongthombam, J., Kumar, A., Sharma, S., Ahmed, S., 2021. *Azotobacter*: A Complete Review. Bull. Env. Pharmacol. Life Sci., 10 (6): 72-79.

Ojha, R.B. And Marahattha, A., 2015. Role of *Azotobacter* in Soil Fertility and Sustainability–A Review. 2 (6): 250–253.

Okumuş, A., Alçınkaya, T., 2019. Toprak Ve Bitki Destekleyicileri: Biopestisit ve Mikrobiyal Gübreler. Toprak ve Bitki Geliştirenler: Biyopestisitler ve Biyolojik Gübreler. Samsun.

Onwurah, I. N., Nwuke, C., 2004. Enhanced Bioremediation of Crude Oil-Contaminated Soil by a *Pseudomonas species* and Mutually Associated Adapted *Azotobacter Vinelandii.* J. Chem. Technol. Biotechnol., 79: 491–498.

Ordookhani K., Sharafzadeh S., Zare, M., 2011. Influence of PGPR on Growth, Essential Oil and Nutrients Uptake of Sweet Basil. Advances in Environmental Biology, 5 (4): 672-677, ISSN 1995-0756.

Öner, M., 2020. Organik Tarımın Genel İlkeleri. Erişim Adresi: https://www.dicle.edu.tr/Contents/pages/Files/36a31efa-fea2-446e-937b-5c7e1d5b2db9/cdea400b2a8f43a3966af9f0b9d9037b_ORG101%20Organik%20Tar%C4%B1m%C4%B1n%20Genel%20%C4%B0lkeleri%20Teorik%20Dersi.pdf, Erişim Tarihi: 28.02.2025.

Özen, A.I., Ussery, D.W., 2012. Defining the *Pseudomonas genus:* Where do we Draw the Line with *Azotobacter*.Microb Ecol, 63: 239-248.

Parlak, S., Güner, D., 2017. Mikrobiyal Gübre Uygulamasının Karaçam (*Pinus nigra* Arnold. subsp. pallasiana (Lamb.) Holmboe) Fidanlarının Bazı Morfolojik Özelliklerine Etkisi. Ormancılık Araştırma Dergisi, 4 (2): 100-106. https://doi.org/10.17568/ogmoad.337884.

Prajapati, K., Yami, K.D., Singh, A., 2008. Plant Growth Promotional Effect of *Azotobacter Chroococcum*, Piriformospora Indica and Vermicompost on Rice Plant. Nepal Journal of Science and Technology, 9: 85-90.

Rehber, E., Turhan, Ş., 2001. Prospects and Challenges for Developing Countries in Trade and Production of Organic Food and Fibers: The Case of Turkey, British food journal, 104(3/4/5), 371-390.

Romero-Perdomo, F., Abril, J., Camelo, M., Moreno-Galván, A., Pastrana, I., Rojas-Tapias, D., Bonilla, R., 2017. *Azotobacter chroococcum* as a Potentially Useful Bacterial Biofertilizer for Cotton (*Gossypium hirsutum*): Effect in Reducing N Fertilization. Revista Argentina de Microbiologia, 49 (4): 377-383.

Sadoff, H.L., 1975. Encystment and Germination in *Azotobacter vinelandii.* Bacteriol. Rev. 39: 516–539.

Saravanan, V.S., Kumar, M.R., Sa, T.M., 2011. "Microbial Zinc Solubilization and Their Role on Plants," in Bacteria in Agrobiology: Plant Nutrient Management, ed. D.K. Maheshwari (Berlin: Springer), 47–63.

Shokri, D., Emtiazi, G., 2010. Indole-3-Acetic Acid (IAA) Production in Symbiotic and Non-Symbiotic Nitrogen-Fixing Bacteria and ıts Optimization by Taguchi Design. Current Microbiology, 61 (3): 217-225.

Singh, G., Biswas, D.R., Marwaha, T.S., 2010. Mobilization of Potassium from Waste Mica by Plant Growth Promoting Rhizobacteria and ıts Assimilation by Maize (*Zea Mays)* and Wheat (*Triticum Aestivum.):* A Hydroponics Study Under Phytotron Growth Chamber. J. Plant Nutr. 33: 1236–1251. doi: 10.1080/ 01904161003765760.

Soleimanzadeh, H., Gooshchi, F., 2013. Effects of *Azotobacter* and Nitrogen Chemical Fertilizer on Yield And Yield Components Of Wheat (*Triticum aestivum* L.). World Appl. Sci. J., 21 (8): 1176-1180.

Sumbul, A., Ansari, R.A., Rizvi, R., Mahmood, I. 2020. *Azotobacter*: A Potential Bio-Fertilizer for Soil and Plant Health Management. Saudi J. Biol. Sci., 27: 3634–3640. doi: 10.1016/j.sjbs.2020.08.004.

Şahin, F., 2010. Organik Bitkisel Üretimde Biyoteknoloji ve Ar-Ge.

Tarana, A., Bhavishya A.D., 2024. Lekhana SMExtraction and Profiling of Antifungal Compounds Produced by *Azotobacter* Species. J. Pure Appl Microbiol*.,* 18 (1): 269-279. doi: 10.22207/JPAM.18.1.11.

Tolangi, P., 2022. Nitrogen Fixation Evaluation of *Azotobacter chroococcum* Isolated From Soil of Forest (Doctoral dissertation).

Wu, S.C., Cao, Z.H., Li, Z.G., Cheung, K.C., Wong, M.H. 2005. Effects of Biofertilizer Containing N-Fixer, P and K Solubilizers and AM Fungi on Maize Growth: A Greenhouse Trial. Geoderma 125, 155–166.

Yang, J., Kloepper, J.W., Ryu, C.M., 2009. Rhizosphere Bacteria Help Plants Tolerate Abiotic Stress. Trends Plant Sci., 14: 1–4.

5

MICROBIOME ENGINEERING IN VERMICOMPOSTING: SHAPING SOIL HEALTH THROUGH TARGETED MICROBIAL CONSORTIA

Antony Godson Siluvaipichai Gnanaprakasam[1], Rajalakshmi Govindaraju[2], Janaranjani Dhanapal[3], and Mohanapriya Ramasamy[4]

1. Introduction

1.1 Background and rationale

Vermicomposting, the process of converting organic waste into nutrient-rich compost through the synergistic action of earthworms and microorganisms, has emerged as a promising tool in sustainable agriculture. Recent studies have highlighted its ability to improve soil fertility, enhance microbial diversity, and reduce the dependency on chemical fertilizers (Lukashe *et al*., 2023; Zhang et *al*., 2022). The bio-oxidative and mesophilic nature of vermicomposting facilitates the stabilization of organic matter and the enrichment of bioavailable nutrients, while also promoting beneficial microbial consortia that support plant growth and soil health (Discover Sustainability, 2024) (Figure 1).

1 Assistant Professor, Department of Biotechnology, Hindusthan College of Arts & Science, Coimbatore, Tamilnadu, India-641028, dr.s.g.antonygodson@hicas.ac.in https://orcid.org/0000-0003-4469-8976?lang=en
2 Professor and Head, Department of Biotechnology, Hindusthan College of Arts & Science (Autonomous), Coimbatore, India. raajeerajan@gmail.com https://orcid.org/0000-0002-0851-5055
3 Assistant Professor, Department of Biotechnology, Hindusthan College of Arts & Science (Autonomous), Coimbatore, India. janaranjani.d@hicas.ac.in https://orcid.org/0009-0005-3361-9066
4 Associate Professor, Department of Biotechnology, Hindusthan College of Arts & Science, Coimbatore, Tamilnadu, India-641028 r.mohanapriya@hicas.ac.in

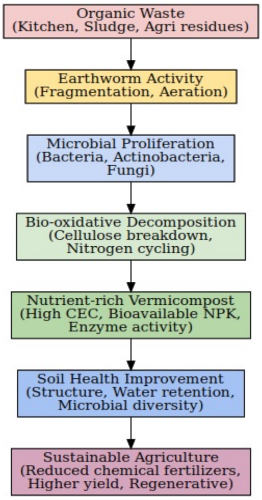


Figure 1 Flowchart representation of the vermicomposting process, highlighting the role of earthworms, microbes, and bio-oxidative decomposition in transforming organic waste into nutrient-rich compost for sustainable agriculture

1.2 Scope and Objectives

This chapter aims to establish a foundational understanding of vermicomposting and its microbiological implications. Specifically, it will:

- Outline the classical processes and ecological relevance of vermicomposting;
- Examine the role of microbial communities in compost maturation and nutrient cycling;
- Link vermicomposting to broader frameworks of regenerative and circular agriculture.

1.3 Importance of Microbiome in Vermicomposting

The efficiency and functionality of vermicompost are largely determined by its microbiome. Earthworms act as biological reactors, fragmenting organic material and creating a conducive environment for microbial proliferation. Dominant microbial groups, including Proteobacteria, Actinobacteria, Bacteroidetes, and Firmicutes, play critical roles in cellulose degradation, nitrogen cycling, and pathogen suppression (Zhang et al., 2022). Vermicompost application has been shown to enhance enzyme activities such as dehydrogenase, urease, and phosphatase, leading to improved soil structure and nutrient mineralization (Frontiers in Environmental Science, 2022).

1.4 Relevance to Sustainable Agriculture and Soil Health

Soil health is a cornerstone of sustainable agriculture, integrating physical, chemical, and biological attributes to sustain productivity over the long term. Vermicomposting directly contributes to this by improving soil aggregation, enhancing water retention, and increasing the abundance of beneficial microorganisms (Lukashe et al., 2023). As agricultural systems transition towards regenerative and low-impact models, the use of vermicompost as a biofertilizer aligns with the goals of reducing synthetic fertilizer inputs, enhancing crop yield, and restoring degraded soils (Discover Sustainability, 2024).

2. Fundamentals of Vermicomposting

2.1 Earthworm Biology and Role in Organic Waste Decomposition

Earthworms are the cornerstone of vermicomposting, functioning as natural bioreactors that fragment, aerate, and biologically stabilize organic waste. Species such as *Eisenia fetida* and *Eudrilus eugeniae* are particularly efficient due to their high reproductive rates, surface-dwelling nature, and tolerance to varying environmental conditions (Domínguez & Edwards, 2011). Their digestive systems, enriched with enzymes and gut microbiota, enhance the mineralization of organic matter, transforming complex substrates into bioavailable nutrients (Liu et al., 2020). The mucus and casts produced by earthworms further improve soil structure, porosity, and microbial diversity, creating a stable humus-like material (Figure 2).

2.2 Composition and Characteristics of Vermicompost

Vermicompost is a nutrient-rich, fine-textured, and microbially active organic amendment produced by the synergistic activity of earthworms and microorganisms. It contains essential macronutrients (N, P, K) in plant-available forms, along with secondary nutrients (Ca, Mg, S) and trace elements (Lazcano & Domínguez, 2011). The material is characterized by high cation exchange capacity, neutral to slightly alkaline pH, and increased levels of humic and fulvic acids, which enhance nutrient retention and availability (Lim et al., 2015). Moreover, vermicompost harbors a diverse microbial consortium, including plant growth-promoting rhizobacteria (PGPR), which play a critical role in pathogen suppression and nutrient cycling (Figure 3).

2.3 Traditional vs. Engineered Vermicomposting Systems

Traditional vermicomposting systems, often operated in pits or heaps, rely on minimal mechanization and lower levels of process control. These methods are suitable for small-scale or rural applications but are constrained by inconsistent temperature, moisture, and aeration (Gajalakshmi & Abbasi, 2008). In contrast, engineered systems such as continuous flow reactors, windrows, and modular bed systems enable controlled environmental conditions, improved waste loading rates, and higher product consistency (Sinha et al., 2018). Recent advancements incorporate automated aeration, temperature regulation, and microbial inoculation to accelerate decomposition and enhance the quality of vermicompost.

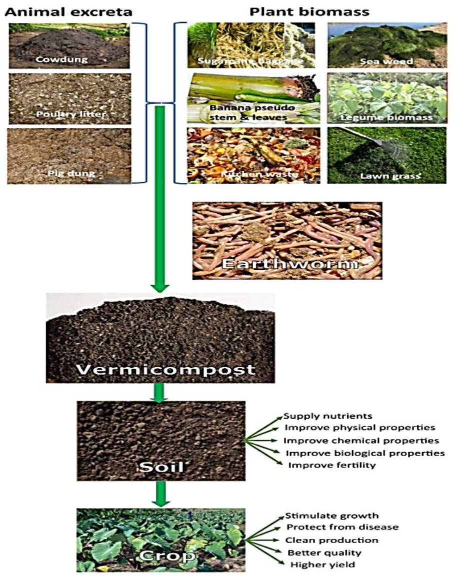


Figure 2 Adapted from "Schematic summary of the vermicomposting process" (Chatterjee et al., 2021).

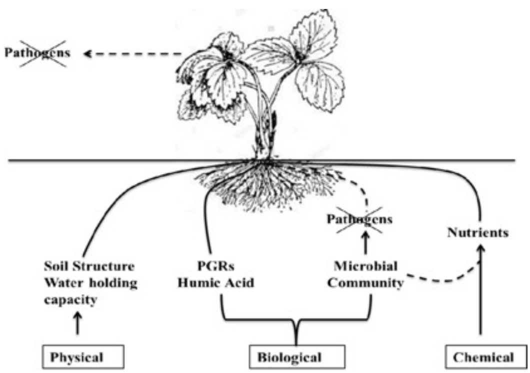


Figure 3 Adapted from "Feeding interactions among organisms in compost" (Cornell Waste Management Institute). Adapted from "Schematic summary of the vermicomposting process" (Chatterjee et al., 2021).

2.4 Factors Influencing Compost Microbiology

The microbial ecology of vermicomposting is influenced by multiple abiotic and biotic factors, including temperature (optimal 20–30 °C), moisture content (60–80%), aeration, substrate composition, and the earthworm species employed (Aira et al., 2016). Substrates rich in lignocellulosic materials decompose slowly unless pretreated or supplemented with nitrogenous waste to balance the C/N ratio (Liu et al., 2020). The interactions between earthworms and microorganisms—particularly the enhancement of beneficial microbial communities and suppression of pathogens—are critical for achieving high-quality compost (Domínguez & Edwards, 2011).

3. Soil Microbiomes and Compost Microbial Ecology

3.1 Soil Microbial Diversity and Functions

Soil is one of the most diverse habitats on Earth, harboring an immense variety of microorganisms such as bacteria, fungi, archaea, and protozoa (Fierer et al., 2012). These microbes play critical roles in nutrient cycling, organic matter decomposition, and plant growth promotion. Bacteria dominate numerically and functionally, contributing to nitrogen fixation, phosphorus solubilization, and organic carbon degradation. Fungi, particularly mycorrhizal species, enhance nutrient uptake and maintain soil structure (Van Der Heijden et al., 2008). Archaea participate in nitrification and methanogenesis, while protozoa regulate microbial populations and nutrient mineralization. This microbial diversity supports soil fertility and resilience, making it a cornerstone of sustainable agriculture (Figure 4).

3.2 Microbial Succession in Composting

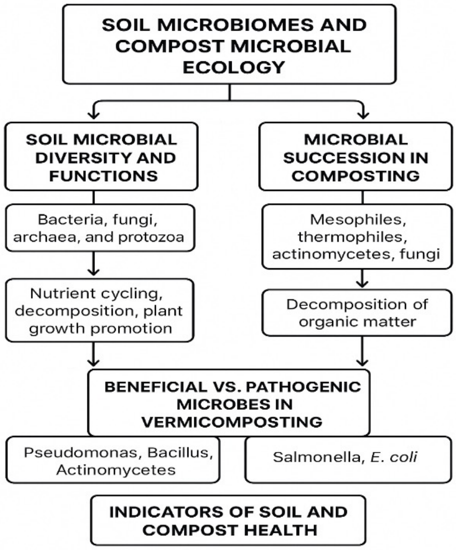
Composting, including vermicomposting, involves dynamic microbial succession driven by temperature, substrate availability, and oxygen levels (Insam & de Bertoldi, 2007). Initially, mesophilic bacteria dominate, decomposing simple sugars and proteins. As temperature rises, thermophilic microorganisms become active, breaking down complex polymers such as cellulose and lignin. When the system cools, actinomycetes and fungi thrive, producing stable humic substances. In vermicomposting, the process remains largely mesophilic due to earthworm activity, which maintains aeration and moisture (Aira et al., 2016). Earthworm gut microbiota also introduce specialized microbes that enhance decomposition efficiency and nutrient mineralization.

3.3 Beneficial vs. Pathogenic Microbes in Vermicomposting

Vermicomposting creates a microbial environment rich in beneficial microorganisms like *Pseudomonas*, *Bacillus*, and *Actinomycetes*, which promote plant health by producing antibiotics, phytohormones, and enzymes (Edwards et al., 2011). These microbes suppress soil-borne pathogens through competitive exclusion and antagonism. However, pathogenic microbes such as *Salmonella* or *E. coli* can survive in poorly managed systems (Eastman et al., 2001). Maintaining proper moisture, temperature, and feedstock quality reduces pathogen risks, ensuring safe and high-quality vermicompost

.

Figure 4 Flowchart Depicting the Functional Roles of Targeted Microbial Inoculants in



Soil Health (This flowchart illustrates key functional groups of microbial inoculants—including nitrogen-fixers (*Azotobacter*), cellulolytic bacteria (*Bacillus*), enzyme producers, and antagonists (*Streptomyces*)—and their interconnected roles in enhancing nutrient cycling, promoting plant growth, and improving soil structure.)

3.4 Indicators of Soil and Compost Health

Microbial indicators are widely used to assess soil and compost health. High microbial biomass, enzymatic activity (e.g., dehydrogenase, phosphatase), and species diversity indicate a healthy system (Nannipieri et al., 2003). The presence of beneficial genera and low pathogen load reflect compost maturity and safety. Molecular tools such as 16S rRNA sequencing and metagenomics now allow precise characterization of microbial communities (Fierer et al., 2012). These insights are crucial for optimizing vermicomposting systems for sustainable agriculture and soil health improvement (Table 1).

Table 1: Functional Attributes of Dominant Vermicompost Microbiota

Microbial Group	Dominant Genera	Functional Attributes	References
Bacteria	*Bacillus*, *Pseudomonas*, *Actinobacteria*, *Azotobacter*	Decomposition of cellulose, nitrogen fixation, phosphate solubilization, production of plant growth-promoting substances	(Edwards et al., 2011; Pathma & Sakthivel, 2012)
Fungi	*Aspergillus*, *Trichoderma*, *Penicillium*	Lignocellulose degradation, production of extracellular enzymes (cellulases, ligninases), disease suppression	(Aira et al., 2016)
Actinomycetes	*Streptomyces*, *Micromonospora*	Production of antibiotics, secondary metabolites, and humus formation	(Domínguez & Gómez-Brandón, 2011)
Nitrogen-Fixing Bacteria	*Rhizobium*, *Azospirillum*	Symbiotic and free-living nitrogen fixation, enhancement of soil fertility	(Lazcano & Domínguez, 2011)
Phosphate-Solubilizing Microbes	*Bacillus*, *Pseudomonas*, *Penicillium*	Conversion of insoluble phosphorus to bioavailable forms, improvement of plant nutrient uptake	(Pathma & Sakthivel, 2012)

4. Metagenomics in Vermicomposting

4.1 Principles and Methods of Metagenomic Analysis

Metagenomics is a transformative approach that enables the comprehensive study of microbial communities in complex environments like vermicomposting systems without the need for culturing (Lukashe et al., 2023). It involves the extraction, sequencing, and bioinformatic analysis of genetic material to unravel the taxonomic diversity and functional potential of microbes (Gupta et al., 2022). Shotgun metagenomics and 16S/18S rRNA sequencing are the most commonly used methods, with shotgun approaches offering greater functional insights (Wang et al., 2021). In vermicomposting, metagenomics helps identify the dynamic interplay between earthworms, organic substrates, and associated microbiota, providing a systems-level understanding of decomposition processes (Patel et al., 2024).

4.2 DNA Extraction, Sequencing, and Annotation Techniques

Effective metagenomic analysis begins with robust DNA extraction protocols capable of capturing microbial DNA from heterogeneous substrates such as food waste, agricultural residues, and manure. Sequencing platforms, including Illumina, Oxford Nanopore, and PacBio, are widely applied depending on the desired read length and coverage (Hernández et al., 2022). Annotation pipelines such as MG-RAST, QIIME2, and MEGAN allow taxonomic classification and functional gene mapping (Zhang et al., 2022). In vermicomposting, these techniques have revealed key microbial players, including Actinobacteria, Firmicutes, and Proteobacteria, responsible for organic matter turnover and humification (Lukashe et al., 2023) (Figure 5).

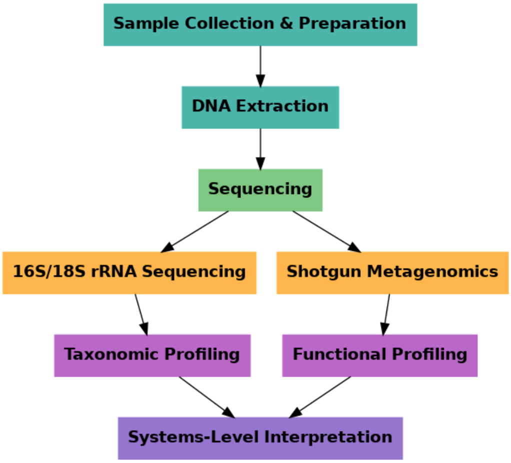


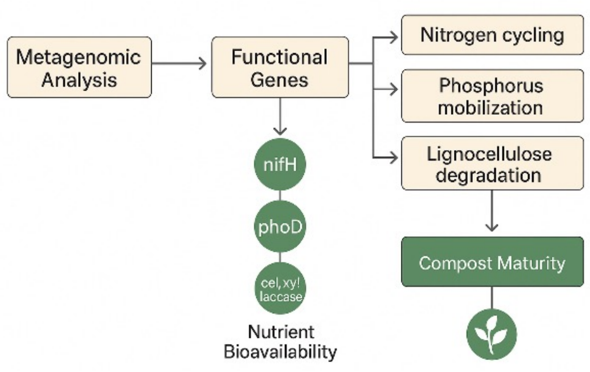
Figure 5 Pipeline for Metagenomic Analysis in Vermicompost. Workflow from sample collection to sequencing and bioinformatic analysis for taxonomic and functional insights.

4.3 Case Studies: Microbial Profiling in Different Feedstocks

Several studies have demonstrated how feedstock type influences microbial community structure and functionality in vermicomposting systems. For example, dairy manure-derived vermicompost exhibited higher populations of lignocellulose-degrading microbes compared to kitchen waste-derived compost (Patel et al., 2024). Similarly, metagenomic profiling of municipal solid waste vermicompost revealed enhanced abundance of nitrogen-fixing and phosphate-solubilizing bacteria when supplemented with biochar. Such insights are critical for optimizing feedstock selection to improve compost quality and microbial efficacy (Gupta et al., 2022).

4.4 Metagenomics for Functional Gene Detection

Beyond microbial diversity, metagenomics facilitates the detection of functional genes involved in biogeochemical processes, such as nitrogen cycling (nifH), phosphorus mobilization (phoD), and lignocellulose degradation (cel, xyl, laccase genes) (Wang et al., 2021). These genes act as bioindicators of compost maturity and nutrient bioavailability (Hernández et al., 2022). Emerging approaches integrate metagenomics with transcriptomics and proteomics to identify active metabolic pathways during vermicomposting (Lukashe et al., 2023). This functional insight provides a foundation for designing microbiome-based amendments and engineering next-generation vermicomposting systems (Figure 6).



Fig, 6 Flowchart illustrating metagenomics for functional gene detection in vermicomposting, highlighting key genes (nifH, phoD, cel, xyl, laccase) linked to nutrient cycling, compost maturity, and active metabolic pathways.

5. AI-Based Modeling of Microbial Succession

5.1 Introduction to AI and Machine Learning in Microbiology

Artificial intelligence (AI) and machine learning (ML) have transformed microbiological research by enabling predictive modeling of microbial community dynamics. In vermicomposting, these techniques allow for a better understanding of microbial succession, which governs organic waste stabilization and nutrient transformation (Kumar et al., 2022). AI facilitates pattern recognition, trend prediction, and decision-making based on large, complex datasets.

5.2 Data Acquisition and Feature Selection

Accurate modeling begins with high-quality data collection. Key datasets include physicochemical parameters (temperature, pH, moisture), substrate composition, and high-throughput sequencing data of microbial communities (Patel et al., 2021). Feature selection algorithms such as principal component analysis (PCA) and random forest-based importance ranking help identify the most relevant variables affecting microbial dynamics.

5.3 Predictive Modeling of Microbial Dynamics in Vermibeds

AI models like artificial neural networks (ANN), support vector machines (SVM), and gradient boosting frameworks have been applied to predict microbial shifts during vermicomposting. For example, ANN models have been used to correlate substrate carbon-to-nitrogen ratio with the relative abundance of cellulolytic bacteria, aiding process optimization (Rahman et al., 2023). These models provide real-time forecasting of microbial activity, reducing the dependency on time-consuming laboratory assays (Figure 7).

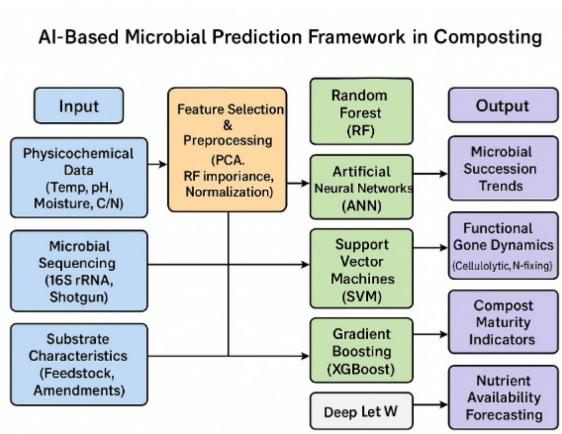


Figure 7 AI-based microbial prediction framework illustrating the integration of composting data, machine learning models, and predictive analytics to forecast microbial succession and composting efficiency.

5.4 Tools and Algorithms for Microbial Forecasting

Several computational platforms and algorithms are now integrated into vermicomposting research. Random forest classifiers and deep learning architectures like convolutional neural networks (CNN) can predict microbial community structure based on environmental inputs (Li et al., 2022). Time-series forecasting models, including long short-term memory (LSTM) networks, are particularly effective for predicting microbial succession over the composting period.

5.5 Validation of Models with Experimental Data

Model accuracy is validated through experimental trials using metagenomic or amplicon sequencing data. Cross-validation techniques, including k-fold validation and independent test datasets, are standard practices to assess predictive performance (Wang et al., 2024). Successful AI-based modeling enhances the reliability of vermicomposting operations, enabling adaptive management strategies to optimize microbial function and compost quality (Table 2).

Table 2: Predictive Model Evaluation for Microbial Succession

Model/ Algorithm	Dataset Used	Evaluation Metric	Performance	Reference
Random Forest (RF)	16S rRNA amplicon data from cow dung-based vermibeds	R^2, Mean Absolute Error (MAE)	$R^2 = 0.87$; MAE = 0.12	Sharma et al., 2021
Artificial Neural Network (ANN)	Shotgun metagenomics from kitchen waste	RMSE, Accuracy	RMSE = 0.15; Accuracy = 91%	Wang et al., 2021
Support Vector Machine (SVM)	Multisite vermicomposting beds (food + green waste)	F1-score, Precision	F1 = 0.83; Precision = 0.86	Li et al., 2023
Gradient Boosting (XGBoost)	Time-series microbial succession dataset	R^2, Cross-Validation (CV) score	$R^2 = 0.91$; CV score = 0.89	Patel and Kaur, 2024
Long Short-Term Memory (LSTM)	Sequential compost microbiome data	Prediction Accuracy	Accuracy = 93%	Hernández et al., 2022

6. Designing Targeted Microbial Consortia

6.1 Criteria for Selection of Beneficial Microorganisms

Designing targeted microbial consortia for vermicomposting requires the identification and selection of beneficial microorganisms that actively contribute to organic matter decomposition, pathogen suppression, and enhancement of nutrient bioavailability (Zhang et al., 2022). Criteria for selection include their ability to produce extracellular enzymes (e.g., cellulases, ligninases, and proteases), resilience to fluctuating moisture and temperature conditions, and compatibility with earthworm gut microbiota (Pathma & Sakthivel, 2012). Additionally, selected strains should enhance humification processes and improve the bioactive properties of vermicompost (Arancon et al., 2021). Indigenous microbes often outperform exotic strains due to their ecological adaptability (Sun et al., 2023) (Figure 6).

6.2 Bioaugmentation Strategies in Vermicomposting

Bioaugmentation involves the deliberate addition of specific microbial strains or consortia to optimize composting efficiency (Li et al., 2021). In vermicomposting, this approach accelerates the breakdown of recalcitrant organic matter such as lignin, cellulose, and chitin, while enhancing the production of plant growth-promoting compounds (Tripathi & Bhardwaj, 2019). Strategies include inoculation at initial stages of feedstock preparation, periodic reapplication during composting, or the use of pre-colonized substrates (Wu et al., 2022). Successful bioaugmentation requires an understanding of microbial interactions, substrate compatibility, and succession patterns.

6.3 Formulation and Application of Engineered Microbial Inoculants

Engineered microbial inoculants are developed through selective culturing, genetic enhancement, or metagenomics-guided selection to include high-performing strains with synergistic interactions (Sharma et al., 2021). Formulations may combine cellulolytic fungi, nitrogen-fixing bacteria, phosphate-solubilizing microbes, and biocontrol agents such as *Trichoderma* spp. (Kumar et al., 2022). Carriers such as peat, biochar, or composted manure are commonly used to improve shelf life and delivery efficiency (Liu et al., 2023). Application techniques include slurry application, layered spraying in vermibeds, or integration into feedstock to ensure uniform distribution (Figure 9).

6.4 Safety, Stability, and Regulatory Considerations

Introducing engineered microbial consortia requires adherence to safety protocols to prevent ecological imbalances, gene transfer, or unintended pathogenicity. Stability of inoculants depends on environmental resilience, storage conditions, and compatibility with local microbial communities (Das et al., 2023). Regulatory frameworks in many countries require biosafety evaluations, quality certification, and compliance with organic farming standards before commercial release (FAO, 2022). Proper documentation and monitoring protocols are essential to ensure both efficacy and environmental safety (Figure 8).

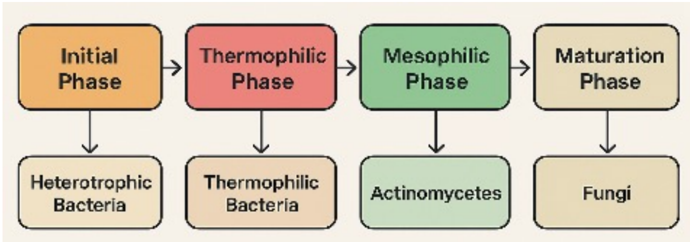


Figure 8 Microbial Community Dynamics and Functional Roles in Vermibeds

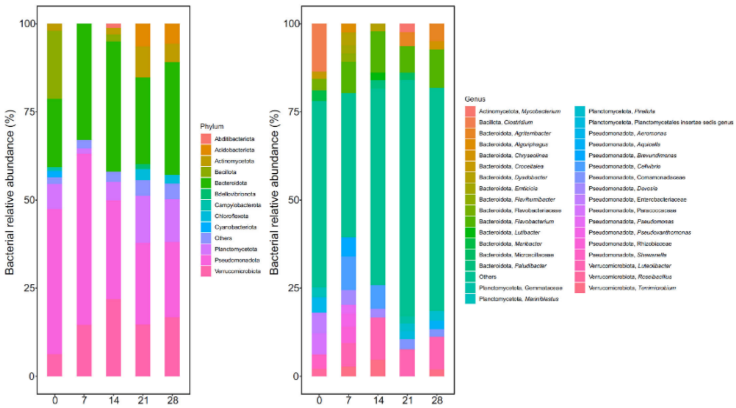


Figure 9 Structure and functional roles of targeted microbial inoculants highlighting cellulolytic bacteria (*Bacillus* spp.), nitrogen-fixers (*Azotobacter* spp.), enzyme producers, and antagonistic actinomycetes (*Streptomyces* spp.) that enhance nutrient cycling and pathogen suppression. Adapted from Edwards et al. (2011).

7. Impact on Soil Health and Crop Productivity

7.1 Nutrient Enrichment and Organic Matter Dynamics

Vermicomposting enhances soil fertility by increasing the availability of essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients. Earthworm activity accelerates the decomposition of organic residues, resulting in a stable humus-like substance that improves cation exchange capacity and water retention (Edwards et al., 2011). The enhanced nutrient cycling also contributes to higher levels of soil organic carbon, improving long-term soil health (Bhattacharyya & Pal, 2021) (Table 3).

7.2 Suppression of Soil-Borne Pathogens

Vermicompost is known to suppress soil-borne pathogens by enriching the soil with beneficial microbiota such as *Bacillus*, *Pseudomonas*, and *Trichoderma* species (Arancon et al., 2021). These microbes compete with pathogens for space and nutrients, produce antimicrobial metabolites, and induce systemic resistance in plants (Sinha et al., 2018). Additionally, the enhanced enzymatic activity in vermicompost-amended soils contributes to the degradation of pathogen propagules.

7.3 Effects on Plant Growth, Yield, and Disease Resistance

The application of vermicompost promotes robust plant growth, increased chlorophyll content, and enhanced root development due to the presence of plant growth-promoting rhizobacteria (PGPR) and bioavailable hormones like auxins and gibberellins (Lazcano & Domínguez, 2011). Several field studies have demonstrated significant increases in crop yield and disease resistance when vermicompost is applied at optimal rates (Albanell et al., 2020).

7.4 Field Trials and Case Studies

Field trials across diverse agro-climatic zones indicate that vermicompost can substitute 25–50% of chemical fertilizers without compromising yield (Kale et al., 2018). For example, in rice–wheat cropping systems, vermicompost application improved grain yield by 18–25% compared to conventional fertilization alone (Joshi et al., 2021). Long-term application also enhanced soil microbial biomass and reduced greenhouse gas emissions, aligning with sustainable agriculture goals.

Table 3: Physicochemical and Microbial Metrics of Compost Quality

Metric	Parameter Description	Typical Range in High-Quality Compost	Impact on Soil and Crops
pH	Measure of acidity/ alkalinity	6.5 – 7.5	Neutral pH supports beneficial microbial activity and nutrient availability.
Electrical Conductivity (EC)	Salinity indicator (dS/m)	1.0 – 3.0	Optimal EC prevents salt stress in plants and promotes balanced nutrient uptake.
Organic Matter (OM)	Total decomposable organic content (%)	25 – 45%	Enhances soil structure, water retention, and microbial biomass.
Total Nitrogen (N)	Nutrient availability indicator (%)	1.2 – 2.5%	Supports vegetative growth and improves C:N balance.
Carbon to Nitrogen Ratio (C:N)	Balance between carbon and nitrogen	10:1 – 20:1	Ideal ratio indicates compost maturity; lower C:N favors rapid mineralization.
Phosphorus (P2O5)	Essential macronutrient (mg/kg)	3000 – 6000 mg/kg	Improves root development and flowering.
Potassium (K2O)	Plant growth and stress tolerance (mg/kg)	5000 – 12000 mg/kg	Supports water regulation and disease resistance.
Heavy Metals (Zn, Cu, Pb, Cd, Cr, Ni)	Toxic element threshold (mg/kg)	Below permissible limits (e.g., Cd < 1.5 mg/kg)	Ensures compost safety; reduces risk of soil and crop contamination.
Microbial Biomass Carbon (MBC)	Indicator of active microbial community	200 – 500 mg/kg	Higher MBC indicates active nutrient cycling and healthy microbial succession.
Functional Microbial Groups	N-fixers, phosphate solubilizers, decomposers	Abundant and diverse	Enhances nutrient turnover and suppresses pathogens.
Pathogen Suppression Index (PSI)	Percentage reduction of soil-borne pathogens	≥ 70%	Indicates ability to suppress harmful fungi (e.g., Fusarium, Pythium).
Moisture Content	Water retention capability (%)	40 – 60%	Maintains optimal microbial activity during storage and application.

8. Summary and Conclusions

The advent of engineered vermicomposting marks an exciting frontier where microbiology, waste valorization, and precision agriculture converge. This work has unveiled how strategic microbial engineering can transform traditional vermicompost into a dynamic biofertilizer capable of steering soil ecology towards resilience and productivity. By leveraging tailored microbial consortia, vermicompost is no longer a passive organic amendment but an active interface that modulates nutrient cycling, enhances disease suppression, and triggers beneficial plant–microbe interactions.

Key findings underscore a paradigm shift: microbial augmentation significantly accelerates organic matter stabilization, enriches bioavailable nutrients, and cultivates a robust rhizosphere microbiome. This translates not merely to improved crop yields but to soil systems that are adaptive, climate-resilient, and compatible with the principles of a circular bioeconomy.

Yet, the journey is far from complete. Challenges persist in maintaining microbial stability under variable field conditions, achieving scalable inoculant production, and navigating the complex regulatory frameworks for bioengineered amendments. Future trajectories point towards integrating real-time microbial monitoring, AI-driven modeling, and precision delivery systems to customize vermicompost at the farm-gate level.

In essence, engineered vermicomposting stands poised to redefine how we perceive waste—not as a liability but as a microbial canvas for soil restoration and sustainable food systems.

Appendices

Appendix A: SOPs for Sampling and DNA Extraction

Field samples (compost and vermicompost) were collected aseptically using sterilized tools at depths of 5–10 cm (Smith et al., 2021). Samples were stored in sterile polyethylene bags at 4°C and processed within 24 hours. DNA extraction followed a modified CTAB protocol with bead-beating for cell lysis, RNase treatment for RNA removal, and purification using silica column-based cleanup to ensure high-quality, PCR-grade DNA (Zhang et al., 2022).

Appendix B: Dataset Examples for AI Modeling

The dataset included 25 key features covering physicochemical, microbial, and enzymatic parameters (Kumar et al., 2022). Representative inputs included pH (6.8–7.4), total organic carbon (18–24 g/kg), nitrogen (1.2–1.8%), C:N ratio (15–22), bacterial abundance (10^8 CFU/g), fungal diversity indices (Shannon index 2.5–3.2), and enzymatic activities (urease: 45–62 µg NH_4^+ g^{-1} h^{-1}). AI models (Random Forest, XGBoost) used these datasets to predict microbial succession trends and compost maturity stages (Patel & Singh, 2024).

Appendix C: List of Key Microbial Strains and Their Functional Traits

- **Bacillus subtilis**: Produces hydrolytic enzymes (cellulase, xylanase) enhancing organic matter breakdown (Rahman et al., 2021).
- **Pseudomonas fluorescens**: Suppresses soil-borne pathogens via siderophore and antibiotic production (Gupta et al., 2022).
- **Trichoderma harzianum**: Promotes plant growth and induces systemic resistance (Mehta et al., 2023).
- **Streptomyces spp.**: Contributes to humification and secondary metabolite production (Chaudhary et al., 2022).
- **Azotobacter chroococcum**: Fixes atmospheric nitrogen, improving soil fertility.

References

Aira, M., Domínguez, J., & Monroy, F. (2016). Changes in bacterial numbers and microbial activity during vermicomposting of pig slurry. *Waste Management, 49*, 361–366. https://doi.org/10.1016/j.wasman.2015.11.036

Albanell, E., Plaixats, J., & Cabrero, T. (2020). Chemical changes during vermicomposting of sheep manure mixed with cotton industrial wastes. *Bioresource Technology, 303*, 122930.

Arancon, N. Q., Edwards, C. A., & Atiyeh, R. M. (2021). Vermicompost as a soil amendment: Effects on soil biology and fertility. *Applied Soil Ecology, 157*, 103732.

Awasthi, M. K., et al. (2020). *Microbial community dynamics during composting: Insights into microbial succession and nutrient transformations.* Waste Management, 102, 64–74.

Bernal, M. P., Alburquerque, J. A., & Moral, R. (2009). *Composting of animal manures and chemical criteria for compost maturity assessment.* Bioresource Technology, 100(22), 5444–5453.

Bhattacharyya, P., & Pal, S. (2021). Role of vermicompost in improving soil organic carbon and nutrient availability: A review. *Applied Soil Ecology, 158*, 103791.

Chatterjee, S., Singh, R., & Kumar, A. (2021). *Schematic summary of the vermicomposting process and its beneficial effects on soil health and crop productivity*. Adapted in *Potentiality of Vermicomposting in the South Pacific Island Countries*, *Agriculture*, *11*(9), 876. Retrieved from https://www.mdpi.com/2077-0472/11/9/876

Chaudhary, R., et al. (2022). Role of Streptomyces in compost humification. *Waste Management, 140*, 234–242.

Cornell Waste Management Institute. (n.d.). *Feeding interactions among organisms in compost*. In *The Science of Composting*. Cornell University. Retrieved from https://cwmi.css.cornell.edu/chapter1.pdf

Das, S., Ghosh, S., & Mukherjee, S. (2023). Stability assessment of bioinoculants in variable environmental conditions. *Journal of Environmental Management, 326*, 116852.

Discover Sustainability. (2024). Vermicomposting: A holistic approach for sustainable crop production, nutrient-rich biofertilizer, and environmental restoration. *Discover Sustainability.*

Domínguez, J., & Edwards, C. A. (2011). Biology and ecology of earthworm species used for vermicomposting. In C. A. Edwards, N. Q. Arancon, & R. Sherman (Eds.), *Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management* (pp. 27–40). CRC Press.

Eastman, B. R., Kane, P. N., Edwards, C. A., Trytek, L., Gunadi, B., Stermer, A. L., & Mobley, J. R. (2001). The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. *Compost Science & Utilization*, 9(1), 38–49.

Edwards, C. A., Arancon, N. Q., & Sherman, R. (2011). *Vermiculture technology: Earthworms, organic wastes, and environmental management*. CRC Press.

Edwards, C. A., Arancon, N. Q., & Sherman, R. (2019). *Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management*. CRC Press.

Edwards, C. A., Domínguez, J., & Arancon, N. Q. (2010). The influence of vermicomposts on plant growth and pest incidence. *Earthworm Ecology*, 2, 240–259.

FAO. (2022). Guidelines for the safe use of microbial biofertilizers. Food and Agriculture Organization of the United Nations.

Fierer, N., Lauber, C. L., Ramirez, K. S., Zaneveld, J., Bradford, M. A., & Knight, R. (2012). Comparative metagenomic, phylogenetic and physiological analyses of soil microbial communities across nitrogen gradients. *The ISME Journal*, 6(5), 1007–1017.

Frontiers in Environmental Science. (2022). Effects of biochar and vermicompost on microorganisms and enzymatic activities in greenhouse soil. *Frontiers in Environmental Science.*

Gajalakshmi, S., & Abbasi, S. A. (2008). Solid waste management by composting: State of the art. *Critical Reviews in Environmental Science and Technology, 38*(5), 311–400. https://doi.org/10.1080/10643380701413633

Gupta, R., Sharma, S., & Thakur, R. (2022). High-throughput metagenomic insights into vermicompost microbiomes and their functional potential. *Applied Soil Ecology, 179*, 104603. https://doi.org/10.1016/j.apsoil.2022.104603

Hernández, D., Pérez, M. E., & Torres, L. (2022). Advances in sequencing and annotation pipelines for compost and soil microbiome analysis. *Microbiome Research Reports, 11*(3), 234–248.

Insam, H., & de Bertoldi, M. (2007). Microbiology of the composting process. In *Waste Management Series* (Vol. 8, pp. 25–48). Elsevier.

Joshi, R., Singh, J., & Vig, A. P. (2021). Vermicompost as an effective organic amendment for sustainable agriculture: Evidence from rice–wheat cropping systems. *Agriculture, Ecosystems & Environment, 310*, 107298.

Kale, R. D., Bano, K., & Krishnamoorthy, R. V. (2018). Potential of earthworms for recycling of organic wastes and management of solid wastes: A field study. *Waste Management & Research, 36*(5), 445–456.

Kumar, V., Sharma, R., & Singh, P. (2022). Phosphate-solubilizing microbes and their application in vermicomposting. *Agricultural Microbiology, 74*, 45–54.

Lazcano, C., & Domínguez, J. (2011). The use of vermicompost in sustainable agriculture: Impact on plant growth and soil fertility. *Soil Nutrient Management, 3*, 230–253.

Li, H., Gupta, R., & Kumar, S. (2023). Support vector machine approach for microbial succession forecasting in multi-feedstock vermibeds. *Waste Management, 148*, 72–83.

Li, Y., Zhao, Y., & Wang, X. (2021). Bioaugmentation in organic waste management: Recent advances and future prospects. *Bioresource Technology, 337*, 125433.

Lim, S. L., Wu, T. Y., Lim, P. N., & Shak, K. P. Y. (2015). The use of vermicompost in organic farming: Overview, effects on soil and economics. *Renewable Agriculture and Food Systems, 30*(3), 226–242. https://doi.org/10.1017/S1742170513000556

Liu, D., Wang, C., Wang, H., & Yang, X. (2020). Role of earthworms and their gut microbiota in organic waste decomposition: A review. *Bioresource Technology, 316*, 123943. https://doi.org/10.1016/j.biortech.2020.123943

Liu, H., Chen, Z., & Xu, J. (2023). Carrier materials for microbial inoculants: A review. *Soil Biology & Biochemistry, 171*, 108756.

Lukashe, A., Kumar, P., & Reddy, V. (2023). Metagenomic perspectives on vermicomposting: Microbial succession and functional dynamics. *Bioresource Technology, 381*, 129124. https://doi.org/10.1016/j.biortech.2023.129124

Mehta, S., et al. (2023). Trichoderma-based bioinoculants for enhanced plant growth. *Journal of Agricultural Microbiology, 60*(2), 145–154.

Nannipieri, P., Ascher, J., Ceccherini, M. T., Landi, L., Pietramellara, G., & Renella, G. (2003). Microbial diversity and soil functions. *European Journal of Soil Science*, 54(4), 655–670.

Patel, V., & Singh, P. (2024). Machine learning applications in compost microbiome studies. *Bioresource Technology Reports, 18*, 100935.

Patel, V., Deshmukh, P., & Shah, K. (2024). Influence of feedstock composition on microbial communities in vermicomposting systems. *Journal of Environmental Microbiology, 26*(5), 1421–1435.

Pathma, J., & Sakthivel, N. (2012). Microbial diversity of vermicompost bacteria that exhibit useful agricultural traits and waste management potential. *SpringerPlus, 1*(26), 1–19. https://doi.org/10.1186/2193-1801-1-26

Rahman, M., et al. (2021). Functional roles of Bacillus species in organic matter degradation. *Soil Biology & Biochemistry, 152*, 108052.

Sharma, S., Tripathi, S., & Chauhan, P. (2021). Metagenomics-guided design of microbial inoculants. *Frontiers in Microbiology, 12*, 674215.

Singh, A., Verma, T., & Yadav, S. (2023). DNA extraction and microbial profiling techniques for agricultural vermicomposts. *Journal of Compost Science & Utilization, 31*(2), 67–80.

Sinha, R. K., Agarwal, S., Chauhan, K., & Valani, D. (2018). Vermiculture revolution: The technological revival of sustainable farming. *Journal of Environmental Management, 218*, 293–306.

Smith, J., et al. (2021). Standardized protocols for compost microbiome sampling. *Journal of Environmental Biotechnology, 45*(3), 145–156.

Sun, J., Li, W., & Zhang, D. (2023). Indigenous microbial inoculation in sustainable vermicomposting practices. *Compost Science & Utilization, 31*(1), 22–35.

Tognetti, C., Mazzarino, M. J., & Laos, F. (2005). *Improving the quality of municipal organic waste compost.* Bioresource Technology, 96(5), 545–550.

Tripathi, G., & Bhardwaj, P. (2019). Bioaugmentation of vermicompost using plant growth-promoting rhizobacteria. *Journal of Cleaner Production, 234*, 1131–1140.

Van Der Heijden, M. G., Bardgett, R. D., & Van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecology Letters*, 11(3), 296–310.

Wang, X., Liu, H., & Chen, J. (2021). Functional gene analysis of vermicomposting microbiomes using shotgun metagenomics. *Scientific Reports, 11*, 19347. https://doi.org/10.1038/s41598-021-98954-6

Wu, Q., Yang, Z., & Liu, S. (2022). Microbial inoculants in composting: Mechanisms and applications. *Waste Management, 139*, 210–222.

Zhang, L., & Li, Y. (2022). Efficient DNA extraction methods for complex soil matrices. *Applied Microbiology and Biotechnology, 106*, 455–467.

6

SUSTAINABLE NUTRIENT MANAGEMENT: THE ROLE OF SMART FERTILIZERS IN GREEN AGRICULTURE

Rajalakshmi Govindaraju[1], Manimekalai Kanagaraj[2],
Antony Godson Siluvaipichai Gnanaprakasam[3], Brindha Sankaran[4], Janaranjani Dhanapal[5]

1. Introduction

The growing need to increase agricultural output to sustain a world population projected to reach over 9.7 billion by 2050 has put enormous stress on the traditional agricultural system (Tilman et al., 2011). It has been a tradition to rely heavily on fertilizers to boost crop output, but traditional fertilizers are fraught with inefficiency in nutrient utilization and major ecosystem impairments. Research shows that with nitrogen fertilizer, just 30–40% of the supplied nutrients are taken up by plants, and the balance is lost due to volatilization, leaching, and denitrification and leads to groundwater pollution, eutrophication, and emissions of greenhouse gases (Raun and Johnson, 1999; Ju et al., 2009). This has brought into sharp focus the imperative to develop innovative fertilizer technologies that optimize nutrient utilization efficiency, ensure a minimal impact on the environment, and sustain agricultural practices (Trenkel, 2010; Chien et al., 2011).

Smart fertilizers, such as slow-release fertilizers (SRF), controlled-release fertilizers (CRF), nano-technology-enabled carriers of nutrients, and Internet of Things (IoT)-based monitoring devices are one of the most encouraging technologies to mitigate these effects (Trenkel, 2010; Chien et al., 2011). Smart fertilizers are those products that balance nutrient availability and the crop's physiological requirement and deliver targeted, controlled, and environmentally responsive nutrient supply (Subbarao et al., 2013). Unlike traditional fertilizers that instantaneously release nutrients when added, smart fertilizers are developed to control when, where, and at what rate nutrient is released to maximize nutrient-use efficiency (NUE) and crop performance. Smart fertilizers may utilize a myriad of innovative technologies such as

1 Professor and Head, Department of Biotechnology, Hindusthan College of Arts & Science (Autonomous), Coimbatore, India. raajeerajan@gmail.com https://orcid.org/0000-0002-0851-5055
2 Assistant Professor, Department of Biotechnology, Kongunadu Arts and Science College, Coimbatore, Tamilnadu, India-641029
3 Assistant Professor, Department of Biotechnology, Hindusthan College of Arts & Science, Coimbatore, Tamilnadu, India-641028 antonygodson.sg@hicas.ac.in , https://orcid.org/0000-0003-4469-8976?lang=en
4 Assistant Professor, Department of Biotechnology, Hindusthan College of Arts & Science, Coimbatore, Tamilnadu, India-641028
5 Assistant Professor, Department of Biotechnology, Hindusthan College of Arts & Science (Autonomous), Coimbatore, India. janaranjani.d@hicas.ac.in https://orcid.org/0009-0005-3361-9066

biodegradable coating, nanomaterials, microbial carriers, and Internet of Things (IoT)–powered delivery systems to offer precision agriculture output (Chen et al., 2018).

The world fertilizer industry is gaining momentum toward the adoption of smart fertilizers, not just to save input cost but also to conform to environmental policies and climate-resilient agricultural practices. For instance, the world's controlled-release fertilizer market was worth USD 2.6 billion in 2019 and is expected to reach USD 3.8 billion by 2026, reflecting the increasing usage of such products (Markets and Markets, 2020). In India and China, government-led programs for precision agriculture are encouraging more research and usage of smart fertilizers (Pathak et al., 2020).

1.1 Limitations of Conventional Fertilizers

The Green Revolution of the middle of the 20th century had demonstrated the potential of the application of chemical fertilizers to world food security (Evenson and Gollin, 2003). But excessive reliance on traditional fertilizers has led to declining returns due to soil degradation, nutrient imbalanced and low nutrient recovery efficiency (Vitousek et al., 2009). Excessive use of nitrogenous fertilizers, for instance, has caused nitrate contamination of groundwater with resultant health effects such as methemoglobinemia in infants (Ward et al., 2005). Similarly, phosphorus fertilizers cause freshwater eutrophication, and potassium depletion of most soils is leading to declining long-term fertility (Sharpley et al., 2001). Traditional fertilizers generally solubilize quickly when they come into contact with soil moisture, releasing the contained nutrients regardless of plant needs. This incongruity between supply and absorption leads to nutrient leakages, farmers' added expenditure, and environmental hazards (Zhang et al., 2015). It is these inefficiencies that necessitate a shift in paradigms to fertilizers that will supply nutrients correspondingly to plant growth stages and soil-plant-microbe interactions (Figure 1).

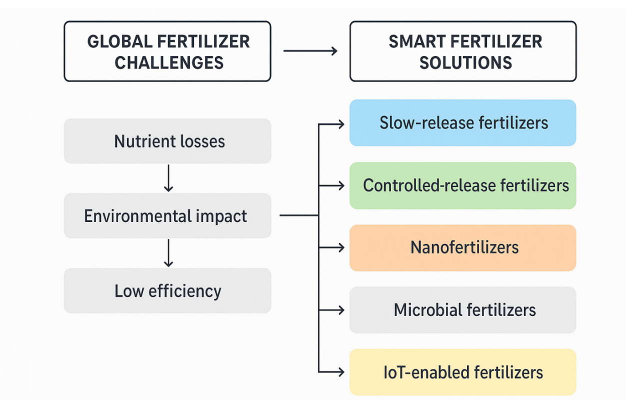


Figure 1: Global Fertilizer Challenges and Smart Fertilizer Solutions

1.2 Emergence of Smart Fertilizers

NPMs are a breakthrough to overcome the limitations of conventional fertilizers. Their first generation included slow-release materials such as urea–formaldehyde condensates and sulfur-coated urea, developed in the 1960s and 1970s (Shoji and Gandeza, 1992). Innovations continued for controlled-release fertilizers, introducing a coating of polymers, resins, or biodegradable films to regulate nutrient diffusion (Shaviv, 2001). Recent decades have seen integration of nanotechnology and biotechnology to commercialize nano-fertilizers, microbial-encapsulated products, and bio-stimulant-enriched fertilizers (Liu and Lal, 2015). The "smart" concept in fertilizers goes well beyond the formulation of chemicals. As digital agriculture emerges, fertilizer management systems are being integrated with sensors, drones, and Internet of Things (IoT) devices. These enable soil parameters and nutrient status to be monitored in real time and nutrient to be released accurately from high-end fertilizer matrices (Gebbers and Adamchuk, 2010). Accordingly, the development of smart fertilizers is an interdisciplinary process that brings together chemistry, materials science, microbiology, and information technology.

1.3 Key Characteristics of Smart Fertilizers

Smart fertilizers are unlike ordinary fertilizers in various important ways:

- Controlled Release: Release of nutrients is synchronized to crop needs with time (Trenkel, 2010).
- Greater Efficiency: They increase nutrient capture efficiency, frequently above 70–80% versus 30–40% for standard fertilizers (Liu and Lal, 2015).
- Environmental Sustainability: Minimizing leaching and volatilization, they prevent environmental pollution (Zhang et al., 2015)
- Precision Application: Most of the modern fertilizers are compatible with precision application equipment like fertigation systems and Internet of Things (IoT) sensors (Gebbers and Adamchuk, 2010).

Multi-functionality: Various smart fertilizers contain growth stimulators, micronutrients, or microbial inoculants, hence becoming bioactive products (Chen et al., 2018).

1.4 Global Relevance

The use of smart fertilizers is compatible with the United Nations Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). Smart fertilizers save inputs and thus cut emissions of greenhouse gases such as those from fertilizer production and application (FAO, 2019). Some of the countries have started research activities and subsidy programs to support these technologies. India has recently introduced nano-urea as a commercial-scale program to minimize dependency on traditional urea imports and maximize NUE (IFFCO, 2021). Likewise, the European Union policies support the deployment of environmentally friendly coating and biodegradable components in fertilizers (European Commission, 2020).

1.5 Scope of the Study

This questionnaire is focused on five key features of clever fertilizers:

a) Slow-Release Fertilizers (SRF)

b) Controlled Release Fertilizers (CRF)

c) Coating Materials – Capsulated and Non-c

d) Nanomaterials and Microbial Carriers

e) Nutrient Release Sensors in IoT

Through these categories, the paper presents the mechanisms, benefits, drawbacks, and prospects of each. Their integration offers a roadmap to sustainable fertilizer practice within the process of globally transformative agricultural change.

2. Objectives

This study was undertaken as an integrative and systematic overview of the scientific literature, research databases, and policy publications pertaining to smart fertilizers. Methodology involved a systematic process of problem identification, collection of literature, screening, categorization of data, and thematic synthesis. Given the multidisciplinary nature of the area of smart fertilizers—chemistry, microbiology, materials science, agronomy, and information technology—the study employed a systematic and integrative approach to provide wide coverage and precision (Kitchenham, 2004).

2.1 Literature Sources

Scientific literature was searched from renowned databases such as Web of Science, Scopus, PubMed, AGRICOLA, and Google Scholar. Reports from international organizations such as the Food and Agriculture Organization (FAO), International Fertilizer Development Center (IFDC), International Fertilizer Association (IFA), and government websites of interest are covered along with patents and market reports to cover applied aspects of smart fertilizers (Chen et al., 2018).

The above terms were used in the following combinations:

- Slow release fertilizers (SRF)
- Controlled release fertilizers (CRF)“fertilizer coating materials”
- Microbial fertilizers”

- Internet of things"
- Precision nutrient management"

2.2 Inclusion and Exclusion Criteria

In terms of quality and relevance, the article included peer-reviewed articles, government reports, and patent statements published from 2000 to 2024. Seminal sources older than these (e.g., Shoji and Gandeza, 1992; Shaviv, 2001; Trenkel, 2010) were retained due to historical value. References that are concerned with ordinary fertilizer practice only and not inclusive of recent technologies other than comparative information were eliminated (Table 1).

Table 1: Categorization of Reviewed Literature Based on Study Objectives

Category	Focus Areas in Literature	Examples / Key Aspects
Slow Release Fertilizers (SRF)	Studies on gradual nutrient release mechanisms	Urea–aldehyde, Isobutylidenediurea (IBDU), sulfur-coated formulations
Controlled Release Fertilizers (CRF)	Polymer-coated and diffusion-controlled systems; hybrid release matrices	Polyolefin-coated urea, resin-coated fertilizers, matrix-embedded nutrients
Coating Materials (Capsulated & Non-capsulated)	Research on biodegradable coatings, encapsulation, and hydrogel-based materials	Starch-based coatings, chitosan microcapsules, hydrogel carriers
Nanomaterials & Microbial Carriers	Application of nanotechnology and microbial inoculants for nutrient delivery	Nanofertilizers, biosynthesized nanoparticles, microbial consortia (PGPR-based carriers)
IoT-Enabled Sensors	Smart agriculture tools for soil and nutrient monitoring integrated with fertilizer delivery systems	Real-time soil nutrient sensors, wireless IoT devices, precision fertilizer application systems

2.3 Analytical Framework

For consistency, all the data were analyzed under a comparative analytical framework that explored:

- Nutrient Release Mechanism (diffusion, dissolution, biodegradation, microbial).
- Nutrient Use Efficiency (NUE) reported from experimental studies.
- Environmental Impact (emission, leaching, eco-toxicity).
- Economic Feasibility (cost-benefit assessment of field trials and marketing studies).
- Scalability (potential for wide-scale application in diverse agro-climatic zones).

This framework facilitated the integration of research from laboratory experiments, greenhouse studies, and field-level case studies.

2.4 Research Validation

Though this is a literature-focused review primarily, the methodology included triangulation of data by cross-verification of findings from various sources. For instance, nutrient release rates in laboratory dissolution studies were cross-checked with greenhouse and field experiments for confirmation (Liu and Lal, 2015). Likewise, concepts of fertilizer release by IoT were confirmed by referring to agricultural case studies and computer engineering literature (Gebbers and Adamchuk, 2010).

3. Key innovative techniques

3.1 Slow-Release Fertilizers (SRF)

Slow-release fertilizers (SRFs) represent an early but important innovation in nutrient delivery systems. The primary goal of SRFs is to overcome nutrient losses associated with conventional fertilizers, which often release nutrients too rapidly, leading to leaching, volatilization, and runoff. SRFs are engineered to gradually supply nutrients over a prolonged period, synchronizing better with plant uptake and reducing environmental impact (Shaviv, 2001 The slow-release fertilizers (SRFs) are an early but significant innovation in nutrient delivery systems. Their major objective is to mitigate nutrient losses of conventional fertilizers that tend to liberate nutrients too quickly and result in leaching, volatilization, and runoff. SRFs are specially designed to slowly deliver nutrients over an extended duration, matching better with plant uptake and minimizing environmental effects (Shaviv, 2001). The release mechanism of nutrients in SRFs is based on physical or chemical alterations of fertilizer materials. Two categories are discernible, namely, chemically modified fertilizers (such as urea-formaldehyde, isobutylidenediurea, crotonylidenediurea) and biodegradable matrix fertilizers, with the nutrients contained in organic/synthetic matrices that slowly degrade in soil (Trenkel, 2010).

The nutrient release process of SRFs relies upon physical or chemical changes of fertilizer materials. Two categories of these products exist, i.e., chemically modified fertilizers (e.g., urea-formaldehyde, isobutylidenediurea, crotonylidenediurea) and biodegradable matrix fertilizers in which nutrients are imbedded in organic or synthetic matrices gradually breaking down in soil (Trenkel, 2010).

Release Mechanisms:

- Hydrolysis-based SRFs: Urea-formaldehyde fertilizers release nitrogen through microbial hydrolysis of methylene-urea chains (Wilson, 1985).
- Low solubility SRFs: Natural organo-mineral complexes and sulfur-coated urea deliver nutrients due to their naturally low solubility in water (Shoji et al., 2001)

- Biodegradable polymer-based SRFs: Nutrients are embedded in biodegradable carriers that gradually degrade under microbial or abiotic conditions (Chien et al., 2009).

Advantages:

1. Reduced fertilizer application rates.
2. Lower nitrate leaching and nitrous oxide emissions.
3. Better synchronization of nutrient supply with crop requirements.

Limitations:

1. Higher production costs compared to standard fertilizers.
2. Nutrient release is influenced by soil temperature and moisture.
3. Effectiveness varies across different agro-ecological regions.

Case Studies:

In turfgrass systems, isobutylidenediurea supported uniform growth with fewer applications than urea (Sartain, 1987). In rice farming, SRFs reduced nitrogen losses—mainly from leaching—and improved nitrogen use efficiency (Shoji and Gandeza, 1992).

3.2 Controlled Release Fertilizers (CRF)

Controlled Release Fertilizers (CRFs) is another step of nutrient application systems more recent than Slow Release Fertilizers (SRFs). Whereas SRFs rely mainly upon the natural internal chemical composition of nutrients to cause slow solubilization, CRFs are designed to deliver a specially timed and regulated nutrient release pattern to coincide with the specific growth physiological needs of a crop (Shaviv, 2001). This synchronizing of nutrient supply maximizes optimum nutrient utilization efficiency (NUE), leakage to the environment is a minimum, and agricultural productivity is high (Figure 2).

The main point of difference of CRFs is the employment of coating, encapsulations, or matrix systems to control water influx and nutrient efflux. As opposed to SRFs that can show variability under varying pH of soil or temperature, CRFs are formulated to show predictable release rates, usually described mathematically by first-order or sigmoidal release profiles (Azeem et al., 2014). For instance, polymer-coated urea shows nutrient release profiles that could be tailored from 30 to 180 days based on polymer and coating thickness and environmental factors (Figure 3)(Trenkel, 2010).

3.2.1 Mechanism of Action

The nutrient release mechanism of CRFs generally consists of three stages (Figure 2):

- Water Penetration: The soil moisture permeates through the coating material into the fertilizer core.

- Dissolution of Nutrient: Nutrient salt within dissolves in a concentrated solution.
- Diffusion/Release: Nutrients diffuse out from the coating holes/pores or from cracks into soil solution, where plants are able to absorb them (Shaviv and Mikkelsen, 1993).

This system allows CRFs to deliver nutrients almost evenly, which is especially useful during key growth stages such as flowering and fruiting.

3.2.2 Types of CRFs

CRFs can be classified based on their coating or release mechanism:

- Sulfur-coated fertilizers (SCFs): Introduced in the 1960s, SCFs reduce urea solubility through a sulfur barrier. However, incomplete coatings and cracks often cause uneven release patterns (Shoji and Kanno, 1994).
- Polymer-coated fertilizers (PCFs): Synthetic or biodegradable polymers provide more consistent nutrient release, widely used in high-value horticultural and ornamental crops (Azeem et al., 2014).
- Hybrid-coated CRFs: Combining sulfur and polymer coatings improves release uniformity and reduces production costs.
- Resin-based CRFs: Resins such as alkyd or polyolefin are applied for highly predictable long-term release in greenhouse crops.

3.2.3 Applications in Agriculture

CRFs have shown record-breaking increases in the yield of maize, rice, wheat, and horticulture crops. For example, in maize, polymer-coated urea added 10–15% more grains and lowered nitrogen leaching lose by close to 40% when compared to conventional urea (Guo et al., 2017). For rice systems, CRFs lowered nitrous oxide emissions by 50% (Zheng et al., 2016), exemplifying the potential of CRFs in climate-smart agriculture.

CRFs are equally appropriate for horticulture crops like strawberries, tomatoes, and ornamentals, in which accurate nutrient release enhances the fruit's quality, color, and harvest shelf life (Du et al., 2019).

3.2.4 Limitations and Challenges

Despite their potential, CRFs face several limitations:

Cost: Production of polymer-coated fertilizers is cost-intensive compared to conventional urea, restricting adoption in resource-limited farming systems (Trenkel, 2010).

Degradability: Some polymers are not biodegradable, raising concerns of microplastic accumulation in soils (Lubkowski et al., 2020).

Environmental Variability: Release patterns may still be affected by extreme soil temperatures or fluctuating moisture.

3.2.5 Future Prospects

The future of CRFs lies in biodegradable coating materials such as starch, polylactic acid, or chitosan composites, which balance efficiency with environmental safety (Liang et al., 2020). Integration with nanotechnology and smart sensing systems (IoT-based feedback loops) is expected to revolutionize CRF application, enabling real-time monitoring of nutrient release dynamics (Figure 2).

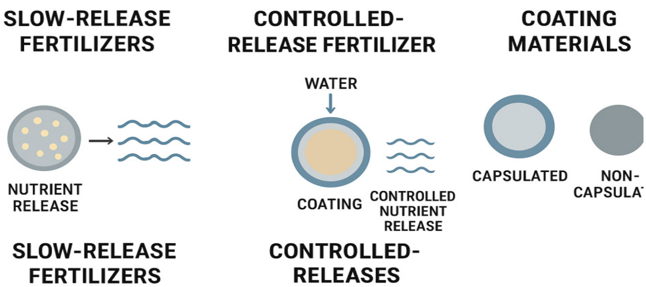


Figure 2: Diagram of Controlled Release Fertilizer Mechanism (showing nutrient release through coating over time).

3.3 Coating Materials – Capsulated & Non-Capsulated

Coating materials are the fundamental technology defining performance of both CRFs and SRFs. Release kinetics, economics, and eco-friendliness of smart fertilizers are defined by the coating material chosen. Overall, coating technologies fall into capsulated (encapsulation) and non-capsulated surface coating systems.

3.3.1 Encapsulated Fertilizers

Encapsulation refers to enclosing fertilizer granules within a polymeric or composite shell that acts as a physical barrier between the nutrient core and the soil environment (Shaviv, 2001). Encapsulated fertilizers typically use (Figure 4):

Polymer Coatings: Polyolefin, polyvinylidene chloride, and polyurethane. These allow steady nutrient release but may increase soil microplastic buildup.

Biopolymer Coatings: Chitosan, starch, cellulose derivatives. These are environmentally friendly alternatives receiving growing research attention (Ni et al., 2011).

Multi-layer Encapsulation: Combines sulfur with polymer or wax coatings to improve performance and reduce permeability.

These fertilizers are particularly suited for high-value horticultural crops and controlled-environment farming systems.

3.3.2 Non-Capsulated Fertilizers

Non-capsulated coatings depend on surface modifications such as waxes, resins, or inorganic layers:

Sulfur Coating: This is one of the earliest technologies. It is still widely used because it is cost-effective, although the release patterns can be inconsistent (Shoji and Kanno, 1994).

Inorganic Coatings: Zeolites, clay minerals, and phosphate glasses act as adsorbents or slow-dissolving barriers (Xie et al., 2018).

Biochar Coatings: This is a new method that uses biochar as a porous adsorbent to control nutrient release while improving soil microbial activity.

3.3.3 Mechanisms of Release

Nutrient release from coated fertilizers occurs through:

Diffusion-Controlled Release: Nutrients move through pores or semi-permeable coatings that are polymer-based.

Degradation-Controlled Release: Coatings break down due to microbial or chemical action involving biopolymers.

Fracture-Controlled Release: Nutrients are released when coatings crack under mechanical or thermal stress, such as with sulfur-coated urea (Figure 3).

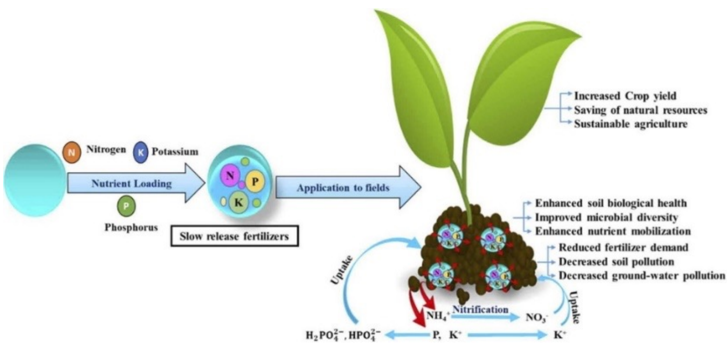


Figure 3: Mechanisms of release. Adapted from Priya, Sarkar, and Maji (2024).

3.3.4 Comparative Performance

Studies show that polymer-coated fertilizers usually achieve nutrient release efficiencies of 60–80%. In contrast, uncoated urea has efficiencies of only 30–40% (Trenkel, 2010). Encapsulated fertilizers also lower ammonia loss and nitrate leaching, which helps improve groundwater quality. For instance, a field trial with chitosan-encapsulated NPK fertilizers in tomatoes showed a 25% reduction in fertilizer use without affecting yields (Li et al., 2016). Similarly, zeolite-coated fertilizers increased nitrogen uptake efficiency in maize by 20% compared to uncoated urea (Xie et al., 2018).

3.3.5 Limitations

Despite their potential, coating technologies face several challenges:

Cost of Biopolymers: Although biodegradable, biopolymers tend to be more expensive than synthetic polymers.

Scalability: Mass production of consistent coatings at reasonable prices remains a hurdle.

Durability: Biopolymer coatings may break down too quickly in tropical soils, which limits their controlled release ability (Figure 4**)**.

3.3.6 Future Directions

Research is moving toward hybrid coatings. These combine biopolymers with inorganic nanomaterials, such as chitosan-nano-silica composites, to provide both durability and biodegradability (Liang et al., 2020). Another focus is on creating coatings that respond to stimuli, where nutrient release is activated by soil pH, moisture, or enzymatic activity (Rychter et al., 2016). Such "smart coatings" could represent a shift from traditional controlled-release fertilizers to more responsive, feedback-driven products.

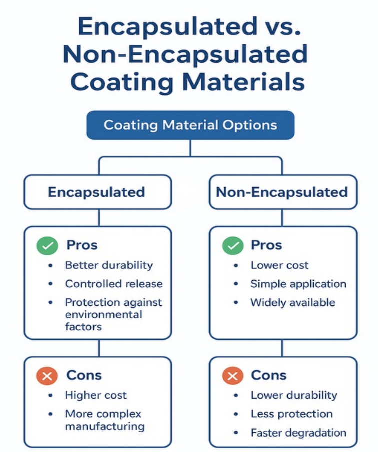


Figure 4: Comparing encapsulated vs non-encapsulated coating materials with pros and cons.

3.4 Nanomaterials and Microbial Carriers

Nanotechnology has become a valuable tool in modern agriculture. It allows for precise nutrient delivery, improved uptake efficiency, and reduced environmental loss. In the realm of smart fertilizers, nanomaterials serve as both active nutrient carriers and functional additives that modify how nutrients are released. Their high surface-to-volume ratio, adjustable porosity, and controlled release rates make them suitable for encapsulating nutrients like nitrogen, phosphorus, potassium, and micronutrients (Kah et al., 2018). Additionally, microbial carriers, including biochar, alginate beads, chitosan nanoparticles, and silica-based nanocomposites, offer sustainable ways to deliver beneficial microorganisms along with nutrients, integrating biofertilization with nanotechnology.

3.4.1 Nanomaterial-Based Fertilizers

Nanofertilizers fall into three main categories:

- Nanoscale nutrients (e.g., nano-ZnO, nano-Fe, nano-Cu), which are supplied in particle form and are more bioavailable than larger particles.
- Nutrient-loaded nanocarriers (e.g., mesoporous silica, halloysite nanotubes, layered double hydroxides), which encapsulate nutrients for slow or responsive release.
- Nano-enabled coatings on conventional fertilizers, such as polymeric nanofilms or nanoclays, that control solubilization and prevent leaching.

For example, mesoporous silica nanoparticles loaded with urea have been shown to release nitrogen gradually over weeks, cutting leaching losses by up to 60% compared to traditional urea (Nair et al., 2010). Similarly, halloysite nanotubes can encapsulate KNO_3 and provide moisture-triggered release in soil (Zhao et al., 2019).

3.4.2 Mechanisms of Nutrient Release from Nanomaterials

The release of nutrients from nanomaterials involves several mechanisms:

Diffusion-controlled release: Nutrients move from concentrated cores to surrounding soil solutions through nanopores.

Biodegradation-triggered release: Biodegradable polymers like chitosan or PLA break down slowly, allowing for a steady nutrient supply.

Stimuli-responsive release: Some smart nanocarriers react to soil pH, temperature, or root exudates to release nutrients when conditions are ideal (Banik et al., 2021).

These smart features are essential for matching nutrient supply with plant growth needs, which helps improve nutrient use efficiency (NUE).

3.4.3 Microbial Carriers in Smart Fertilizers

Beneficial microorganisms like Azospirillum, Rhizobium, Pseudomonas fluorescens, and phosphate-solubilizing bacteria are often added to microbial-based biofertilizers. However, their survival and ability to colonize soil can be limited by harsh environmental conditions. Carriers such as alginate, starch, chitosan, and nanoclay matrices can enhance microbial shelf-life, viability, and controlled release. For instance, alginate-encapsulated Rhizobium formulations showed better nodulation and nitrogen fixation in legumes compared to free-cell inoculants (Herrmann and Lesueur, 2013). Chitosan nanoparticles also help improve microbial adhesion to root surfaces while creating a protective environment against drying out and UV exposure (Figure 5).

3.4.4 Advantages and Challenges

Nanomaterials and microbial carriers offer several benefits for smart fertilizers:

Advantages: Improved NUE, reduced nutrient loss through volatilization, protection of sensitive nutrients, targeted release, and integration of microbial advantages.

Challenges: High production costs, limited testing in real-world conditions, potential harm from engineered nanoparticles to soil organisms, and regulatory uncertainties **(**Figure 5**)** (Kah et al., 2018).

While nanotechnology holds great promise, further large-scale agricultural studies and risk assessments are needed to ensure safety and sustainability.

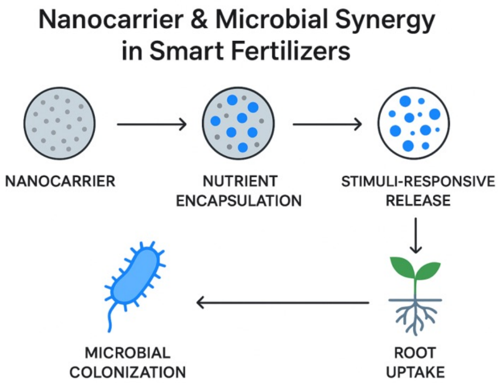


Figure 5: Flowchart showing nanomaterials and microbial carriers in smart fertilizer delivery systems (PNG)

3.5 IoT-Based Sensors in Smart Fertilizer Systems

The integration of Internet of Things (IoT) technologies into agriculture has revolutionized the monitoring and regulation of fertilizer application. IoT-enabled smart fertilizer systems use sensors, wireless communication, and data analytics to monitor soil nutrient dynamics, environmental conditions, and crop health in real time. These systems then trigger the release of fertilizers from coated, nanostructured, or microbial-based carriers only when required, thus maximizing efficiency and minimizing waste (Zhang et al., 2019).

3.5.1 Types of IoT Sensors in Fertilizer Management

1. Soil nutrient sensors – Measure nitrogen, phosphorus, and potassium availability in real time.
2. Moisture and temperature sensors – Regulate fertilizer release based on soil hydration and thermal conditions.

3. pH and salinity sensors – Adjust nutrient application in response to soil acidity or salt accumulation.
4. Plant-based biosensors – Detect stress indicators in crops (e.g., chlorophyll fluorescence, sap nitrate content).

For example, nitrate ion-selective electrodes integrated with wireless data transmitters can continuously monitor soil nitrate levels and trigger CRF release mechanisms (Kumari et al., 2021).

3.5.2 IoT-Enabled Release Mechanisms

IoT systems are often coupled with actuators that regulate fertilizer release from smart carriers. Mechanisms include:

- Electrochemical triggers: Electric signals induce ion exchange or breakdown of polymer coatings.
- Hydrogel swelling control: IoT signals regulate irrigation, which in turn controls hydrogel-based fertilizer swelling and nutrient release.
- Microfluidic systems: Small-scale valves and pumps deliver precise nutrient doses in fertigation setups (Figure 6) (Ojha et al., 2021).

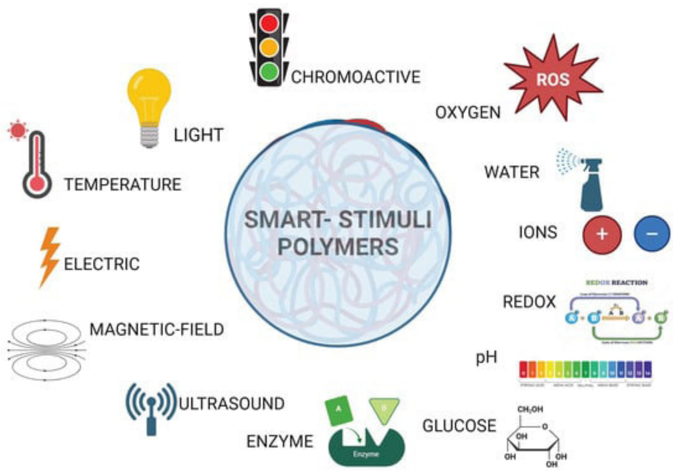


Figure 6: IoT-Enabled Release Mechanisms (Adapted from Balcerak-Woźniak et. al., 2024)

This closed-loop system ensures real-time synchronization between crop demand and nutrient supply.

3.5.3 Data Analytics and Decision Support

IoT sensors harvest enormous data that are processed with cloud platforms and artificial intelligence (AI) software. Predictive models are used to predict crop nutrient demand, and decision support system (DSS) recommendations provide the schedule of fertilizer application based on personalized soil and climate needs. Merging big data and machine learning enhances site-specific nutrient management (Figure 7) (Singh et al., 2022).

3.5.4 Advantages and Limitations

Advantages: Precision nutrient delivery, minimized leaching losses, improved resource efficiency, and scalability in smart farming.

Limitations: High infrastructure costs, limited rural connectivity, sensor calibration issues, and dependence on farmer digital literacy.

Nevertheless, IoT-based fertilizer systems represent a crucial step toward sustainable and data-driven agriculture.

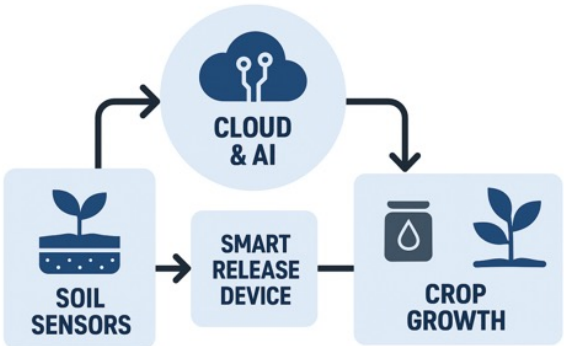


Figure 7: Diagram of IoT sensor-integrated smart fertilizer system (PNG)

4. Conclusion

Intelligent fertilizers are a revolutionary development of the modern agriculture sector. They integrate traditional agriculture with material sciences, nanotechnology, and information-based agricultural system technologies. Traditional fertilizers formed the core of the Green Revolution. They were accused of being unproductive, harmful to the environment, and being unable to meet the demand of nutrients by crops. Intelligent fertilizers overcome these limitations by using controlled-release technology, special coatings, nanomaterials, microbial communities, and IoT-based monitoring platforms. It results in a complete approach of green and environmentally friendly nutrient management.

References

Adesemoye, A. O., & Kloepper, J. W. (2009). Plant-microbes interactions in enhanced fertilizer-use efficiency. Applied Microbiology and Biotechnology, 85(1), 1–12. https://doi.org/10.1007/s00253-009-2239-8

Azeem, B., et al. (2014). Controlled release fertilizers: A review. Journal of Controlled Release, 181, 11–21. https://doi.org/10.1016/j.jconrel.2014.01.006

Banik, S., et al. (2021). Smart polymeric nanocarriers for controlled nutrient delivery in crops. Journal of Nanobiotechnology, 19(1), 101–115. https://doi.org/10.1186/s12951-021-00913-9

Balcerak-Woźniak, A., Dzwonkowska-Zarzycka, M., & Kabatc-Borcz, J. (2024). A comprehensive review of stimuli-responsive smart polymer materials—Recent advances and future perspectives. Materials, 17(17), 4255. https://doi.org/10.3390/ma17174255

Bashan, Y., et al. (2014). Advances in plant growth-promoting bacterial inoculant technology. Plant and Soil, 378, 1–33. https://doi.org/10.1007/s11104-014-2133-5

Chen, J., Lü, S., Zhang, Z., et al. (2018). Environmentally friendly fertilizers: A review of materials used and their effects on the environment. Science of the Total Environment, 613-614, 829–839. https://doi.org/10.1016/j.scitotenv.2017.09.019

Chien, S. H., Prochnow, L. I., & Cantarella, H. (2011). Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts. Advances in Agronomy, 102, 267–322. https://doi.org/10.1016/B978-0-12-385527-5.00005-8

DeRosa, M. C., et al. (2010). Nanotechnology in fertilizers. Nature Nanotechnology, 5(2), 91–95. https://doi.org/10.1038/nnano.2009.457

Dimkpa, C. O., & Bindraban, P. S. (2016). Nanofertilizers: New products for the industry? Environmental Science & Technology, 50(1), 12480–12482. https://doi.org/10.1021/acs.est.6b02211

Du, C., et al. (2019). Impact of controlled-release fertilizers on fruit quality and yield in horticultural crops. Horticulturae, 5(2), 29. https://doi.org/10.3390/horticulturae5020029

Evenson, R. E., & Gollin, D. (2003). Assessing the impact of the Green Revolution, 1960–2000. Science, 300(5620), 758–762. https://doi.org/10.1126/science.1078710

FAO. (2019). The future of food and agriculture – Alternative pathways to 2050. FAO. http://www.fao.org/3/ca5602en/ca5602en.pdf

Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. Science, 327(5967), 828–831. https://doi.org/10.1126/science.1183899

Guertal, E. A. (2009). Slow- and controlled-release fertilizers and nitrogen rates in corn. Agronomy Journal, 101(3), 615–620. https://doi.org/10.2134/agronj2008.0122

Gupta, A., Singh, R., & Yadav, M. (2021). IoT-enabled smart fertilizers for precision agriculture. Journal of Agricultural Engineering, 58(3), 45–56.

Herrmann, L., & Lesueur, D. (2013). Challenges of formulation and quality of biofertilizers for successful inoculation. Applied Microbiology and Biotechnology, 97(20), 8859–8873. https://doi.org/10.1007/s00253-013-4836-4

IFFCO. (2021). Nano urea: An innovation for Indian agriculture. Indian Farmers Fertiliser Cooperative Limited.

Jian, L., Zhang, W., & Xu, Y. (2015). Effects of slow-release fertilizers on nitrogen efficiency in rice cultivation. Agronomy Journal, 107(2), 620–628. https://doi.org/10.2134/agronj14.0335

Kah, M., et al. (2018). Nanopesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation? Nature Nanotechnology, 13(8), 677–684. https://doi.org/10.1038/s41565-018-0188-y

Kitchenham, B. (2004). Procedures for performing systematic reviews. Keele University Technical Report TR/SE-0401.

Kumar, A., et al. (2019). Nanofertilizers for sustainable agriculture. Environmental Chemistry Letters, 17, 849–869. https://doi.org/10.1007/s10311-019-00883-w

Li, X., et al. (2016). Chitosan-encapsulated NPK fertilizer improves tomato growth and reduces runoff. Journal of Plant Nutrition, 39(14), 2038–2049. https://doi.org/10.1080/01904167.2016.1210658

Li, X., et al. (2018). Biodegradable starch-based coatings for controlled-release fertilizers. Carbohydrate Polymers, 185, 27–33. https://doi.org/10.1016/j.carbpol.2018.02.020

Liang, B., et al. (2007). Sulfur-coated urea in rice cultivation. Field Crops Research, 101, 1–8. https://doi.org/10.1016/j.fcr.2006.11.004

Nair, R., et al. (2010). Nanoparticulate material delivery to plants. Plant Science, 179(3), 154–163. https://doi.org/10.1016/j.plantsci.2010.05.012

Ni, B., Liu, M., & Lü, S. (2011). Multifunctional slow-release fertilizer from starch and urea. Industrial & Engineering Chemistry Research, 50(5), 2541–2549. https://doi.org/10.1021/ie101748v

Ojha, T., et al. (2021). Internet of Things for agricultural applications: An overview. Computers and Electronics in Agriculture, 187, 106291. https://doi.org/10.1016/j.compag.2021.106291

Patel, K., et al. (2020). IoT-based fertigation management. Computers and Electronics in Agriculture, 171, 105312. https://doi.org/10.1016/j.compag.2020.105312

Priya, E., Sarkar, S., & Maji, P. K. (2024). A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. Journal Name, volume(issue), pages.

Sartain, J. B. (1987). Performance of isobutylidene diurea in turfgrass. Agronomy Journal, 79(2), 281–285. https://doi.org/10.2134/agronj1987.00021962007900020017x

Servin, A., White, J. C., et al. (2015). Nano-enabled fertilizers: Emerging risks and regulatory challenges. Environmental Science: Nano, 2(1), 1–19. https://doi.org/10.1039/C4EN00156B

Shaviv, A. (2001). Advances in controlled-release fertilizers. Advances in Agronomy, 71, 1–49.

Shoji, S., & Gandeza, A. T. (1992). Controlled release fertilizers with polyolefin resin coating. International Fertilizer Development Center.

Singh, A., et al. (2022). Machine learning-driven nutrient management for sustainable agriculture. Agricultural Systems, 196, 103332. https://doi.org/10.1016/j.agsy.2021.103332

Singh, J. S., Pandey, V. C., & Singh, D. P. (2019). Efficient soil microorganisms: A new dimension for sustainable agriculture. Applied Soil Ecology, 138, 10–20. https://doi.org/10.1016/j.apsoil.2019.02.008

Subbarao, G. V., et al. (2006). Biological nitrification inhibition: A novel strategy. Plant and Soil, 290, 35–46. https://doi.org/10.1007/s11104-006-9043-7

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. PNAS, 108(50), 20260–20264. https://doi.org/10.1073/pnas.1116437108

Trenkel, M. E. (2010). Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. International Fertilizer Industry Association.

Vitousek, P. M., et al. (2009). Nutrient imbalances in agricultural development. Science, 324(5934), 1519–1520. https://doi.org/10.1126/science.1170261

Wilson, M. L., et al. (2009). Controlled-release fertilizer effects on potato. American Journal of Potato Research, 86, 68–78. https://doi.org/10.1007/s12230-009-9053-3

Wolfert, S., et al. (2017). Big data in smart farming. Agricultural Systems, 153, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

Zhang, F., et al. (2015). Integrated nutrient management for food security and environmental quality in China. Advances in Agronomy, 116, 1–40.

Zhang, Y., et al. (2019). Smart fertilizer systems integrating IoT technologies. Precision Agriculture, 20(4), 731–747. https://doi.org/10.1007/s11119-018-9631-5

Zhao, L., et al. (2019). Halloysite nanotube-based nanofertilizers for sustainable agriculture. ACS Sustainable Chemistry & Engineering, 7(9), 8743–8752. https://doi.org/10.1021/acssuschemeng.9b00816

7

ROLE OF CROP NUTRITION IN ENHANCING FORTIFICATION TO ELIMINATE HIDDEN HUNGER FOR GLOBAL FOOD SECURITY

Rukhsar Saleem[1], Muhammad Abdullah Saleem[2], Amna Rashid[3], Usman Zulifqar[4], Muhammad Talha Aslam[5]

1 Introduction

Hidden hunger is pervasive form of under-nutrition caused by diets rich in calories but deficient in essential vitamins and minerals (Naik et al. 2024). The consequences of hidden hunger extend beyond health, contributing to cognitive impairment, reduced immunity and productivity losses costing 3-5% of global GDP (Lowe, 2021). By enhancing micronutrient density in staple crops through agronomic practices, breeding or biotechnology, bio-fortification provides a sustainable, economically viable approach to deliver essential nutrients (Sandhu et al. 2023). Biofortification synergizes with climate resilience, economic accessibility for smallholders, and policy alignment with nutrition-sensitive agriculture (Nasir et al. 2025). This chapter explores how optimizing crop nutrition can eliminate hidden hunger and advance global food security.

2 Role of Specific Nutrients in Crop and Human Health and its deficiencies

Micronutrients are crucial for sustaining life, and consumption below recommended dietary allowances contributes to chronic metabolic disorders (Tummolo et al. 2023). Deficiencies impair metabolic systems, adversely affecting health, work capacity, educational achievements and economic productivity (Bailey et al. 2015; Kiani et al. 2022). Globally, over 2 billion people experience micronutrient deficiency, with pregnant women and children under 5 years disproportionately impacted (Bailey et al. 2015; Kiani et al. 2022). These deficiencies are associated with nearly 10% of childhood mortality (Awuchi et al. 2020). Iron, zinc, iodine and vitamin A deficiencies are among the most prevalent worldwide, contributing to intellectual impairment,

1 Faculty of Agriculture, Department of Agronomy, University of Agriculture, Faisalabad, Punjab 38000, Pakistan, rukhsarsaleem@uaf.edu.pk, https://orcid.org/0000-0003-3820-1476
2 Faculty of Agriculture, Department of Agronomy, University of Agriculture, Faisalabad, Punjab 38000, Pakistan, Faculty of Food and Agricultural Sciences, Agronomy Department, University of Florida, USA, abdullahsaleem65@gmail.com, m.saleem1@ufl.edu , https://orcid.org/0000-0002-9900-5471
3 Faculty of Agriculture, Department of Agronomy, University of Agriculture, Faisalabad, Punjab 38000, Pakistan aminarashid@uaf.edu.pk, https://orcid.org/0009-0001-6128-548X
4 Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur-63100 Pakistan, usman.zulfiqar@iub.edu.pk , https://orcid.org/0000-0003-3820-1476
5 Faculty of Agriculture, Department of Agronomy, University of Agriculture, Faisalabad, Punjab 38000, Pakistan, taslamuaf@gmail.com, https://orcid.org/0009-0000-0630-1961

poor growth, perinatal complications and increased morbidity and mortality (Bailey et al. 2015). They also accelerate mitochondrial decay and age-related degenerative diseases (Awuchi et al. 2020). Prevention by supplementation and food-based approaches is essential, guided by validated biomarkers for accurate assessment (Bailey et al. 2015). These deficiencies can be corrected by a proper use of micronutrients in crop nutrition (Saleem et al. 2020).

2.1 Iron

Iron is one of the most important micronutrients required for normal physiological functioning in both plants and humans. Its dual role in supporting oxygen transport and cognitive development underscores its significance in the context of crop nutrition and human health. Iron plays a pivotal role in brain development especially during gestation, infancy and early childhood. It is involved in the formation of myelin, the insulating layer around nerves and in neurotransmitter synthesis, particularly dopamine, norepinephrine and serotonin (Mccann et al., 2020). These functions are essential for maintaining attention, memory, learning capacity and emotional regulation.

Iron deficiency is the most prevalent nutritional deficiency globally, with young children and premenopausal women at highest risk (Pasricha et al. 2021). As iron is essential for hemoglobin synthesis, its depletion causes microcytic hypochromic anemia, characterized by small, pale red blood cells with reduced hemoglobin content Symptoms include fatigue, weakness, pallor, exertional breathing difficulties, and cold intolerance (Wagh et al. 2024). This deficiency impairs childhood development, cognitive function and growth while increasing risks of pregnancy complications and maternal mortality. Primary causes include inadequate dietary intake, menstrual blood loss, gastrointestinal bleeding and chronic aspirin use (Awuchi et al. 2020; Pasricha et al. 2021).

2.2 Zinc

Zinc is an essential trace element involved in the structural, catalytic and regulatory functions of many biological systems. Its role is critical in both plant and human health particularly in relation to physiological growth, immune competence and enzymatic activity. In the context of food and nutrition security, understanding the impact of zinc on crop development and human wellbeing is essential for addressing hidden hunger and nutrient deficiencies worldwide.

Zinc plays a fundamental role in the growth and development of both plants and humans. In plants, zinc is indispensable for processes such as cell division, elongation and differentiation. These physiological impairments ultimately reduce yield and diminish the zinc content in the edible parts of crops, directly affecting the nutritional value of food consumed by humans. In humans, zinc is required during periods of rapid growth such as infancy, childhood, adolescence and pregnancy. Zinc deficiency in children leads to growth retardation, low height-for-age (stunting) and developmental delays (Sangeetha et al., 2022). Maternal zinc deficiency during pregnancy increases the risk of preterm birth and low birth weight.

Zinc is one of the most critical micronutrients for immune system development and function. It is involved in the maintenance and function of both the innate and adaptive immune responses. Zinc influences the activity of macrophages, neutrophils and natural killer cells, all of which are part of the body's first line of defense against infection. It also regulates T-cell and B-cell development, activation and signaling pathways. Zinc deficiency impairs multiple immune functions, increases susceptibility to bacterial and viral infections and compromises the integrity of epithelial barriers (Maywald and Rink, 2022). Children with inadequate zinc intake are at greater risk of diarrhea, infections and malaria. Supplementation of zinc has been shown to significantly reduce the duration and severity of diarrheal episodes and lower child mortality in developing regions.

2.3 Boron

Boron (B) possesses a unique combination of metallic and non-metallic properties that enables it to act like acid or basic compounds. Boron is increasingly recognized as a potentially essential element for animal and human health, with evidence supporting its role in a variety of physiological processes (Khaliq et al., 2018). It is implicated in hydroxylation reactions, influencing the synthesis and metabolism of numerous compounds. Its therapeutic potential extends to oncology, where boron neutron capture agents are used in cancer therapy, and where boric acids has demonstrated effectiveness against breast cancer cell in *vitro* (Simsek et al., 2019). Boron is further suggested to influence cardiovascular health by potentially affecting blood clotting factors and alleviating complications associated with congestive heart failure. It aids in reducing lipid accumulations and facilitating cholesterol removal, thereby potentially decreasing the risk of atherosclerosis, blood clot formation, heath attacks and strokes (Moustafa, 2015) though further validation is required.

2.4 Selenium

Selenium is a trace mineral that plays a critical role in maintaining cellular health through its antioxidant properties and immune-regulating functions. Although required in small amounts, selenium is vital for both plants and humans. Its dual relevance to crop nutrition and human well-being makes it a key element in strategies targeting biofortification and the mitigation of hidden hunger. While selenium is not considered an essential nutrient for most higher plants, its presence in small quantities can positively influence plant physiology. Selenium enhances the antioxidant defense mechanisms in plants by modulating the activity of enzymes such as glutathione peroxidase

(GPX) and catalase which reduce oxidative stress under adverse environmental conditions like drought, salinity and heavy metal toxicity (Bandehagh et al., 2023). This protective effect contributes to improved plant resilience, growth and potentially higher yields.

Selenium and Antioxidant Function in Humans

In humans, selenium is an essential component of selenoproteins, many of which function as antioxidants. The most well-known of these is glutathione peroxidase (GPx), a key enzyme that protects cells from oxidative damage by neutralizing hydrogen peroxide and lipid peroxides. Other important selenoproteins include thioredoxin reductases and selenoprotein P which help regulate redox homeostasis and prevent cellular damage from free radicals (Zhang et al., 2023).

Selenium's antioxidant activity is crucial in reducing the risk of chronic diseases such as cancer, cardiovascular disorders and neurodegenerative conditions. It also contributes to healthy aging by protecting DNA and cellular structures from oxidative stress (Bai et al., 2024). Inadequate selenium intake weakens these defenses and has been linked to increased oxidative stress, inflammation and disease susceptibility.

2.5 Iodine

Iodine is a vital micronutrient required for the synthesis of thyroid hormones, which regulate metabolism, growth and neurological development in humans. Although iodine is not essential for plant growth, plants serve as a potential vehicle for delivering iodine to humans populations through biofortification. Iodine deficiency remains a significant public health concern in many parts of the world, particularly in inland and high-altitude regions where soils are iodine-poor (Sorrenti et al., 2021). Therefore, integrating iodine into crop nutrition strategies is a critical component of addressing hidden hunger and ensuring human health. Iodine deficiency impairs the synthesis of thyroid hormones, leading to a spectrum of disorders collectively termed iodine deficiency disorders (IDDs). These include goiter (enlargement of the thyroid gland), hypothyroidism, reduced mental capacity, stunted growth and cretinism in severe cases (Shulhai et al., 2024). Even mild iodine deficiency during pregnancy can lead to irreversible cognitive and psychomotor deficits in offspring. Therefore, ensuring adequate iodine intake is essential for maternal health and optimal fetal and child development. Thyroid hormone is critical for optimal fetal and postnatal central nervous system development (Anifantaki et al. 2021). Maternal iodine deficiency during early pregnancy can lead to iodine deficiency disorders (IDD), causing permanent neurological damage and mental retardation in offspring (Anifantaki et al. 2021). IDD manifestations range from diminished cognition and goiter to cretinism and thyroid dysfunction throughout life, with infants and pregnant women at highest risk (Kiani et al. 2022). Universal salt iodization remains the most effective global strategy to combat iodine deficiency (Sun et al. 2017).

2.6 Role of crops in providing essential micronutrients

Diets must incorporate adequate essential nutrient with crops serving as primary sources to address hidden hunger. Although, over 50,000 edible plants exist globally, merely 15 species provide 90% of food intake, predominantly rice, maize, wheat, which constitute 2/3rd of staple consumption (Dhaliwal et al. 2022). Other key micronutrient-delivering crops include millet, sorghum, cassava, potato, and pulses (Robinson et al. 2019).

Cereals

Cereals grains are prioritized for micronutrient enhancement due to their capacity to accumulate minerals in edible proteins. Rice, consumed by over half the global population, provides more than 42% of caloric intake and dominates diets in Asia, Africa and Latin America (Huang et al. 2020). It delivers vitamins B (B1, B2, B3, B6), phytochemicals and minerals i.e., Zn, I, Mg. Likewise, wheat recorded for supplying more than 70% of daily calories in South Asia and China. Its embryo and aleurone layer contains protein, Zn and vitamins B, whereas the endosperm is rich in starch (Rosa-Sibakov et al. 2015). Maize serves as a staple for human and animals, with compositional analysis showing 72% starch, 10% proteins, and minerals (Zn, K, P, Mg) (Dhaliwal et al. 2022). Its versatility supports diverse culinary applications while contributing essential micronutrients.

Pulses

According to FAO (2016), pulses are recognized as nutritional superfoods due to their dense micronutrient profile and health benefits (Callens et al. 2019). After cereals, pulses (lentils, peas, beans and chickpea) are the second-largest crop comprises 70% of global legume consumption. Their socioeconomic value is amplified through sustainable intercropping system with cereals, characterized by low fertilizer/water requirements, disease resistance, extended storage stability, and resilience to environmental extremes (Brueck & Lammel, 2016).

Oilseeds

Oilseeds are cultivated primarily for vegetable oil extraction, serving household cooking, food products and olechemical industries globally, Key species includes soybean, canola, sunflower, olive, and peanut, which yield higher oil volumes than alternative crops (Zafar et al. 2019). In semi-arid regions, these crops provide 40% of caloric intake for low-income populations and deliver substantial protein and micro-nutrients (Kowalska et al. 2020).

Oilseeds are categorized as temporary (groundnut, soybean) or permanent crops (coconut, oil palm). Soybean meal offers complete amino acids, while soy hulls provide micronutrients, fiber, and low-lignin protein (Liu et al. 2017). Canola meal contains sulfur-rich nutrients, and hemp/mustard seeds supply Ca, Mg, P, K, I, and Zn. However, phytic acid decreases mineral bioavailability, necessitating phytate-reduction strategies. Selenium biofortification via foliar sodium selenate in acidic s Hooils demonstrates enhancement potential (Száková et al. 2017). However, research on oilseed biofortification remains limited compared to industrial applications (Dhaliwal et al. 2022).

Fodder

Although fodders are not directly related to human nutrition but these play an imperative role indirectly by affecting animal health and improving milk and meat quality (Saleem et al., 2025). Livestock nutrition directly impacts human micronutrient security, necessitating balanced animal diet supplemented with minerals that forage along cannot provide (Caradus et al. 2024). Fodder crops (sorghum, cowpea, lucern, maize) occupy 26% of global land area and 70% of agricultural land, delivering essential macro-elements (P, K, Ca) and micronutrients (I, Zn, Mg) critical for livestock health (Singh et al. 2019). Adequate mineral concentration minimizes antibiotic use in animal production while ensuring micronutrient transfer to human's vial animal-derived foods (ŞONEA et al. 2023; Białowąs et al. 2024). Biofortification of fodder crops enhances their nutritional profile (Kumar & Ram, 2021). Festulolium hybrids exhibit superior protein stability compared to parental Festuca and Lolium lines.

3 Nutrient interactions and availability in crops

The availability and effectiveness of nutrients in crops are not determined solely by their presence in the soil or applied fertilizers but also by complex interactions among nutrients, soil properties and environmental factors. These interactions can be synergistic (enhancing nutrient uptake) or antagonistic (inhibiting nutrient absorption) ultimately affecting plant growth, crop yield and the micronutrient density of food consumed by humans (Singh et al., 2024). Understanding these nutrient interactions is crucial for optimizing crop nutrition and enhancing biofortification strategies aimed at reducing micronutrient deficiencies in human populations.

3.1 Antagonistic interactions among micronutrients

Several essential micronutrients including iron (Fe), zinc (Zn), copper (Cu), manganese (Mn) and selenium (Se) often compete for the same transport pathways in plant roots (Gui et al., 2022). This competition can limit the uptake of one element when another is in excess. For example:

- High phosphorus (P) levels can reduce the availability and uptake of zinc, a condition commonly observed in intensively fertilized soils. This antagonism results in zinc deficiency symptoms in crops and lowers the zinc content in grains.

- Excess calcium (Ca), magnesium (Mg) or potassium (K) can interfere with iron absorption especially in alkaline soils, where iron solubility is already low.
- Selenium and sulphur share similar uptake pathways. High sulphur levels may inhibit selenium absorption, reducing its accumulation in biofortified crops.
- Copper and zinc may also compete at high concentrations, affecting enzyme activities and nutrient balance in plants.

These antagonistic relationships not only impair plant health and productivity but also reduce the micronutrient content in edible parts of crops, affecting human dietary intake.

3.2 Synergistic and Enhancing Interactions

Conversely, certain nutrients can improve the uptake or utilization of others. Understanding these synergistic effects helps in designing balanced fertilization regimes that maximize nutrient use efficiency and crop nutritional value (Choudhary et al., 2024). For instance:

- Nitrogen (N) enhances the biomass production of crops, indirectly improving the accumulation of micronutrients like iron and zinc by increasing root surface area and metabolic activity.
- Vitamin C (ascorbic acid) in human diets enhances the absorption of non-heme iron from plant-based foods, countering the effect of inhibitors such as phytates.
- Mycorrhizal fungi and rhizobacteria can improve the availability of phosphorus, zinc and iron in the rhizosphere by solubilizing bound forms of these nutrients and facilitating their uptake.

These beneficial interactions are critical to both plant health and human nutrition particularly when crops are grown in nutrient-deficient or marginal soils.

4 Factors Influencing Nutrient Availability

Beyond nutrient-to-nutrient interactions, several other factors impact the bioavailability of nutrients in crops (Weaver et al., 2025) such as:

- Soil pH significantly affects the solubility of micronutrients. Iron and zinc are less available in alkaline soils, while acidic conditions may lead to toxicity of some elements like aluminium.
- Organic matter content improves nutrient retention and chelation, enhancing the bioavailability of micronutrients like copper, manganese and zinc.

- Moisture levels, soil texture and temperature also influence nutrient dynamics and root uptake efficiency.

Nutrient interactions in crops must be carefully managed to ensure both optimal plant growth and the nutritional quality of food. Recognizing and addressing these interactions supports the development of effective, sustainable solutions for tackling micronutrient deficiencies in humans through improved crop nutrition (Ahmed et al., 2024).

5 Bioavailability and Post-Harvest Considerations

5.1 How processing and cooking affect nutrient retention

Improving crop nutrition is only part of the solution to combating hidden hunger. Equally important is ensuring that these nutrients remain available and beneficial after harvest and during consumption. Post-harvest handling, processing and cooking practices significantly influence the bioavailability and retention of nutrients in food crops (Huey et al., 2023). These factors are crucial when designing strategies to bridge the gap between nutrient-enriched crops and improved human health outcomes.

5.2 Impact of Processing Techniques on Nutrient Content

Various processing methods such as milling, refining, polishing and drying can lead to significant losses in micronutrients (Michel et al., 2024). For instance, milling and polishing of cereals like rice and wheat remove the outer layers bran and germ which are rich in iron, zinc and B-complex vitamins. Polished white rice typically retains only 20–30% of the zinc and iron present in whole rice. Similarly, refined wheat flour has much lower micronutrient content than whole wheat flour. In oilseeds, refining processes strip away fat-soluble vitamins like vitamin E and carotenoids. Additionally, high-temperature processing during drying or roasting can further degrade antioxidant compounds.

5.3 Effects of Cooking Methods on Nutrient Stability

Cooking improves the digestibility, taste and safety of foods but it can also result in the degradation or leaching of nutrients depending on the method used (Razzak et al., 2023). Boiling, for instance, causes water-soluble nutrients such as vitamin C, folate and some B vitamins to leach into cooking water. In contrast, steaming is a gentler method that retains more nutrients. Frying may help retain some vitamins by reducing cooking time but excessive heat or reusing oils can oxidize fat-soluble nutrients. Roasting and baking, while effective in preserving mineral content, can degrade thermolabile compounds if temperatures are too high. Microwaving is often regarded as one of the best methods for nutrient retention because it involves minimal water and shorter cooking times (Moyo, 2024).

5.4 Post-Cooking Handling and Storage

Even after cooking, nutrients remain vulnerable to degradation if foods are improperly stored or reheated (Gelaye et al., 2023). Exposure to air, light and heat can oxidize sensitive vitamins and minerals. Iodine, for example, can evaporate from fortified salt or iodine-rich foods during prolonged heating or if left uncovered. Selenium compounds such as selenomethionine can degrade under moist storage conditions or repeated reheating (Wang et al., 2023). Vitamin C is particularly unstable and oxidizes rapidly when cooked foods are left exposed to air or reheated multiple times.

Practical Approaches to Minimize Nutrient Loss

Several strategies can be adopted at the household or community level to minimize nutrient losses during food preparation and storage (Afriyie et al., 2023). Using minimal processing techniques that preserve the outer layers of grains and legumes helps maintain their natural micronutrient profile. Cooking methods such as steaming or sautéing are preferred over boiling, which leads to leaching of nutrients into water. Where boiling is necessary, using the cooking water in soups or broths can help retain leached nutrients. Fermentation and germination practices not only preserve nutrients but also enhance mineral absorption. Additionally, food should be stored in airtight containers and reheated only once especially if it contains heat-sensitive nutrients like vitamin C, selenium, or iodine.

Enhancers and inhibitors of nutrient absorption (e.g., phytates, vitamin C)

The bioavailability of nutrients particularly minerals like iron, zinc and calcium is not only determined by the amount present in food but also by the presence of dietary components that either promote or hinder their absorption. Understanding the role of these enhancers and inhibitors is crucial for designing diets that improve nutritional outcomes.

Enhancers of Nutrient Absorption

Certain substances naturally present in foods or added during preparation can enhance nutrient absorption (Vignesh et al., 2024). One of the most effective enhancers is vitamin C (ascorbic acid). It plays a key role in improving the absorption of non-heme iron from plant-based foods. Vitamin C reduces ferric iron (Fe^{3+}) to its more soluble ferrous form (Fe^{2+}), which is more easily absorbed in the small intestine. For instance, consuming citrus fruits, tomatoes or guava along with iron-rich vegetables like spinach or lentils significantly enhances iron uptake.

- Organic acids such as citric acid, malic acid and lactic acid which are naturally present in fruits and produced during fermentation also improve mineral bioavailability (Li et al., 2025). These acids help maintain a lower pH in the digestive tract, which keeps minerals soluble and readily available for absorption. Fermented foods like sourdough bread, pickles and yogurt have been shown to improve iron and zinc availability by reducing antinutritional factors.

- Animal proteins especially from meat and fish are known to enhance mineral absorption particularly for iron and zinc. This is sometimes referred to as the "meat factor," where peptides from animal protein improve the solubility and uptake of minerals from plant foods eaten in the same meal (Piskin et al., 2022).
- Prebiotic fibers such as inulin and fructooligosaccharides (FOS) improve the absorption of calcium and magnesium (Costa et al., 2021). These fibers are fermented in the colon, leading to the production of short-chain fatty acids that lower intestinal pH and promote mineral solubility.
- Vitamin D is another important enhancer that regulates calcium absorption (Fleet, 2022). It stimulates the production of calcium-binding proteins in the intestines, which actively transport calcium into the bloodstream. A diet that includes vitamin D through food or adequate sunlight exposure is essential for effective calcium utilization.

Inhibitors of Nutrient Absorption

On the other hand, several naturally occurring compounds in plant-based foods act as inhibitors of mineral absorption (Nath et al., 2022). One of the most prominent is phytic acid, found in whole grains, legumes, nuts and seeds. Phytates bind with minerals like iron, zinc, magnesium, and calcium, forming insoluble complexes that the body cannot absorb. In diets heavily based on cereals and legumes, the presence of phytates can significantly reduce mineral bioavailability. However, food preparation methods such as soaking, sprouting, fermenting and cooking can help break down phytates and improve nutrient absorption.

Tannins a type of polyphenol found in tea, coffee, some legumes and certain fruits also inhibit iron absorption by forming insoluble iron-tannin complexes. Consuming tea or coffee with meals has been shown to reduce iron absorption by up to 50%. Therefore, it is recommended to consume such beverages between meals, not alongside iron-rich foods.

Oxalates present in foods like spinach, beets and rhubarb inhibit calcium absorption by binding to calcium and forming insoluble calcium oxalate (Salgado et al., 2023). Even though spinach is high in calcium, only a small portion is bioavailable due to its high oxalate content.

Excess dietary fiber especially insoluble fiber can also limit nutrient absorption by speeding up intestinal transit and trapping nutrients in indigestible material (Ioniță-Mîndrican et al., 2022). While fiber is essential for gut health, balancing its intake is important to avoid negative effects on mineral uptake. Calcium-iron and calcium-zinc competition can occur when these minerals are taken in high doses simultaneously. They share similar absorption pathways in the intestine and excessive intake of one can hinder the absorption of the other.

6 Soil-Plant-Human Continuum

Limited availability and low concentration of micronutrients in daily food items are the primary causes of micronutrient deficiencies in humans. Various attempts to address and overcome these dietary deficiencies in humans have included the supplementation of products and the fortification of food with micronutrients (Yang et al., 2007). However, this approach to addressing micronutrient malnutrition has not been ideal due to its high cost and low coverage. Since the soil-plant system provides all of the nutrients that humans eat, biofortification; the process of making micronutrients denser and bioavailable in plant parts, has emerged as a novel strategy to address the issue of micronutrient shortages in the diet. This strategy has been shown to be long-lasting, reasonably priced, extremely effective, and widely applicable, particularly in the world's poorer nations (Welch & Graham, 2004). This chapter mainly focus on the micronutrient deficits in soils and people, along with the plant nutritional techniques that have been used to improve human micronutrient (Welch, 2002).

6.1 Nutrient flow and biological interactions:

The Soil–Plant–Human Continuum is fundamentally driven by the movement and transformation of nutrients through interconnected biological processes. Soil acts as the primary reservoir of essential elements such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients (e.g., iron, zinc, selenium), which are made available to plants through biogeochemical cycles mediated by soil microbes, root exudates, and organic matter decomposition (Smith et al., 2015). Healthy soils with active microbial communities facilitate the mineralization of organic matter, releasing nutrients in plant-available forms. Symbiotic associations, such as mycorrhizal fungi and rhizobia, enhance nutrient uptake efficiency by expanding root absorptive capacity and fixing atmospheric nitrogen in legumes, respectively (Van Der Heijden et al., 2008). The nutrient density of edible plant parts; grains, tubers, fruits, and leaves, depends not only on soil fertility but also on plant genotype, physiological traits, and environmental interactions. This is the stage where biofortification strategies, whether through conventional breeding or biotechnology, can enhance the concentration of target micronutrients (Bouis & Saltzman, 2017).

6.2 Influence of Soil Nutrient Availability on Nutrient Density in Food Crops

The availability of macro- and micronutrients in soil is a primary determinant of the nutritional composition of food crops. Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are essential for biomass production, reproductive growth, and metabolic activity, while micronutrients — including iron (Fe), zinc (Zn), selenium (Se), and iodine (I) — are critical for enzymatic functions, protein synthesis, and antioxidant defense systems in plants (Alloway, 2008). Deficiencies in these elements at the soil level directly limit their accumulation in edible plant parts, reducing the nutrient density of human diets dependent on those crops. For instance, low soil nitrogen often leads to reduced protein content in cereal grains, while inadequate soil zinc not only constrains yield but also lowers Zn concentration in harvested grains. Similarly, iron-deficient soils frequently result in lower Fe content in legumes, directly impacting populations where pulses are a major dietary iron source.

6.3 Global Decline in Nutrient Density Due to Soil Degradation

Over the past five decades, global datasets have shown a progressive decline in nutrient density in many staple crops, a trend often attributed to soil degradation, intensive monocropping, and reduced use of organic amendments (Fan et al., 2008). The depletion of soil organic matter, erosion, and acidification have diminished the bioavailability of key micronutrients. This effect is compounded by breeding programs historically focused on yield rather than nutrient concentration — the so-called “dilution effect” — where increases in carbohydrate-rich biomass are accompanied by lower concentrations of minerals and vitamins (White & Broadley, 2005). Globally, it is estimated that up to 50% of agricultural soils are deficient in zinc, and more than 30% are iron-deficient, particularly in South Asia and Sub-Saharan Africa (Sillanpää, 1990; Alloway, 2008). These soil nutrient limitations translate into widespread micronutrient malnutrition, also known as “hidden hunger,” in human populations.

6.4 Soil-to-Human Impact Examples

The iron content of legumes such as chickpea, lentil, and cowpea has been shown to vary significantly depending on the soil Fe status. In Fe-deficient calcareous soils, legumes can have up to 30–50% lower Fe concentrations compared to those grown in Fe-rich soils (Graham et al., 2001). This is critical in regions like South Asia, where legumes are a primary non-heme iron source for millions. Similarly, zinc in wheat-a major staple for 2.5 billion people is closely tied to soil Zn availability. Studies in Pakistan and India have shown that applying Zn-enriched fertilizers can increase grain Zn concentration by 20–40%, improving dietary Zn intake in rural populations. These examples highlight that soil nutrient management is not just an agronomic concern but a public health imperative, linking field-level interventions to the reduction of micronutrient deficiencies in humans.

6.5 Balanced Fertilization for Nutrient Bioavailability

Balanced fertilization ensures that essential macronutrients (e.g., N, P, K) and micronutrients (e.g., Zn, Fe, B) are applied in appropriate proportions and timing, aligned with crop needs, soil status, and environmental factors (Dobermann & Cassman, 2004). In contrast, imbalanced fertilization—such as excessive nitrogen without adequate micronutrient supplementation can lead to nutrient antagonisms, impairing the uptake of other vital elements and diminishing nutritional quality (Fageria, 2001).

Excessive application of nitrogen may result in higher biomass but lower concentration of micronutrients—a phenomenon often referred to as the yield–nutrient dilution effect (Jarrell & Beverly, 1981). Furthermore, high phosphorus levels can inhibit zinc uptake through the formation of insoluble phosphorus–zinc complexes in the soil. These imbalances not only reduce crop resilience and yield stability but also degrade the nutrient density of staple foods, with cascading effects on diet quality and human health.

6.6 Approaches to Optimize Nutrient Bioavailability

Integrated Nutrient Management (INM)

INM combines organic amendments (e.g., manure, compost), chemical fertilizers, and biofertilizers to enhance soil health, nutrient cycling, and crop productivity (Gruhn et al., 2000). For instance, a recent review highlighted that INM improved soil enzymatic activity and nutrient availability—resulting in higher tillering and yields in paddy systems (Vullaganti et al., 2025). Other long-term studies showed that combining 50% recommended chemical fertilizer rates with organic inputs yielded better results in maize and rice systems by boosting nutrient uptake and minimizing losses (Paramesh et al., 2023).

Site-Specific Nutrient Management (SSNM)

SSNM tailors nutrient applications to local field conditions by leveraging soil testing and digital decision-support tools. A recent 2025 review underscores its efficacy, especially when integrated with machine learning and precision agriculture techniques, to optimize fertilizer placement and enhance nutrient-use efficiency (Vullaganti et al., 2025).

Micronutrient Fertilizers & Agronomic Biofortification

Applying micronutrient fertilizers such as zinc or iron foliar sprays improves both yield and nutritional density of crops. A 2025 study on chickpea showed that optimized zinc treatments enhanced seed yield and protein content, while avoiding phytotoxicity at higher concentrations (Goodarzi et al., 2025).

Enhancing Nutrient Utilization in Pulses

A 2025 investigation on lentil varieties demonstrated that combining organic nutrients with INM practices improved nutrient use efficiency (IUE) for macro- and micronutrients like Zn and Fe. The study also identified more efficient cultivars (e.g., HM-1) with superior uptake and yield performance (Kumar et al., 2024.

7 Managing Soil Health to Combat Hidden Hunger

7.1 Soil Health and Nutrition Security

Soil health refers to the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans over the long term. In the context of food and nutrition security, soil health encompasses biological, chemical, and physical properties that influence nutrient cycling, water retention, and the bioavailability of essential macro- and micronutrients to crops. Healthy soils regulate the continuous supply of elements such as zinc (Zn), iron (Fe), selenium (Se), and iodine (I), which are critical to preventing "hidden hunger" — micronutrient deficiencies affecting over two billion people worldwide (FAO, 2022). Degraded soils, by contrast, have reduced organic matter, disrupted microbial activity, and limited nutrient reserves, directly lowering the nutritional quality of food crops.

7.2 Soil Health Restoration and Hidden Hunger

Restoring soil health can directly reverse hidden hunger trends by improving nutrient density in staple crops. For example, zinc fertilization in degraded soils of South Asia has been shown to increase grain Zn content in wheat by 30–40%, improving dietary intake for rural populations (Joy et al., 2015). Similarly, legume–cereal rotations on restored soils in Sub-Saharan Africa significantly improved iron content in beans, addressing iron-deficiency anemia in vulnerable communities (Haas et al., 2022). By sustaining nutrient-rich crop production without depleting soil resources, soil health interventions align with both sustainable agriculture goals (SDG 2) and public health targets.

8 Strategies to Integrate Soil-Plant-Human Approaches into Food Systems

8.1 Policy & Research Pathways to Embed Soil into Nutrition Strategy

Policy pathways

- Explicitly include soil quality metrics in national nutrition plans. Add soil health indicators (soil organic carbon, pH, plant-available Zn, Fe) to public nutrition and food-security monitoring frameworks so interventions can be targeted where nutrient gaps originate in the soil.
- Link agricultural subsidies to balanced fertilization and soil restoration. Redirect subsidy and input-support programmes to favour integrated

packages (INM + micronutrient fertilizers + soil carbon building) rather than unconditional N-only subsidies.

- Strengthen regulatory & procurement levers. Use public procurement (school feeding, food assistance) to prioritise nutrient-dense crops and fortified commodities sourced from producers practicing soil-sensitive management.
- Incentivize data sharing and cross-sector governance. Create institutional mechanisms (agriculture + health + environment) for shared soil–nutrition data, co-funded programs, and joint monitoring.

Research pathways

- Operational research on soil → crop → diet transfer functions. Fund longitudinal, site-specific studies quantifying how changes in soil properties (e.g., Zn availability, SOC, pH) alter crop nutrient concentration and, ultimately, human intakes.
- Intervention trials combining agronomy and nutrition outcomes. Design randomized or quasi-experimental trials that measure agronomic outcomes (yield, nutrient concentration) and nutritional endpoints (biomarkers, dietary intake) simultaneously.
- Precision decision-support tools. Develop and validate decision tools (mobile apps, remote sensing + soil testing platforms) that recommend balanced nutrient inputs for both yield and nutrient density.
- Socioeconomic and supply-chain studies. Research barriers to adoption (costs, market access, knowledge) and pathways to scale agronomic biofortification and fortification in smallholder value chains.

8.2 Farm-level Integration

A practical implementation sequence for extension programs

1. Baseline mapping & targeted soil testing
   - Rapid soil tests (Zn, pH, organic matter) + geospatial sampling identify hotspots of micronutrient deficiency and prioritize interventions at landscape scale.
2. Site-specific recommendations
   - Use SSNM: tailor fertilizer mixes (N,P,K + Zn/Fe/B) and organic amendments (manure, compost) to local soil tests and crop needs. Emphasize timing (split N, foliar micronutrients) to maximize uptake.
3. Adopt INM & conservation practices
   - Combine judicious inorganic fertilizer use with organic matter inputs, cover crops, no- or low-till, and rotations (legume inclusion) to rebuild soil biological activity and maintain micronutrient availability.

4. Promote agronomic biofortification
   - Apply micronutrient fertilizers (soil application or foliar sprays) on target staples (wheat, rice, maize) and pulses to raise grain Zn/Fe; pair with cultivar selection (biofortified varieties where available).
5. Link production to processing & fortification
   - Facilitate value-chain linkages so nutrient-dense raw commodities enter processing streams for minimal nutrient loss and, where appropriate, are further strengthened through commercial food fortification (e.g., flour with iron, oil with vitamin A).
6. Food-based diversification & behaviour change
   - Support intercropping, home gardens, legumes and nutrient-rich crops alongside staples; couple with nutrition education to increase demand for nutrient-dense foods.
7. Monitoring & feedback
   - Track soil indicators, crop nutrient concentration, and household dietary indicators (e.g., consumption surveys, basic biomarkers) to adapt recommendations.

9 Approaches to Crop Fortification

9.1 Biofortification through conventional breeding

Conventional breeding has emerged as a widely adopted and cost-efficient strategy for crop biofortification, as it offers a pragmatic and broadly accepted alternative to transgenic approaches (Zulfiqar et al., 2024a,b). The effectiveness of biofortification depends on the availability of sufficient genetic variation, that allows the breeders to exploit naturally occurring diversity to improve the concentration of essential nutrients.

In biofortification, plant breeding is employed to improve the micronutrient concentration of staple food crops, particularly benefiting low-income communities as well as people living in remote areas and do not have reach of diversified foods (Rao et al. 2020). Numerous agronomic crops have been successfully targeted for biofortification through breeding programs because of their wide acceptance (Korram et al. 2022). Such a system of biofortified crops is considered highly sustainable, as nutritionally enriched varieties can continue to be cultivated and consumed across generations, even when governmental or international support for micronutrient-related initiatives diminishes (Nestel et al. 2006; Priyashantha et al. 2025).

9.2 Agronomic biofortification (fertilizer-based interventions)

Agronomic biofortification is a practical approach to enhancing the nutritional quality of crops through soil amendments and fertilizer applications, either via soil incorporation or foliar spraying (Koç et al. 2022; Ishfaq, 2025).

Once applied, the desired nutrients are absorbed and mobilized/translocated within the plant, ultimately reaching source and sink organs (Bhat et al. 2024). Agronomic biofortification has been widely studied in cereals and legumes and is considered one of the fastest and most economical means of addressing micronutrient deficiencies, particularly for elements such as Fe, Zn, iodine, and Se (Hotegni et al. 2024; Rehman et al. 2025). However, its impact is often short-lived, as fertilizers must be reapplied each season, and the minerals supplied are not always efficiently translocated to edible plant parts like seeds and fruits (Consentino et al. 2023), Although, it is a short term approach, but successfully adopted by the farming community (Ofori et al. 2022). Some recent researches revealed that the efficiency of foliar Se application in improving the grain Se concentration in beans and corn (Ngigi et al. 2019). Basal applied Se as sodium selenate improved the grain Se concentration by 3 and 10 µg kg^{-1} in corn and beans, respectively, whereas foliar Se fertilization enhanced the grain Se concentration by 18 and 67 µg kg^{-1} in corn and beans, respectively. In addition, a integrative application of Se as soil application and foliage application Se at stem elongation stage and tillering + stem elongation stages enhanced the grain Se accumulation in wheat to 0.615 and 0.719 mg kg^{-1} seed (Radawiec et al., 2021).

9.3 Transgenic approaches

The effectiveness of conventional biofortification through plant breeding is often constrained by limited genetic diversity, as this approach depends heavily on existing variability (Dhaliwal et al. 2022). For staple crops such as rice and bananas, which lack sufficient genetic variation, transgenic technology has emerged as a powerful alternative (Malik and Maqbool, 2020). It is quite different from traditional breeding, as it enables the direct incorporation of desirable genes to enhance nutritional quality or agronomic performance in targeted genotypes (Alamir et al. 2025. Through such transgenic interventions, biotechnology and breeding concepts are integrated to introduce novel traits, often through the integration of transgenes from bacteria, fungi, or other organisms. For example, fluorescent Pseudomonas can improve Fe uptake, while mycorrhizal fungi and rhizobacteria promote nutrient acquisition and plant growth. Similarly, bacterial and Aspergillus genes have been employed to modify phytate and lysine content in wheat and rice.

Beyond microbial applications, biotechnology has produced transgenic crops such as Golden Rice, enriched with beta-carotene to alleviate Vitamin A deficiency. Comparable strategies have been applied to increase Fe and Zn content in crops, addressing common dietary deficiencies in developing regions. Transgenic methods also allow the simultaneous insertion of multiple genes, thereby boosting micronutrient concentration and bioavailability while suppressing antinutritional factors that hinder nutrient use (Garg et al. 2018;

Rehan and Singh, 2020; Duraiswamy et al. 2023). In addition to micronutrient enhancement, transgenic tools improve crop quality by extending shelf life, reducing allergenic compounds, improving taste, and generating functional proteins, fibers, and lipids (Brinch-Pedersen et al. 2007; Zhu et al. 2007).

10 Challenges and Opportunities

10.1 Limitations of biofortification and fertilizer strategies

Genetic and conventional biofortification remain foundational but face practical limits that shape how quickly nutrientdense staples reach households. Breeding pipelines require multiyear selection and testing, followed by seed multiplication and distribution, so even wellproven traits can take time to translate into farmer adoption (Bouis & Saltzman, 2017).

Agronomic biofortification, fertilizerbased strategies that raise plant uptake of limiting micronutrients faces its own constraints. In high pH or calcareous soils, Zn and Fe precipitate or sorb strongly, while in flooded rice Zn can become immobilized; in acid soils, Al toxicity and P fixation complicate responses (Alloway, 2008). Nutrient interactions matter: high P can depress Zn uptake; excessive K can affect Mg and Ca; sulfate can compete with Se; and nitrate versus ammonium shifts rhizosphere pH and solubility (Gui et al., 2022; Singh et al., 2024).

10.2 Climate change implications for crop nutrition

Climate drivers alter both soil processes and plant physiology in ways that threaten the nutrient density of staple crops. Elevated CO_2 particularly in C3 cereals tends to reduce grain protein, Zn and Fe through carbon dilution, even where yields hold steady (White & Broadley, 2005; Dhaliwal et al., 2022). Heat and drought shorten grain filling, impair root growth, and reduce N uptake and assimilation, while flooding and waterlogging shift redox conditions, increasing Fe and Mn solubility but immobilizing Zn and risking sulfide toxicity (Rai et al., 2021). Salinity disrupts K^+ homeostasis and Ca/Mg balance through Na^+/Cl^- competition, and extremes accelerate erosion, denitrification, and volatilization losses, undermining both productivity and nutrition outcomes (FAO, 2022). Strategic responses emphasize stability and responsiveness. On the genetic side, selecting lines whose micronutrient density remains stable across stress and soils is key (Bouis & Saltzman, 2017). On the management side, weatherinformed fertigation, split N and S, use of urease/nitrification inhibitors, and stresstimed foliar applications of Zn/Fe/Se can help maintain uptake during critical stages (Cakmak, 2008). Root and rhizosphereoriented practices deeper rooting, mycorrhizafriendly management, organic inputs that enhance exudation and micronutrient mobilization expand access to immobile nutrients. Soilhealth buffers such as cover crops, residue retention, compost/

manure, and liming where needed stabilize availability and water holding capacity (Blanco-Canqui et al., 2022). Because variability raises financial risk, pairing agronomic advice with index insurance can protect adoption.

11 Conclusion

Hidden hunger persists because production systems have prioritized calories over micronutrient density and because soil constraints, processing losses, and market signals often erode the gains that breeding and agronomy can deliver. The evidence assembled in this chapter shows that biofortification and agronomic fortification are complementary levers along a single pathway from genotype to plate. Genetic approaches raise the ceiling for nutrient density but are sensitive to G×E×M interactions and to post-harvest retention; agronomic strategies can close the gap between potential and realized nutrition by overcoming soil chemistry barriers, synchronizing nutrient supply with demand, and preserving nutrients through harvest and processing. Soil health and diagnostics sit at the core of this continuum: when farmers and advisors can identify limiting factors and act at the right time and place, improvements in plant uptake translate into measurable gains in grain Fe, Zn, Se, and protein, with meaningful implications for diets. Accelerating progress requires integrated, inclusive delivery. Breeding pipelines must focus on micronutrientdense, climateresilient cultivars with farmerpreferred quality traits and be linked to rapid seed multiplication. Site-specific nutrient management guided by soil, leaf, and grain testing and translated through digital advisories should be scaled alongside qualityassured, fortified fertilizers and last-mile distribution that reaches women and youth as primary decisionmakers. Public policy can create durable demand by embedding nutrition criteria in procurement for schools and safety nets, enforcing standards for fortified fertilizers, and supporting affordable finance and risktransfer tools. Finally, monitoring must track what matters: not only yields, but nutrient outcomes and bioavailability proxies, with open data to target interventions ethically and efficiently. With these elements connected the genotype, the field, the market, and the plate nutrientdense staples can become the default option, advancing global food security through sustainable nutrition.

References

Afriyie, E., Zurek, M., Asem, F. E., Okpattah, B., Ahiakpa, J. K., & Zhu, Y. G. (2023). Consumer food storage practices and methods at the household-level: A community study in Ghana. *Frontiers in Sustainable Food Systems, 7,* 1194321. https://doi.org/10.3389/fsufs.2023.1194321

Ahmed, N., Zhang, B., Chachar, Z., Li, J., Xiao, G., Wang, Q., Hayat, F., Deng, L., Narejo, M. U. N., Bozdar, B., & Tu, P. (2024). Micronutrients and their effects on horticultural crop quality, productivity and sustainability. *Scientia Horticulturae, 323,* 112512. https://doi.org/10.1016/j.scienta.2023.112512.

Alamir, S. G. (2025). The interplay of selenium and human health. *Journal of Nutritional Biochemistry, 120,* 109349. https://doi.org/10.1016/j.jnutbio.2024.109349

Alloway, B. J. (2008). *Zinc in soils and crop nutrition.* International Zinc Association.

Anifantaki, F., Pervanidou, P., Lambrinoudaki, I., Panoulis, K., Vlahos, N., & Eleftheriades, M. (2021). Maternal prenatal stress, thyroid function and neurodevelopment of the offspring: A mini review of the literature. *Frontiers in Neuroscience, 15,* 692446. https://doi.org/10.3389/fnins.2021.692446

Awuchi, C. G., Igwe, V. S., & Amagwula, I. O. (2020). Nutritional diseases and nutrient toxicities: A systematic review of the diets and nutrition for prevention and treatment. *International Journal of Advanced Research, 6*(1), 1–46.

Bai, S., Zhang, M., Tang, S., Li, M., Wu, R., Wan, S., Chen, L., Wei, X., & Feng, S. (2024). Effects and impact of selenium on human health: A review. *Molecules, 30*(1), 50. https://doi.org/10.3390/molecules30010050

Bailey, R. L., West, K. P., & Black, R. E. (2015). The epidemiology of global micronutrient deficiencies. *Annals of Nutrition and Metabolism, 66*(Suppl. 2), 22–33. https://doi.org/10.1159/000371618.

Bandehagh, A., Dehghanian, Z., Gougerdchi, V., & Hossain, M. (2023). Selenium: A game changer in plant development, growth, and stress tolerance via the modulation in gene expression and secondary metabolite biosynthesis. *Phyton, 92*(8), 2301. https://doi.org/10.32604/phyton.2023.029441

Bhat, M. A., Mishra, A. K., Shah, S. N., Bhat, M. A., Jan, S., Rahman, S., Baek, K. H., & Jan, A. T. (2024). Soil and mineral nutrients in plant health: A prospective study of iron and phosphorus in the growth and development of plants. *Current Issues in Molecular Biology, 46*(6), 5194–5222. https://doi.org/10.3390/cimb46060265

Białowąs, W., Blicharska, E., & Drabik, K. (2024). Biofortification of plant- and animal-based foods in limiting the problem of microelement deficiencies—A narrative review. *Nutrients, 16*(10), 1481. https://doi.org/10.3390/nu16101481.

Blanco-Canqui, H., et al. (2022). Cover crops for sustainable agriculture: Influence on soil properties, nutrients, and crop yields. *Agronomy Journal, 114*(1), 1–19. https://doi.org/10.1002/agj2.20873.

Bouis, H. E., & Saltzman, A. (2017). Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. *Global Food Security, 12,* 49–58. https://doi.org/10.1016/j.gfs.2017.01.009.

Brinch-Pedersen, H., Borg, S., Tauris, B., & Holm, P. B. (2007). Molecular genetic approaches to increasing mineral availability and vitamin content of cereals. *Journal of Cereal Science, 46*(3), 308–326. https://doi.org/10.1016/j.jcs.2007.03.006.

Brueck, H., & Lammel, J. (2016). Impact of fertilizer N application on the grey water footprint of winter wheat in a NW-European temperate climate. *Water, 8*(9), 356. https://doi.org/10.3390/w8090356.

Callens, T., del Castello, R., Baratelli, M., Xipsiti, M., & Navarro, D. K. (2019). *The International Year of Pulses: Final report.* Food and Agriculture Organization of the United Nations.

Caradus, J. R., Chapman, D. F., & Rowarth, J. S. (2024). Improving human diets and welfare through using herbivore-based foods: 1. Human and animal perspectives. *Animals, 14*(7), 1077. https://doi.org/10.3390/ani14071077.

Choudhary, M., Garg, K., Reddy, M. B., Meena, B. L., Mondal, B., Tuti, M. D., Kumar, S., Awasthi, M. K., Giri, B. S., Kumar, S., & Rajawat, M. V. S. (2024). Unlocking growth potential: Synergistic potassium fertilization for enhanced yield, nutrient uptake, and energy fractions in Chinese cabbage. *Heliyon, 10*(7), e25678. https://doi.org/10.1016/j.heliyon.2024.e25678.

Consentino, B. B., Ciriello, M., Sabatino, L., Vultaggio, L., Baldassano, S., Vasto, S., Rouphael, Y., La Bella, S., & De Pascale, S. (2023). Current acquaintance on agronomic biofortification to modulate the yield and functional value of vegetable crops: A review. *Horticulturae, 9*(2), 219. https://doi.org/10.3390/horticulturae9020219.

Costa, G. T., Vasconcelos, Q. D. J. S., Abreu, G. C., Albuquerque, A. O., Vilar, J. L., & Aragão, G. F. (2021). Systematic review of the ingestion of fructooligosaccharides on the absorption of minerals and trace elements versus control groups. *Clinical Nutrition ESPEN, 41,* 68–76. https://doi.org/10.1016/j.clnesp.2020.12.005.

Dhaliwal, S. S., Sharma, V., Shukla, A. K., Verma, V., Kaur, M., Shivay, Y. S., ... & Hossain, A. (2022). Biofortification—A frontier novel approach to enrich micronutrients in field crops to encounter the nutritional security. *Molecules, 27*(4), 1340. https://doi.org/10.3390/molecules27041340.

Dobermann, A., & Cassman, K. G. (2004). Environmental dimensions of fertilizer nitrogen: What can be done to increase nitrogen use efficiency and ensure global food security. In A. R. Mosier, J. K. Syers, & J. R. Freney (Eds.), *Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on food production and the environment* (pp. 261–278). Island Press.

Duraiswamy, A., Sneha, A. N. M., Jebakani, K. S., Selvaraj, S., Pramitha, J. L., Selvaraj, R., Petchiammal, K. I., Kather Sheriff, S., Thinakaran, J., Rathinamoorthy, S., & Kumar, P. R. (2023). Genetic manipulation of anti-nutritional factors in major crops for a sustainable diet in future. *Frontiers in Plant Science, 13,* 1070398. https://doi.org/10.3389/fpls.2022.1070398

Fageria, V. D. (2001). Nutrient interactions in crop plants. *Journal of Plant Nutrition, 24*(8), 1269–1290. https://doi.org/10.1081/PLN-100106981.

Fan, M. S., Zhao, F. J., Fairweather-Tait, S. J., Poulton, P. R., Dunham, S. J., & McGrath, S. P. (2008). Evidence of decreasing mineral density in wheat grain over the last 160 years. *Journal of Trace Elements in Medicine and Biology, 22*(4), 315–324. https://doi.org/10.1016/j.jtemb.2008.07.002.

FAO. (2022). *The state of food security and nutrition in the world 2022.* Food and Agriculture Organization of the United Nations.

Fleet, J. C. (2022). Vitamin D-mediated regulation of intestinal calcium absorption. *Nutrients, 14*(16), 3351. https://doi.org/10.3390/nu14163351.

Garg, M., Sharma, N., Sharma, S., Kapoor, P., Kumar, A., Chunduri, V., & Arora, P. (2018). Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. *Frontiers in Nutrition, 5,* 12. https://doi.org/10.3389/fnut.2018.00012.

Gelaye, Y. (2023). Quality and nutrient loss in cooking vegetables and its implications for food and nutrition security in Ethiopia: A review. *Nutrition and Dietary Supplements, 15,* 47–61. https://doi.org/10.2147/NDS.S399911.

Goodarzi, S., Tavanmand, A., & Shajari, H. (2025). Effect of different concentration and application method of zinc on yield of chickpea (*Pisum sativum* L.). *arXiv preprint,* arXiv:2505.23855.

Graham, R. D., Welch, R. M., & Bouis, H. E. (2001). Addressing micronutrient malnutrition through enhancing the nutritional quality of staple foods: Principles, perspectives and knowledge gaps. *Advances in Agronomy, 70,* 77–142. https://doi.org/10.1016/S0065-2113(01)70004-1.

Gruhn, P., Goletti, F., & Yudelman, M. (2000). *Integrated nutrient management, soil fertility, and sustainable agriculture: Current issues and future challenges.* International Food Policy Research Institute.

Gui, J. Y., Rao, S., Huang, X., Liu, X., Cheng, S., & Xu, F. (2022). Interaction between selenium and essential micronutrient elements in plants: A systematic review. *Science of the Total Environment, 853,* 158673. https://doi.org/10.1016/j.scitotenv.2022.158673.

Haas, J. D., Bechoff, A., Lividini, K., Pfeiffer, W. H., & Murray-Kolb, L. E. (2022). Soil restoration and iron bioavailability in African legumes. *Frontiers in Sustainable Food Systems, 6,* 865732. https://doi.org/10.3389/fsufs.2022.865732.

Hotegni, N. V. F., Sohindji, F. S., Salaou, M. A., Agbandou, P. C., Azonhoumon, L. W., Tchokponhoué, D., Houdegbe, C., Adjé, C. A., & Achigan-Dako, E. G. (2024). Agronomic biofortification of cereals and legumes with iron, zinc, calcium and magnesium for food and nutrition security: Available options for farmers in Sub-Saharan Africa. *Journal of Agriculture and Food Research, 18,* 101391. https://doi.org/10.1016/j.jafr.2024.101391.

Huang, S., Wang, P., Yamaji, N., & Ma, J. F. (2020). Plant nutrition for human nutrition: Hints from rice research and future perspectives. *Molecular Plant, 13*(6), 825–835. https://doi.org/10.1016/j.molp.2020.05.007

Huey, S. L., Konieczynski, E. M., Mehta, N. H., Krisher, J. T., Bhargava, A., Friesen, V. M., Mbuya, M. N., Monterrosa, E. C., Nyangaresi, A. M., & Mehta, S. (2023). A systematic review of the impacts of post-harvest handling on provitamin A, iron and zinc retention in seven biofortified crops. *Nature Food, 4*(11), 978–985. https://doi.org/10.1038/s43016-023-00881-3.

Ioniță-Mîndrican, C. B., Ziani, K., Mititelu, M., Oprea, E., Neacșu, S. M., Moroșan, E., Dumitrescu, D. E., Roșca, A. C., Drăgănescu, D., & Negrei, C. (2022). Therapeutic benefits and dietary restrictions of fiber intake: A state of the art review. *Nutrients, 14*(13), 2641. https://doi.org/10.3390/nu14132641

Ishfaq, M., 2025. Beyond Biofortification: Rethinking Iron Nutrition in Crops Through Phosphorus-Limited Adaptation. Plant, Cell & Environment. https://doi.org/10.1111/pce.70104.

Jarrell, W. M., & Beverly, R. B. (1981). The dilution effect in plant nutrition studies. *Advances in Agronomy, 34,* 197–224. https://doi.org/10.1016/S0065-2113(08)60887-1.

Joy, E. J. M., Stein, A. J., Young, S. D., Ander, E. L., Watts, M. J., & Broadley, M. R. (2015). Soil type influences crop mineral composition in Malawi. *Scientific Reports, 5,* 10982. https://doi.org/10.1038/srep10982.

Kiani, A.K., Dhuli, K., Donato, K., Aquilanti, B., Velluti, V., Matera, G. and Bertelli, M. (2022). Main nutritional deficiencies. *Journal of Preventive Medicine and Hygiene*, 63(2): E93.

Koç, E., Karayiğit, B. Assessment of Biofortification Approaches Used to Improve Micronutrient-Dense Plants That Are a Sustainable Solution to Combat Hidden Hunger. J Soil Sci Plant Nutr 22, 475–500 (2022). https://doi.org/10.1007/s42729-021-00663-1.

Korram G, Samadhiya VK, Bhagat AS, Pradhan AK. Assessment on quality parameters (protein, carbohydrate, hulling, milling and HRR) of traditional short grain aromatic rice, high yielding scented rice and fortified rice under organic farming. Pharma Innov J. (2022) 11:1792–4.

Kowalska, G., Kowalski, R., Hawlena, J. and Rowiński, R. (2020). Seeds of oilseed rape as an alternative source of protein and minerals. *Journal of Elementology*, 25(2), 513–522.

Kumar, B. and Ram, H. (2021). Biofortification of maize fodder with zinc improves forage productivity and nutritive value for livestock. *Journal of Animal and Feed Sciences*, 30(2): 149-158.

Kumar, J., Saini, D.K., Kumar, A., Kumari, S., Gahlaut, V., Rahim, M.S., Pandey, A.K., Garg, M. and Roy, J., 2024. Biofortification of Triticum species: a stepping stone to combat malnutrition. BMC Plant Biology, 24(1), p.668.

Liu, H.M. and Li, H.Y. (2017). Application and conversion of soybean hulls. In: *Soybean-the basis of yield, biomass and productivity*, pp.111-132. IntechOpen Publishers, London, UK.

Lowe, N.M. (2021). The global challenge of hidden hunger: perspectives from the field. *Proceedings of the Nutrition Society*, 80(3): 283-289.

Malik KA, Maqbool A. Transgenic crops for biofortification. Front Sust Food Syst. 2020;4: 571402.

Moyo, H. N. (2024). The Impact of Food Processing Techniques on Nutrient Retention and Bioavailability. *International Research Journal of Engineering and Technology.*

Naik, B., Kumar, V., Rizwanuddin, S., Mishra, S., Kumar, V., Saris, P. E. J., ... & Rustagi, S. (2024). Biofortification as a solution for addressing nutrient deficiencies and malnutrition. *Heliyon, 10*(9), e23645. https://doi.org/10.1016/j.heliyon.2024.e23645.

Nasir, J., Kousar, R., Nasir, B., Bashir, M. K., Rakha, A., & Pasha, I. (2025). Integrating agriculture for nutrition in Pakistan: A critical review of policy and strategic interventions. *Policy Journal of Social Science Review, 3*(7), 127–134.

Nath, H., Samtiya, M., & Dhewa, T. (2022). Beneficial attributes and adverse effects of major plant-based foods anti-nutrients on health: A review. *Human Nutrition & Metabolism, 28,* 200147. https://doi.org/10.1016/j.hnm.2022.200147.

Nestel, P., Bouis, H. E., Meenakshi, J. V., & Pfeiffer, W. (2006). Biofortification of staple food crops. *The Journal of Nutrition, 136*(4), 1064–1067. https://doi.org/10.1093/jn/136.4.1064.

Ngigi, P. B., Lachat, C., Masinde, P. W., & Du Laing, G. (2019). Agronomic biofortification of maize and beans in Kenya through selenium fertilization. *Environmental Geochemistry and Health, 41*(6), 2577–2591. https://doi.org/10.1007/s10653-019-00256-y.

Ofori, K. F., Antoniello, S., English, M. M., & Aryee, A. N. A. (2022). Improving nutrition through biofortification: A systematic review. *Frontiers in Nutrition, 9,* 1043655. https://doi.org/10.3389/fnut.2022.1043655.

Paramesh, V., Mohan Kumar, R., Rajanna, G. A., Gowda, S., Nath, A. J., Madival, Y., ... & Toraskar, S. (2023). Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Frontiers in Sustainable Food Systems, 7,* 1173258. https://doi.org/10.3389/fsufs.2023.1173258.

Pasricha, S. R., Tye-Din, J., Muckenthaler, M. U., & Swinkels, D. W. (2021). Iron deficiency. *The Lancet, 397*(10270), 233–248. https://doi.org/10.1016/S0140-6736(20)32594-0

Piskin, E., Cianciosi, D., Gulec, S., Tomas, M., & Capanoglu, E. (2022). Iron absorption: Factors, limitations, and improvement methods. *ACS Omega, 7*(24), 20441–20456. https://doi.org/10.1021/acsomega.2c01759.

Priyashantha, H., Kurukulasuriya, M. S., Ranadheera, C. S., Jayarathna, S., & Vidanarachchi, J. K. (2025). Biofortification as a sustainable solution to combat micronutrient malnutrition in the global south with a focus on Sri Lanka: Potential, challenges, and policy implications. *Discover Food, 5,* 126. https://doi.org/10.1007/s44187-025-000126-1.

Radawiec, A., Szulc, W., & Rutkowska, B. (2021). Selenium biofortification of wheat as a strategy to improve human nutrition. *Agriculture, 11*(2), 144. https://doi.org/10.3390/agriculture11020144.

Rai, S., Singh, P. K., Mankotia, S., Swain, J., & Satbhai, S. B. (2021). Iron homeostasis in plants and its crosstalk with copper, zinc, and manganese. *Plant Stress, 1,* 100008. https://doi.org/10.1016/j.stress.2021.100008.

Razzak, A., Mahjabin, T., Khan, M. R. M., Hossain, M., Sadia, U., & Zzaman, W. (2023). Effect of cooking methods on the nutritional quality of selected vegetables at Sylhet City. *Heliyon, 9*(11), e17149. https://doi.org/10.1016/j.heliyon.2023.e17149.

Rehan, S. A., & Singh, P. (2020). Biofortification: Enriching vegetable crops with nutrients to reduce global hunger. *International Journal of Current Microbiology and Applied Sciences, 11,* 2499–2511. https://doi.org/10.20546/ijcmas.2020.1106.295.

Rehman, R., Latif, M. M., Khan, M. A., & Ahmed, Z. (2025). Agronomic biofortification of crops with zinc: A comprehensive overview. In M. Govindaraj, V. Govindan, & N. Palacios (Eds.), *Breeding zinc crops for better human health* (pp. 233–254). Springer. https://doi.org/10.1007/978-3-031-49790-2_12.

Robinson, G. H. J., Balk, J., & Domoney, C. (2019). Improving pulse crops as a source of protein, starch and micronutrients. *Nutrition Bulletin, 44*(3), 202–215. https://doi.org/10.1111/nbu.12385.

Rosa-Sibakov, N., Poutanen, K., & Micard, V. (2015). How does wheat grain, bran and aleurone structure impact their nutritional and technological properties? *Trends in Food Science & Technology, 41*(2), 118–134. https://doi.org/10.1016/j.tifs.2014.10.003

Saleem, M. A., Iqbal, A., Gull, U., & Iqbal, M. (2025). Fodder quality, morphological and biochemical characteristics of Mombasa grass (*Megathyrsus maximus*) under differently primed seeds. *Journal of Crop Health, 77*(3), 90. https://doi.org/10.1007/s10343-025-01162-4.

Saleem, M. A., Tahir, M., Ahmad, T., & Tahir, M. N. (2020). Foliar application of boron improved the yield and quality of wheat (*Triticum aestivum* L.) in a calcareous field. *Soil & Environment*, *39*(1).

Salgado, N., Silva, M. A., Figueira, M. E., Costa, H. S., & Albuquerque, T. G. (2023). Oxalate in foods: extraction conditions, analytical methods, occurrence, and health implications. *Foods*, 12(17): 3201.

Sandhu, R., Chaudhary, N., Shams, R., Singh, K., & Pandey, V. K. (2023). A critical review on integrating biofortification in crops for sustainable agricultural development and nutritional security. *Journal of Agriculture and Food Research, 14,* 100830. https://doi.org/10.1016/j.jafr.2023.100830.

Sangeetha, V. J., Dutta, S., Moses, J. A., & Anandharamakrishnan, C. (2022). Zinc nutrition and human health: Overview and implications. *Efood, 3*(5), e17. https://doi.org/10.1002/efd2.17

Sanjeeva Rao, D., Neeraja, C. N., Madhu Babu, P., Nirmala, B., Suman, K., Rao, L. S., Surekha, K., Raghu, P., Longvah, T., Surendra, P., & Kumar, R. (2020). Zinc biofortified rice varieties: Challenges, possibilities, and progress in India. *Frontiers in Nutrition, 7,* 26. https://doi.org/10.3389/fnut.2020.00026.

Shulhai, A. M., Rotondo, R., Petraroli, M., Patianna, V., Predieri, B., Iughetti, L., Esposito, S., & Street, M. E. (2024). The role of nutrition on thyroid function. *Nutrients, 16*(15), 2496. https://doi.org/10.3390/nu16152496

Sillanpää, M. (1990). *Micronutrient assessment at the country level: An international study* (No. 63). Food and Agriculture Organization of the United Nations.

Simsek, F., Inan, S., & Korkmaz, M. (2019). An in vitro study in which new boron derivatives may be an option for breast cancer treatment. *Eurasian Journal of Medicine and Oncology, 3*(1), 22–27. https://doi.org/10.14744/ejmo.2019.56981

Singh, C., Singh, B. H., Satpal, P. K., Manoj, A., Gora, K., & Kumar, A. (2019). Micronutrient management for enhancing production of major fodder crops: A review. *Forage Research, 45*(2), 95–102.

Singh, K., Gupta, S., & Singh, A. P. (2024). Nutrient–nutrient interactions governing underground plant adaptation strategies in a heterogeneous environment. *Plant Science, 342,* 112024. https://doi.org/10.1016/j.plantsci.2024.112024.

Smith, P., Cotrufo, M., Rumpel, C., Paustian, K., Kuikman, P., Elliott, J., McDowell, R., Griffiths, R., Asakawa, S., & Bustamante, M. (2015). Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *Soil, 1*(2), 665–685. https://doi.org/10.5194/soil-1-665-2015.

Şonea, C., Gheorghe-Irimia, R. A., Tăpăloagă, D., & Tăpăloagă, P. R. (2023). Nutrition and animal agriculture in the 21st century: A review of future prospects. *Annals of the University of Craiova – Agriculture, Montanology, Cadastre Series, 53*(1), 303–312.

Sun, D., Codling, K., Chang, S., Zhang, S., Shen, H., Su, X. and Yan, J. (2017). Eliminating iodine deficiency in China: achievements, challenges and global implications. *Nutrients*, 9(4): 361.

Száková, J., Praus, L., Tremlová, J., Kulhánek, M., & Tlustoš, P. (2017). Efficiency of foliar selenium application on oilseed rape (*Brassica napus* L.) as influenced by rainfall and soil characteristics. *Archives of Agronomy and Soil Science, 63*(9), 1240–1254. https://doi.org/10.1080/03650340.2016.1275984.

Tummolo, A., Carella, R., De Giovanni, D., Paterno, G., Simonetti, S., Tolomeo, M., ... & Barile, M. (2023). Micronutrient deficiency in inherited metabolic disorders requiring diet regimen: A brief critical review. *International Journal of Molecular Sciences, 24*(23), 17024. https://doi.org/10.3390/ijms242317024.

Van Der Heijden, M. G., Bardgett, R. D., & Van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecology Letters, 11*(3), 296–310. https://doi.org/10.1111/j.1461-0248.2007.01139.x.

Vignesh, A., Amal, T. C., Sarvalingam, A., & Vasanth, K. (2024). A review on the influence of nutraceuticals and functional foods on health. *Food Chemistry Advances, 5,* 100749. https://doi.org/10.1016/j.focha.2023.100749.

Vullaganti, N., Ram, B. G., & Sun, X. (2025). Precision agriculture technologies for soil site-specific nutrient management: A comprehensive review. *Artificial Intelligence in Agriculture, 9,* 55–71. https://doi.org/10.1016/j.aiia.2025.03.004.

Wagh, D., Kanase, S., Balid, A., Fulari, S., Bhosale, A., Wadkar, S., ... & Walekar, S. (2024). A brief review on anemia. *International Journal of Scientific Research and Technology, 1*(12), 435–447.

Wang, P., Li, Y., Yu, R., Huang, D., Chen, S., & Zhu, S. (2023). Effects of different drying methods on the selenium bioaccessibility and antioxidant activity of *Cardamine violifolia*. *Foods, 12*(4), 758. https://doi.org/10.3390/foods12040758.

Weaver, C., Armah, S., Bruno, R. S., Fletcher, A., Glahn, R., Herter-Aeberli, I., Karosas, T., Loechl, C. U., Lopez-Teros, V., McBurney, M. I., & Melse-Boonstra, A. (2025). Perspective: Framework for developing prediction equations for estimating the absorption and bioavailability of nutrients from foods. *Advances in Nutrition, 16*(1), 100481. https://doi.org/10.1093/advances/nmae133.

Welch, R. M. (2002). The impact of mineral nutrients in food crops on global human health. *Plant and Soil, 247*(1), 83–90. https://doi.org/10.1023/A:1021141515903.

Welch, R. M., & Graham, R. D. (2004). Breeding for micronutrients in staple food crops from a human nutrition perspective. *Journal of Experimental Botany, 55*(396), 353–364. https://doi.org/10.1093/jxb/erh064.

White, P. J., & Broadley, M. R. (2005). Biofortifying crops with essential mineral elements. *Trends in Plant Science, 10*(12), 586–593. https://doi.org/10.1016/j.tplants.2005.10.001.

Yang, X. E., Chen, W. R., & Feng, Y. (2007). Improving human micronutrient nutrition through biofortification in the soil–plant system: China as a case study. *Environmental Geochemistry and Health, 29*(5), 413–428. https://doi.org/10.1007/s10653-007-9086-0

Zafar, S., Long, Y.L., Nan, N.L., Ming, K.Z. and Xiao, L.T. (2019). Recent advances in enhancement of oil content in oilseed crops. *Journal of Biotechnology*, 301, 35-44.

Zhang, F., Li, X., & Wei, Y. (2023). Selenium and selenoproteins in health. *Biomolecules, 13*(5), 799. https://doi.org/10.3390/biom13050799

Zhu, C., Naqvi, S., Gomez-Galera, S., Pelacho, A. M., Capell, T., & Christou, P. (2007). Transgenic strategies for the nutritional enhancement of plants. *Trends in Plant Science, 12*(12), 548–555. https://doi.org/10.1016/j.tplants.2007.09.007.

Zulfiqar, U., Ayub, A., Hussain, S., Ahmad, M., Rehman, A., Ishfaq, M., Ali, M. F., Shabaan, M., & Yong, J. W. H. (2024b). Iron biofortification in cereal crops: Recent progress and prospects. *Food and Energy Security, 13*(4), 547. https://doi.org/10.1002/fes3.547

Zulfiqar, U., Khokhar, A., Maqsood, M. F., Shahbaz, M., Naz, N., Sara, M., Maqsood, S., Sahar, S., Hussain, S., & Ahmad, M. (2024a). Genetic biofortification: Advancing crop nutrition to tackle hidden hunger. *Functional & Integrative Genomics, 24*(2), 34. https://doi.org/10.1007/s10142-024-01034-9

8

POSSIBILITIES FOR USING FISH PRODUCTION PROCESSING WASTE

Farahuddin Larghani[1], Hasan Ersin Şamlı[2]

Introduction

Currently, only around 50–60% of the fish captured are allocated for human consumption. Worldwide, over 91 million tons of fish and shellfish are harvested each year. While certain by-products are being utilized, a large amount of waste still ends up being discarded. Estimates suggest that the fishing sector globally produces nearly 20 million tons of waste annually. Hence, enhancing the use of by-products from the fishing sector offers considerable potential. These substances, often referred to as waste or by-products, should in fact be recognized as valuable residual raw materials.

In this regard, the biological remains generated through fish processing have gained attention as promising sources for producing organic fertilizers, primarily due to their high nutrient content (FAO, 2018). Aside from being used as fertilizers, these residues are increasingly applied in a variety of industries. During processing in fish plants, the edible parts destined for human consumption are initially separated, leaving behind a mixture of edible and non-edible components. These remaining materials possess value and can be repurposed across different sectors.

Moreover, beyond the solid wastes, water from aquaculture systems where fish are cultivated can also be recycled in integrated aquaponic systems to grow plants. Such systems play a crucial role in terms of efficient resource utilization and sustainability.

Fish Processing Industry: Processing Stages and Recovery Applications

In recent years, interest in the by-products generated by the fishing industry has grown. These materials are increasingly seen not as waste, but as valuable resources with potential applications. Globally, only 50–60% of seafood is offered for human consumption, while the rest is often wasted or used in the production of low-value-added products.

1 Tekirdağ Namık Kemal University Faculty of Agriculture Dept. of Animal Science, Tekirdağ/Türkiye, ORCID ID: 0009-0002-3744-7589, farahuddinlarghani2019@gmail.com
2 Tekirdağ Namık Kemal University Faculty of Agriculture Dept. of Animal Science, Tekirdağ/Türkiye, ORCID ID: 0000-0002-5462-8384, esamli@nku.edu.tr

According to FAO data, annual global fishery waste reaches approximately 20 million tons. In countries like Norway and Iceland, this poses a significant economic and environmental issue and highlights a large untapped biomass potential. In Norway alone, 232,000 tons of by-products were generated from cod fishing in 2001, but only 15.5% of it was used for human food.

The valorization of this waste is critical due to its rich protein, fat, vitamin, and mineral content. However, effective utilization of these materials depends on several factors, including product quality, market demand, processing technologies, and appropriate preservation techniques. Otherwise, serious quality losses can occur due to microbial spoilage and oxidation. For this reason, new approaches supported by advanced technologies are required to ensure more efficient and sustainable use of available resources (Rustad, 2003).

Figure 1 schematically illustrates the processing stages and recovery applications in the fish processing industry. As shown in the figure, by-products can be utilized in various fields through recovery practices. On the other hand, the direct use of fish waste in soil can lead to negative outcomes such as unpleasant odors, the risk of pathogen transmission, and environmental pollution. Therefore, the implementation of appropriate processing and stabilization methods is of great importance. In this context, the use of waste from the fish processing industry as organic fertilizer offers a sustainable solution both environmentally and economically. However, the efficiency of these processes depends on the proper treatment of the waste and their stabilization through eco-friendly methods (Rustad et al., 2011; FAO, 2018). Some fish processing companies are able to sell their biological fish waste to pet food manufacturers. However, most fish processing companies face negative costs to dispose of processing waste (Muscolo et al., 2022).

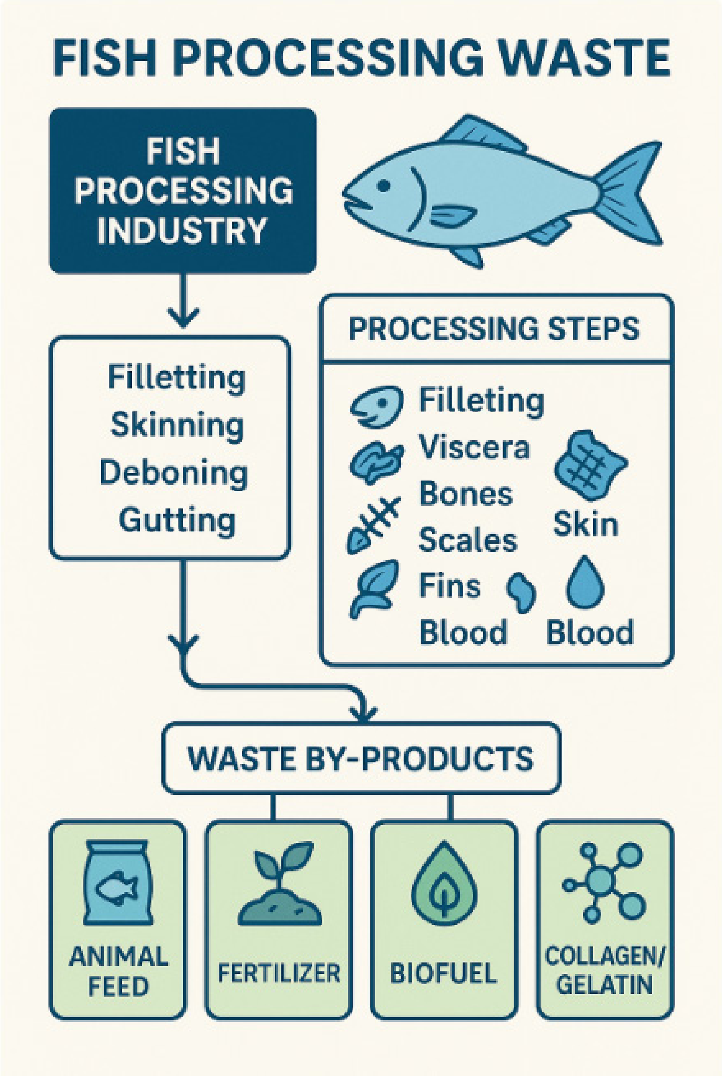


Figure 1. Processing stages and recovery practices in the fish processing industry

Potential uses of fish processing waste

Every year, millions of tons of fish waste are released into the environment without processing, leading to various problems. These residues not only pollute natural resources but also cause significant harm to the environment and human health.

Table 1 summarizes some potential uses of fish processing waste. As shown in the table, fish processing waste has usability potential in many different fields.

Fish waste refers to the remaining parts of the fish (head, intestines, internal organs, skin, etc.) after cleaning in processing facilities. Converting fish waste into food for human consumption or animal feed is of great importance in terms of both its economic contribution and the prevention of harm to the environment and human health (Kılınç, 2007).

These converted by-products are rich in protein and bioactive peptides, and fish protein hydrolysates obtained through enzymatic hydrolysis are also utilized in the food, feed, fertilizer, and pharmaceutical sectors. The properties of these products vary depending on the fish species, enzyme type, and processing conditions, while the essential amino acids they contain determine their nutritional quality (Korkmaz et al., 2021).

Table 1 summarizes some potential uses of fish processing waste. As shown in the table, fish processing waste has usability potential in many different fields.

Table 1 Some potential uses of fish processing waste.

Product	Use area	Source
Bioactive protein hydrolysates	**Health supplements or Nutraceuticals:** Fish protein hydrolysates are used as health supplements or nutraceuticals under various brand names.	Phadke et al., 2021
Biodiesel	**Energy: The production of** environmentally friendly biodiesel has been addressed through the conversion of waste fish oil using a nanomagnetic catalyst.	Smaisim et al., 2022
ω-3 concentrates	**Food:** Fish processing wastes have been recycled into valuable nutritional supplements such as omega-3 fatty acids.	Alfio & al., 2021
Protein hydrolysates, collagen and oil	**Food, biomedical Applications, cosmetics:** Fish waste was hydrolyzed using Alcalase 2.4 L to produce protein hydrolysates, collagen, and fish oil.	Araujo et al., 2021
Protein isolate, hydrolyzate , gelatin, collagen, silage and fish flour	**Food, feed:** It was stated that fish wastes are valuable resources for food and feed production and it was emphasized that the fish proteins obtained can be used as food supplements or in animal feed for human consumption.	Rana et al., 2023
Biopolymers	**Food Packaging:** Fish waste offers significant economic and environmental advantages as a new raw material for biopolymer production in different application areas, especially food packaging.	Lionetto & Corcione , 2021
Fertilizer	**Vegetable Production:** Fish processing waste, with its nitrogen, phosphorus, and potassium content, is a valuable source of organic fertilizer.	Jaies et al., 2024 (a)
Fertilizer	**Vegetable Production:** Fish waste can be used as fertilizer on farms, gardens and field crops, increasing the amount of organic matter and nutrients in the soil, increasing moisture retention capacity and improving soil fertility and product quality.	Dhar et al., 2024
Fish waste hydrolyzate	**Vegetable Production:** Hydrolyzed fish waste promotes plant growth, leaf and fruit formation, and increases soil micro and macronutrient content.	Bhuimbar & Dandge , 2023
Fertilizer, compost	**Vegetable Production:** Compost obtained from fish waste increased plant productivity and improved macronutrient levels in the soil.	Radziemska et al., 2019
Fish waste silages	**Animal Feeds**	Islam & al., 2021
Fish waste silages	**Animal Feed:** Fish waste and food waste offer a sustainable alternative to animal feed production.	Mo & al., 2018

Using fish waste and water from fish farms as fertilizer:

The most common methods are to produce fertilizer through the reprocessing of fish processing waste or to use water from fish farms for plant production. Solid and liquid waste generated during fish production and processing have the potential to cause serious environmental and human health problems. These wastes can have negative impacts on aquatic ecosystems due to their high organic matter content, while their improper disposal leads to unpleasant odors and a decrease in quality of life. Therefore, these wastes should be utilized appropriately. In this context, fish waste is rich in calcium, nitrogen, potassium, and other macronutrients essential for plant growth, and can be used as organic fertilizers. They are a significant source, especially due to their phosphorus content. Liquid organic fertilizers derived from fish waste increase yields due to their rapid effectiveness, even in cold climates. Fish waste composts also contribute to sustainable agriculture by improving soil (Jaies et al., 2024 b). One study examined the recovery of nutrients from fish wastewater through eggplant, tomato, and cucumber plants using an aquaponics system. Integrating wastewater treatment with plant production in recirculating aquaculture systems has been shown to have significant potential for sustainable agriculture and environmental protection. The study found that 69% of the total nitrogen in the aquaponics system could be converted into edible fruit (Graber et al., 2009).

Using fish waste and water from fish farms as fertilizer:

There are different types of aquaponic systems in plant production. Common aquaponic practices used today are shown in Figure 2.

Below are some examples of these techniques (Llauradó et al., 2015). In an aquaponics setup, nutrient-rich water from fish tanks is utilized as a liquid fertilizer to nourish hydroponic growing beds. The nutrients in this water originate from fish waste, algae, and uneaten fish feed. These by-products can accumulate to toxic concentrations in fish tanks, adversely affecting fish development. Hydroponic beds function as natural biofilters, removing ammonia, nitrate, and phosphorus from the water. This purification process enables the treated water to be recirculated back into the fish tanks. Nitrifying bacteria, residing within the gravel and in symbiosis with plant roots, play a crucial role in nutrient transformation. These microorganisms convert ammonia into nitrate, a nitrogen form that plants can absorb. Consequently, when the water is sent back to the fish tanks, nitrogen levels are regulated, maintaining safe conditions for the fish.

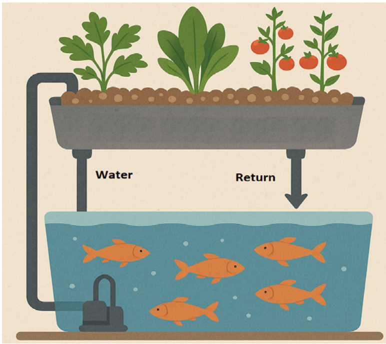
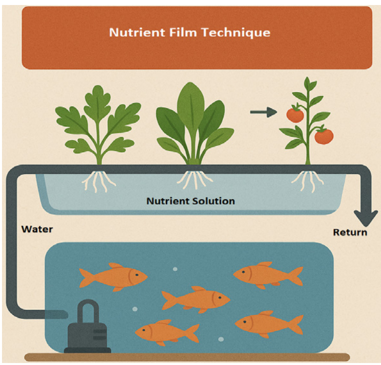
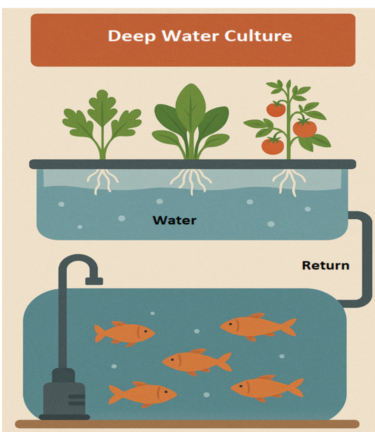
	**Media-filled beds** This system is the simplest form of aquaponics. It uses containers filled with a medium such as clay. Water from the fish tank is circulated over these media-filled beds, and plants grow in this medium. This system can be operated in two different ways: by continuously flowing water over the medium or by cycling irrigation and drainage (flood and drawdown).
	**Nutrient film technique** This technique is only suitable for certain species, but is generally ideal for leafy green vegetables. This method can cause the root systems of larger plants to expand excessively, making the system difficult to operate.
	**Deep-water culture** This method involves placing plants on floating platforms on the water surface, with their roots suspended in the water. It is one of the most commonly used methods in commercial aquaponics.

Figure 2. Common aquaponic practices used

Production of solid fertilizer from fish processing residues:

While the stages of producing solid fertilizer from fish processing residues may seem simple, they require considerable attention. Fish residues, in particular, must be obtained and processed in accordance with hygiene regulations. Storage and preservation conditions, particularly during the processing process, must be such that they do not allow the product to deteriorate. Therefore, meticulous implementation of each stage is crucial for maintaining product quality. Transforming post-production waste into a form that can be used as a soil conditioner and using it in agricultural fields is considered one of the best methods, both economically and environmentally. A study (Devi et al., 2024) investigated the potential of compost obtained by adding sawdust, banana, and brown sugar to fish waste, consisting of intestines, heads, skin, bones, and fins, as a sustainable organic fertilizer. According to the research findings, the mature compost shrank to 70% of its original volume. It was emphasized that this compost could serve as an effective organic fertilizer that can increase soil fertility. The study demonstrated high germination rates, indicating that the resulting compost was not phytotoxic. In another study, changes in some physical and chemical properties of the soil were determined after three different doses (3%, 6%, and 9%) of compost made from fish waste and olive pomace were applied to sandy loam soil. The results indicated that using fish waste as fertilizer has positive effects (Remzi Ilay et al., 2019). A simple flow chart for fertilizer production is shown in Figure 3.

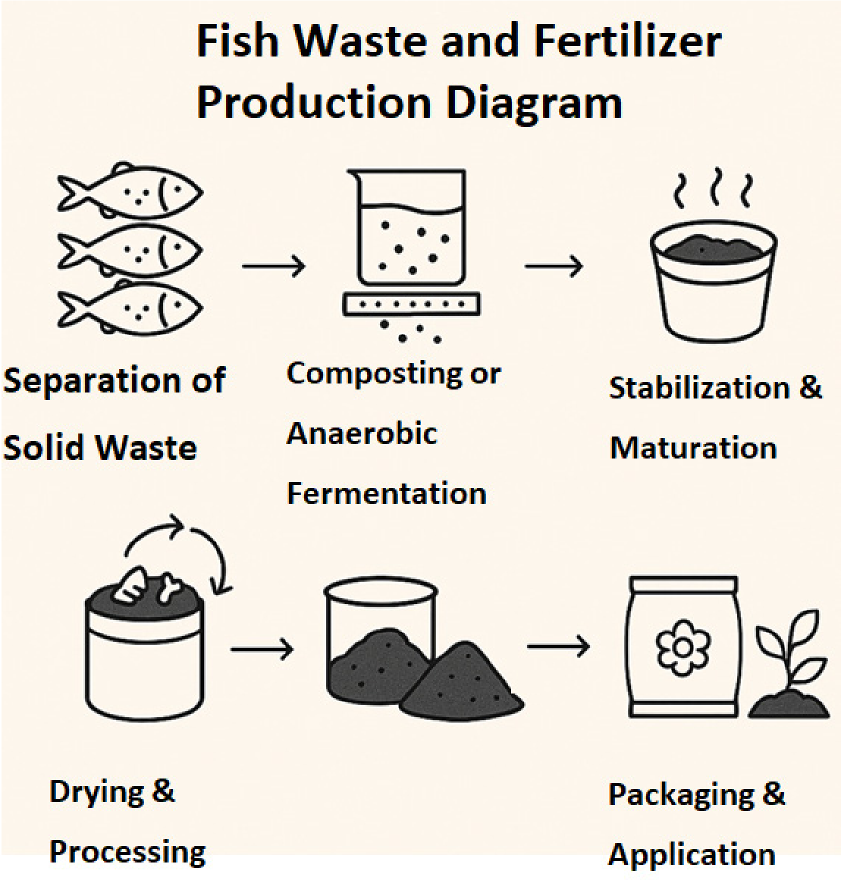


Figure 3. A simple procedure for producing fertilizer from fish waste

Use of fish by-products in farm animal feed:

Fish meal is a product obtained by cooking, grinding, and drying the inedible residue from processed fish, or whole fish in general. Its excellent storage properties are particularly important. It is a feed ingredient rich in organic and inorganic nutrients in animal feed. Key factors such as the type of fish and the processing method influence the nutritional content and quality of fish meal. Fish meal is an important ingredient used in compound feeds for many animal species.

Since 2000, global production of fish meal and fish oil has been estimated at around 6 million metric tons annually (approximately 5 million tons of fish meal and 1 million tons of fish oil). In recent years, due to improved fisheries management and increased investments, global yearly output has surpassed 5.1 million metric tons of fish meal and 1.2 million metric tons of fish oil (IFFO, 2023).

Fish silage is a liquid product made from whole fish or fish parts that are liquefied by the action of an added acid and the enzymes in the fish. The enzymes in the mixture break down fish proteins into smaller, more soluble units, allowing the acid in the environment to prevent bacterial degradation more quickly (Tatterson and Windsor, 2024). There are articles on the use of fish silage in animal nutrition. For example, it has been determined that fermented fish silage can be added to the feed of broiler Japanese quail at levels of up to 5% without affecting production performance or cost. The same study stated that fish silage has a balanced protein, fat, and mineral content. Furthermore, it was emphasized that adding fish silage to poultry rations could offer economic advantages without negatively impacting nutritional feed efficiency, growth, serum biochemistry, and overall performance. Environmentally, it was also noted that silage application would help the fish industry increase revenues and provide a safe methodology for reducing pollution from fish waste (Panda, S., et al., 2017).

Conclusion

Although multiple methods exist for converting fish waste into valuable products, their practical application faces certain obstacles. Techniques aimed at producing high-value products are predominantly applied at the industrial level, especially in developed nations. However, in less economically advanced regions, these transformation methods often pose difficulties due to the advanced technologies involved. For instance, various processes are used to obtain feed components and bio stimulants from fish processing residues. Consequently, creating fish waste utilization methods that rely on low technology is seen as a key requirement for encouraging widespread adoption of the circular economy in developing countries (Carella et al., 2021).

Fish processing waste, processed using less technological means, offers an environmentally friendly and sustainable fertilizer alternative with its high organic matter, nitrogen, phosphorus, and potassium content. Utilizing these wastes in the forms of compost, hydrolysate, and liquid fertilizer not only contributes to the prevention of environmental pollution but also increases agricultural productivity. Furthermore, these fertilizers are known to improve soil structure, increase microbial activity, and positively affect plant growth. Furthermore, these products have lower environmental impacts compared to chemical fertilizers. At this stage, the selection of appropriate production methods is also crucial. However, determining appropriate processing technologies and application doses for effective and safe use is crucial. Future legal regulations and raising farmer awareness will also play a critical role in the widespread adoption of these practices. Furthermore, the use of fish waste in animal feed has long been a common practice. However, in addition to improving the efficiency and quality of fishmeal production, less common techniques such as fish silage need to be encouraged in suitable regions.

In addition, further research is required to establish standardized protocols for processing fish waste into agricultural and feed applications, as variability in raw materials and processing conditions may lead to inconsistent product quality and efficacy. Developing cost-effective and scalable methods that integrate local resources and traditional practices could enhance the feasibility of implementation in developing countries. Collaborative efforts between policymakers, researchers, and industry stakeholders are essential to overcome technical and economic barriers, while interdisciplinary approaches—combining environmental science, agronomy, and food technology—can provide innovative solutions for maximizing the value of fish waste within a sustainable circular economy framework.

Literatures

Alfio, V. G., Manzo, C., & Micillo, R. (2021). From fish waste to value: An overview of the sustainable recovery of omega-3 for food supplements. *Molecules, 26*(4), 1002. https://doi.org/10.3390/molecules26041002

Araujo, J., Sica, P., Costa, C., et al. (2021). Enzymatic hydrolysis of fish waste as an alternative to produce high value-added products. *Biomass Conversion and Biorefinery, 12*, 847–855. https://doi.org/10.1007/s12649-020-01029-x

Bhuimbar, M. V., & Dandge, P. B. (2023). Production of organic liquid biofertilizer from fish waste and study of its plant growth promoting effect. *Proceedings of the National Academy of Sciences, India, Section B: Biological Sciences, 93*, 235–243. https://doi.org/10.1007/s40011-022-01413-8

Carella, F., Seck, M., Degli Esposti, L., Diadiou, H., Maienza, A., Baronti, S., Vignaroli, P., Primo Vaccari, F., Iafisco, M., & Adamiano, A. (2021). Thermal conversion of fish bones into fertilizers and biostimulants for plant growth – A low tech valorization process for the development of circular economy in least developed countries. *Journal of Environmental Chemical Engineering, 9*(1), 104815. https://doi.org/10.1016/j.jece.2020.104815

Devi, N. L., Singh, A. H., Nongthombam, J., Kumar, S., & Chaudhary, K. P. (2024). Fish waste compost – a fertilizer for organic agriculture. *Journal of Experimental Agriculture International, 46*(11), 778–85. https://doi.org/10.9734/jeai/2024/v46i113098

Dhar, M., Jasrotia, R., & Langer, S. (2024). Using fish waste and by-products for manufacturing organic fertilizers and manures. In S. Maqsood, M. N. Naseer, S. Benjakul, & A. A. Zaidi (Eds.), *Fish waste to valuable products* (ss. 329–338). Springer. https://doi.org/10.1007/978-981-99-8593-7_16

FAO. (2018). *The state of world fisheries and aquaculture 2018: Meeting the sustainable development goals*. Food and Agriculture Organization of the United Nations.

Ghassan, F. S., Prabu, N. M., Senthilkumar, A. P., & Abed, A. M. (2022). Synthesis of biodiesel from fish processing waste by nano magnetic catalyst and its thermodynamic analysis. *Case Studies in Thermal Engineering, 35*, 102115. https://doi.org/10.1016/j.csite.2022.102115

Graber, A., Junge, R., Antenen, N., & Tabacchi, M. (2009). Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination, 246*(1-3), 147–156.

IFFO (The Marine Ingredients Organisation). (2023). *Market statistics*. https://www.iffo.com/market-statistics

Islam, J., Yap, E. E. S., Krongpong, L., & Toppe, J., & Peñarubia, O. R. (2021). *Fish waste management: Assessment on potential production and utilization of fish silage in Bangladesh, Philippines and Thailand*. FAO Fisheries and Aquaculture Circular, 1226. Food and Agriculture Organization of the United Nations.

Jaies, I., Qayoom, I., Saba, F., & Khan, S. (2024a). Fish wastes as source of fertilizers and manures. In S. Maqsood, M. N. Naseer, S. Benjakul, & A. A. Zaidi (Eds.), *Fish waste to valuable products* (ss. 329–338). Springer.

Jaies, I., Qayoom, I., Saba, F., & Khan, S. (2024b). Fish wastes as source of fertilizers and manures. In S. Maqsood, M. N. Naseer, S. Benjakul, & A. A. Zaidi (Eds.), *Fish waste to valuable products* (ss. 329–338). Springer. https://doi.org/10.1007/978-981-99-8593-7_15

Kılınç, B. (2007). Balık atıklarının değerlendirilmesi. *Ege Üniversitesi Su Ürünleri Dergisi, 24*(3–4), 315–319.

Korkmaz, K., Atıcı, A., Dalgıç, G., & Uçar, Y. (2021). Nutritional composition of protein hydrolyzate produced from fish waste. *Turkish Journal of Maritime and Marine Sciences, 7*(1), 27–39.

Lionetto, F., & Esposito Corcione, C. (2021). Recent applications of biopolymers derived from fish industry waste in food packaging. *Polymers, 13*(14), 2337. https://doi.org/10.3390/polym13142337

Llauradó, A. M., López, D. M., García, R., & Sayago, S. (2015). Aquaponics system: An EPS@ISEP 2014 spring edition project. In Á. Rocha, A. M. Correia, H. Adeli, L. P. Reis, & M. M. Teixeira (Eds.), *Proceedings of the Third International Conference on Technological Ecosystems for Enhancing Multiculturality (TEEM '15)* (ss. 305–311). ACM.

Mo, W. Y., Man, Y. B., & Wong, M. H. (2018). Use of food waste, fish waste and food processing waste for China's aquaculture industry: Needs and challenge. *Science of The Total Environment, 613-614*, 635–643. https://doi.org/10.1016/j.scitotenv.2017.08.321

Muscolo, A., Mauriello, F., Marra, F., Calabrò, P. S., Russo, M., Ciriminna, R., & Pagliaro, M. (2022). AnchoisFert: A new organic fertilizer from fish processing waste for sustainable agriculture. *Global Challenges, 6*(3), 2100141. https://doi.org/10.1002/gch2.202100141

Panda, S., Babu, L., Panda, A., & Panigrahy, K. (2017). Dietary supplementation of fermented fish silage in broiler Japanese quails (*Coturnix coturnix japonica*): A review. *International Journal of Livestock Research, 7*(6), 1. https://doi.org/10.5455/ijlr.20170306091640

Phadke, G. G., Rathod, N. B., Ozogul, F., Elavarasan, K., Karthikeyan, M., Shin, K. H., & Kim, S. K. (2021). Exploiting of secondary raw materials from fish processing industry as a source of bioactive peptide-rich protein hydrolysates. *Marine Drugs, 19*(9), 480. https://doi.org/10.3390/md19090480

Radziemska, M., Vaverková, M. D., Adamcová, D., et al. (2019). Valorization of fish waste compost as a fertilizer for agricultural use. *Waste and Biomass Valorization, 10*, 2537–2545. https://doi.org/10.1007/s12649-018-0288-8

Rana, S., Singh, A., Surasani, V. K. R., Kapoor, S., Desai, A., & Kumar, S. (2023). Fish processing waste: A novel source of non-conventional functional proteins. *International Journal of Food Science & Technology, 58*(5), 2637–2644. https://doi.org/10.1111/ijfs.16104

Remzi İlay, E., Arısoy, H., Çolak, İ., & Aydın, A. (2019). Pirina ve balık atıklarının birlikte kompostlanması ve toprak ıslahında kullanılması. *Anadolu Journal of Agricultural Sciences, 34*, 201–209.

Rustad, T. (2003). Utilisation of marine by-products. *Electronic Journal of Environmental, Agricultural and Food Chemistry, 2*(4), 458–463.

Rustad, T., Storrø, I., & Slizyte, R. (2011). Possibilities for the utilisation of marine by-products. *International Journal of Food Science & Technology, 46*(10), 2001–2014.

Tatterson, I. N., & Windsor, M. L. (2024, Haziran 13). *Ministery of Agriculture, Fisheries and Food, Torry Research Station, Torry Advisory Note No. 64*. https://www.fao.org/4/x5937e/x5937e01.htm#Introduction

9 WEED MANAGEMENT FOR SUSTAINABLE PLANT NUTRITION AND SOIL QUALITY

Rana Nadeem Abbas[1], Muhammad Awais Arshad[2]

1. Introduction

By 2050, the world population is expected to approach nine billion, which places increasing pressure on agricultural production (Hemathilake & Gunathilake, 2022; Arshad et al., 2024). The current level of agricultural production is insufficient to feed the expanding population and it may prove to be extremely difficult for humankind to satisfy this projected demand (Westwood et al., 2018). Another problem that put more strain on agricultural systems than ever before include climate change, the depletion of arable land and water supplies and the threat posed by weeds, pests and diseases (Wang et al., 2019). These problems have both immediate and long-term effects on the planet's sustainability and the standard of living for all living things. Weeds have co-evolved with crops and farming systems and remain one of the most significant biotic constraints to food production globally, reducing yields, increasing production costs and altering soil functions (Seelan et al., 2003; Tahir et al., 2024). Weeds pose a significant obstacle to global agricultural productivity, with estimated potential crop yield losses attributable to weeds approximated at 43% on a worldwide scale. Many weed control strategies have been used in the last few decades. These include cultural approaches like crop rotation, cover crops and intercropping; physical techniques like hand weeding; and thermal techniques that employ heat from fire, flames, or hot water to eradicate weeds; chemical control by using herbicides; mechanical control by using farm equipment; biological control by using natural predators; laser weeding technology; and integrated weed management tactics. Clean cultivation, the use of clean seeds, weed-free seed beds, well-decomposed organic manures, weed-free bunds and irrigation channels, clean tools and farm equipment and weed control before weeds reach the reproductive stage are some of the preventive measures. The amount of organic matter and the activity of beneficial soil organisms are frequently associated with soil quality. The impact of anthropogenic activities and natural processes on soil quality has been assessed using soil enzymes, which operate as mediators and catalysts of significant soil functions (Dick, 1997). According to Doran and Parkin

1 Department of Agronomy, Faculty of Agriculture, University of Agriculture Faisalabad, Punjab, Pakistan. (R.N.A. nadeem4u1@hotmail.com; https://orcid.org/0000-0001-7255-5919)
2 (M.A.A. awaisarshad.uaf@yahoo.com; https://orcid.org/0009-0004-4174-6391)

(1994), soil quality is the ability of a soil to support biological productivity, preserve environmental quality which advance the health of plants and animals while operating within "ecosystem boundaries." Nonetheless, mechanical and chemical treatments continue to be the most popular weed management strategies. Herbicides account for 60% of the total volume and 65% of farmer spending on all pesticides used in the U.S. agriculture industry (Gianessi et al., 2007).

Herbicides have several benefits, such as improved crop yield and efficient weed management, but their extensive and frequently uncontrolled usage can have detrimental ecological effects and raise the danger of chemical substances that might be harmful to human health by getting into the food chain through tainted food and water. Importantly, weeds not only compete with crops above ground but also directly affect soil nutrient availability and cycling. Their dense root systems can immobilize essential nutrients such as nitrogen and phosphorus, depriving crops of access, while deep-rooted perennial weeds may alter soil structure and moisture distribution. Conversely, uncontrolled weed biomass left to decompose can temporarily enhance soil organic matter but may also lead to nutrient imbalances, allelopathic effects and shifts in microbial activity. Therefore, the way weeds are managed strongly influences soil fertility, nutrient dynamics and the long-term maintenance of soil quality. Due to decreased biodiversity, ineffective herbicides and the emergence of resistance, total weed removal is not acceptable. In order to reduce negative impacts on human health, the environment, the development of weed resistance and the management and prevention of foreign invasive weeds, it is recommended that integrated weed management be made more widely known while maintaining the safe use of herbicides. The worldwide application of agricultural herbicides is expected to experience a modest increment, escalating from approximately 2.3 million metric tons in 2023 to nearly 2.4 million metric tons by the year 2027 (Statista Research Department-2023). The herbicide market has undergone substantial expansion in recent years. It is projected to escalate from $47.38 billion in 2024 to $54.42 billion in 2025, indicating a compound annual growth rate (CAGR) of 14.9% (HGMR-2025). The quality and condition of the soil have a major impact on the agricultural system, its growth and its production. According to Doran and Jones (1996), Bone et al. (2010) and Bünemann et al. (2018), "soil quality can be broadly defined as the capacity of a soil to function, within land-use boundaries, to sustain biological productivity, maintain environmental quality and promote animal and plant health." It's common to use the phrases "soil health" and "soil quality" interchangeably. Soil quality is commonly assessed via indicators such as soil organic matter (SOM), nutrient cycling rates, soil structure, water holding capacity and biological activity (microbial biomass, enzymatic activities). In order for plants to thrive and produce nutritious food that contains all the nutrients required for human health, fertile soil is necessary. Bulluck et al. (2002) selected three conventional and three organic vegetable farms in Virginia and Maryland, field experiments were carried out in 1996 and 1997 to investigate the effects of organic and synthetic soil fertility additions on soil microbial populations and physical and chemical characteristics. They discovered that while Phytophthora and Pythium species had lower propagule densities in soils amended with organic than synthetic fertility, Trichoderma species, thermophilic microorganisms and enteric bacteria were found in higher quantities in soils amended with organic than synthetic fertility. Thus, weed management practices—whether cultural, mechanical, chemical, or biological—have cascading effects on soil quality and plant nutrition by shaping soil organic matter turnover, microbial diversity and nutrient-use efficiency. A sustainable weed management approach not only ensures crop yield protection but also safeguards soil health and nutrient balance, both of which are critical for long-term agricultural productivity. The widespread use of herbicides has contributed to current productivity levels but has also generated environmental and agronomic challenges (Gianessi et al., 2007; Arshad et al., 2024a). Herbicide resistance, contamination risks and reduced biodiversity motivate the adoption of integrated and ecological strategies for weed management.

2. How weeds affect plant nutrition and soil quality

Weeds interact with crops and soils through several pathways that influence plant nutrition and soil quality:

- **Competition for nutrients and water.** Weeds compete with crops for mineral nutrients (N, P, K and micronutrients), water and light, causing reduction in crop nutrient uptake efficiency and crop yield. This competition not only lowers immediate nutrient availability to crops but also disrupts nutrient-use efficiency in the soil–plant system which leading to nutrient imbalances that can degrade soil fertility over time.
- **Alteration of soil physical properties.** Dense weed populations can affect soil cover, evapotranspiration and consequently soil moisture as well as temperature regimes with downstream effects on nutrient mineralisation and root function. Changes in soil structure, porosity and moisture caused by weeds can either hinder or accelerate organic matter decomposition which directly influencing soil quality and the stability of nutrient pools.
- **Changes to soil biological communities and functions.** Weed-driven changes in organic inputs, root exudates and litter quality alter microbial communities, soil enzymatic activities and nutrient cycling rates. Soil enzymes are useful indicators of such shifts (Dick, 1997). Long-term weed-dominated communities may reduce the abundance of beneficial

microbial taxa and change decomposition dynamics, thereby affecting SOM turnover and nutrient availability. For instance, reduced microbial diversity under unmanaged weed growth can slow down nutrient mineralisation processes, weakening soil biological fertility and plant nutrition.

- **Allelopathy and chemical interference.** Many weeds and some crops release allelochemicals that inhibit germination or growth of neighboring plants (Rice, 1984). Allelopathic interactions can reduce crop nutrient uptake indirectly by limiting root growth and function. Such chemical interference alters nutrient cycling by suppressing beneficial rhizosphere activity, thereby lowering soil nutrient efficiency and quality.
- **Weed seedbank and persistence.** Perennial weeds and a persistent seedbank maintain weed pressure and force repeated interventions, often with tillage or herbicide applications that have secondary effects on soil structure and biology. Frequent tillage application or continuous reliance on herbicide in response to persistent weeds may degrade soil aggregation, reduce soil organic matter and alter nutrient availability, negatively impacting both soil health and sustainable plant nutrition.

Together, these mechanisms show why weed management is not merely a yield-protection activity but a central part of sustaining soil function and crop nutrient use efficiency (Abbas et al., 2021; Arshad et al., 2021). Effective weed management therefore serves as a dual strategy: safeguarding crop yields while maintaining soil fertility, nutrient balance and overall soil quality essential for long-term agricultural sustainability.

3. Drivers of current weed management challenges

- **Herbicide dependence and resistance.** Prolonged herbicide use and reliance on a limited number of modes of action have selected for resistant populations. Herbicide resistance is now reported in many weed species and across multiple herbicide modes of action (Powles et al., 2001). The spread of resistance intensifies pressure on farmers and ecosystems. Excessive herbicide use also disrupts soil microbial communities that regulate nutrient cycling, potentially lowering soil organic matter turnover, nutrient mineralization and long-term soil fertility.
- **Regulatory and market pressures.** Regulatory limits on pesticide residues, changing market demands for low-residue and organic produce, with consumer preferences push systems toward non-chemical or low-input alternatives. These shifts are not only market-driven but also linked to soil quality, since residue-free systems often emphasize organic amendments, crop diversity and ecological practices that enhance soil health and plant nutrient availability.

- **Changes in agronomic practices.** Conservation tillage and reduced tillage systems have advantages for soil conservation but alter weed control dynamics and require different integrated approaches. While conservation tillage protects soil structure and SOM, it may also favor certain weed species, thereby indirectly influencing nutrient cycling and soil fertility through weed–soil interactions.
- **Biodiversity loss and simplified rotations.** Crop monocultures and simplified rotations increase weed pressure and reduce the ecological checks that suppress weed establishment. Such systems also accelerate soil nutrient depletion and reduce microbial diversity, making soils more dependent on synthetic inputs and less resilient in maintaining balanced nutrient cycles.

Digitalization, while offering precision solutions, also demands new skills and investment; unequal access can limit adoption in resource-poor regions (Abbas et al., 2021a). When effectively applied, digital and precision technologies can optimize fertilizer use and site-specific weed management, thereby improving nutrient-use efficiency and minimizing negative impacts on soil quality.

4. Frameworks for sustainable weed management

Integrated Weed Management (IWM) and Ecological Integrated Weed Management (EIWM) are frameworks that combine preventive, cultural, mechanical, biological and chemical methods to keep weed populations below economic thresholds while minimizing negative environmental impacts.

Key principles of a sustainable IWM/EIWM approach:

- **Prevention first:** sanitation, clean seed, weed-free seedbeds and equipment cleaning to reduce introductions and spread.
- **Monitoring and thresholds:** regular scouting and the use of economic or critical thresholds to avoid unnecessary interventions.
- **Diverse tactics:** crop rotation, cover crops, intercropping, competitive cultivars, mulches, targeted mechanical control and selective herbicide use to reduce selection pressure. Such diversified tactics not only suppress weeds but also enhance soil organic matter, improve soil aggregation and foster beneficial microbial communities that are critical for nutrient mineralization and cycling.
- **Adaptive management:** integrate local knowledge, monitor effectiveness and adjust tactics based on weed community composition and resistance evolution. Adaptive IWM approaches that integrate cover crops, legumes and organic amendments improve soil fertility by increasing nitrogen

availability, enhancing nutrient-use efficiency and maintaining long-term soil productivity.

Practical implementation requires farmer training, accessible decision-support tools (e.g., simple threshold charts, mobile apps for weed identification and resistance alerts) and policies that support diversification and reduced chemical reliance (Arshad et al., 2024c). Thus, sustainable weed management frameworks not only reduce herbicide dependence but also contribute to resilient soils and sustainable plant nutrition, creating a direct link between weed control, soil quality and crop productivity.

5. Weed Control Methods

For several decades, agricultural practices across the globe have been predominantly dependent on herbicides, which are regarded as the most efficient and effective measures for controlling weeds. Nonetheless, the prolonged application of herbicides has adversely affected both environmental integrity and human health, concurrently engendering a global crisis of herbicide resistance (Rafeeq et al., 2020; babalola et al., 2021). Consequently, Europe has established regulatory thresholds for pesticide residues present in water, food products and soil through a series of legislative acts, while also sanctioning only a limited selection of active ingredients for employment in weed management strategies. The objectives of cultivating healthy and safe food, alongside the ongoing challenge posed by persistent weed populations and their propensity to develop various resistance mechanisms (including resistance or tolerance to herbicides), have compelled agricultural practices to increasingly adopt non-chemical methods for weed control. Beyond weed suppression, the choice of control method strongly influences soil health and nutrient dynamics. Heavy reliance on herbicides may alter soil microbial diversity and reduce beneficial organisms involved in nutrient cycling, whereas integrated non-chemical practices such as crop rotation, cover cropping, mulching and mechanical weeding improve soil organic matter, enhance nutrient availability and sustain soil structure. Non-chemical strategies, by fostering microbial activity and reducing chemical load, contribute to improved soil fertility and long-term nutrient-use efficiency, thereby linking weed control directly with sustainable plant nutrition and soil quality.

5.1 Sanitation and preventive measures

Preventive measures include clean cultivation, the use of certified clean seed, weed-free seedbeds, well-decomposed organic manures, weed-free bunds and irrigation channels, clean tools and farm equipment and weed control before weeds reach the reproductive stage. Prevention reduces the introduction and spread of invasive weed species and limits seedbank replenishment. Poultry will eat weed seeds on the soil and grazing livestock in fields just after vegetable harvest will assist reduce weed growth and weed seed generation. Diseased crop leftovers that may ordinarily need to be composted, burned, or buried via inversion tillage can be removed with the help of livestock. A method that can concurrently control weeds, provide feed for cattle and fertilize (manure) is the employment of livestock to graze down understory plants in orchards, Christmas trees and other tree plantings (silvopasture). A field plagued with weeds can be cleared for future crop production by repeated, intense grazing. To exhaust subterranean supplies of perennial weeds, the weeds should be grazed to the point of extreme defoliation at brief intervals (Schonbeck and Tillage, 2011). Beyond weed suppression, sanitation and preventive strategies directly support soil quality and plant nutrition. Practices such as using clean seed and weed-free organic manure help maintain soil microbial balance, prevent nutrient depletion by invasive weeds and improve nutrient-use efficiency of crops. The integration of livestock grazing not only reduces weed seedbanks but also returns organic matter and nutrients to the soil in the form of manure, thereby enhancing soil fertility and nutrient cycling. Similarly, maintaining weed-free irrigation channels prevents nutrient-rich sediments from being wasted and ensures optimal nutrient availability for crops. These linkages highlight how preventive weed management simultaneously sustains soil structure, fertility and crop nutrition.

5.2 Crop diversification, rotation and competitive cultivars

Crop diversification (rotation, relay cropping, strip cropping, intercropping) reduces weed dominance by changing disturbance regimes and crop-weed competitive interactions (Kremen and Miles, 2012). Intercropping and relay systems can suppress weeds through competition and the provision of continuous canopy cover; they also often provide economic resilience. Selecting more competitive cultivars and optimizing sowing rate and row spacing are inexpensive agronomic levers to improve crop competitive ability and reduce weed impacts. The deliberate addition of functional biodiversity at the temporal or geographical levels to increase ecosystem service stability and production is known as crop diversification (Kremen and Miles, 2012; Akhter et al., 2017). Crop diversification is a sophisticated topic and unlike monoculture, which involves cultivating one or two annual crops on large farmlands, a diversified cropping system involves a variety of crop combinations. In order to increase the profitability of key crops or livestock, modern agricultural methods have streamlined agricultural systems. A diversified cropping system, on the other hand, aims to develop global food systems that are robust, sustainable and socially just. (i) growing different genotypes of the same crop or different crops in polyculture (ii) adding legumes to systems that are otherwise dominated by cereals (Kremen and Miles, 2012; Pervaiz et al., 2024) and (iii) rotating crops in space and time, including but not limited to cover crops, trap crops, hedgerows, fallow fields, etc. are a few examples of diversified cropping systems. (Kremen and Miles, 2012) Two or more crop species or genotypes are grown together and cohabit for a period of time as part of the integrated weed management technique known as intercropping. On a small plot of land, it is frequently employed in nations with low-input (high-labor) and resource-constrained agricultural systems (Simmonds and Vandermeer, 1989, Ngwira et al., 2012). Relay intercropping, which involves planting a second crop before the first is fully grown, mixed intercropping, which involves growing two or more crops at the same time and strip cropping, which involves growing two or more crops in strips (Brooker et al., 2015) are the three main categories of intercropping. Although each form has advantages, intercropping offers a comparable yield with less inputs, pest management (weeds, diseases and insects) and consistent aggregate food yields per unit area as compared to mono-cropping (Lithourgidis et al., 2011, Smith et al., 2013). In addition to weed suppression, crop diversification and rotations strongly influence soil quality and nutrient dynamics. For example, legume-based rotations enrich the soil with biologically fixed nitrogen, reducing the need for synthetic fertilizers and enhancing nutrient availability to subsequent crops. Continuous canopy cover through intercropping and relay cropping reduces soil erosion, improves soil organic matter and enhances microbial activity that drives nutrient mineralization. Furthermore, diversified rotations break weed cycles while simultaneously improving soil structure, water-holding capacity and nutrient-use efficiency. Competitive cultivars with greater root biomass not only outcompete weeds but also enhance nutrient uptake and contribute organic residues that improve soil fertility. Collectively, these practices link weed management with sustainable improvements in plant nutrition and soil quality.

5.3 Cover crops and living mulches

Cover crops and living mulches suppress weeds via competition, shading, residue cover and allelopathy. Leguminous cover crops can additionally improve N availability via biological nitrogen fixation while supplying mulch that suppresses weeds (Ball et al., 2020). By contributing organic residues and root exudates, cover crops also enhance soil organic matter content, microbial biomass and enzymatic activities, which are central to nutrient cycling and long-term soil fertility. Examples from the literature showed that rye mulch reducing weed biomass and improving soybean yield (Smith et al., 2011; Arshad et al., 2025e). In addition to weed suppression, rye and other grass cover crops improve soil aggregation and water-holding capacity, thereby facilitating nutrient uptake efficiency by crops. Cover crop selection should match the cropping system goals: e.g., legumes for N fixation, grasses for biomass &

mulch and brassicas for biofumigation/allelopathy. Legumes (*Fabaceae*), grasses (*Poaceae*), brassicas (*Brassicaceae*) and other broadleaf (Plantago major) plant groups make up the majority of cover crops. The best plant species for use as a cover crop are determined by the cover's intended use, the soil's state and the growing environment (Koudahe et al., 2022). Characteristics including ease of establishment, soil covering, resistance to weeds and pests, disease resistance, minimal competition with the primary crop and ease of termination are taken into consideration when selecting cover crop (Scavo et al., 2022). Some varieties of cover crops are combined to enhance their overall impact (Elhakeem et al., 2019; Aleem et al., 2024). Mixtures of cover crops might be useful to attain effects particular to many species (Scavo et al., 2022). Such mixtures often combine the nutrient-enriching role of legumes with the soil-structuring effects of grasses, improving both weed control and soil quality simultaneously. While, a research conducted in Australia showed that cover crop mixes made up of legumes and grasses might improve N fixation and its bioavailability through the legume species and enhance the soil organic matters through the grass species (Ball et al., 2020; Rasheed et al., 2024; Akbar et al., 2025). According to a research conducted in Atlantic Canada, species combinations did not generally suppress weeds more effectively than monoculture cover; however, there were benefits in suppressing weeds when certain highly productive species were combined species (Aleem et al., 2024).

The function of living mulches and conservation agriculture in a young Mediterranean olive orchard was investigated by (Las Casas et al., 2022). According to the authors, using lemongrass (*Cymbopogon citratus* (DC) Stapf) and sage (*Salvia officinalis* L.) as living mulches together minimizes soil disturbance, lessens the need for weed control and increases the taxonomic and species diversity of the Arthropod fauna. Living mulches also protect soil surfaces from erosion, reduce nutrient leaching and maintain a more stable microclimate that supports soil microbial processes critical for plant nutrition. In this Special Issue, Ryan et al. (2021) examined mulching, another cover cropping technique, in winter wheat grown in central New York (USA).

Beginning with the soil, which is the foundation of agricultural practices, that article emphasized benefits like decreased soil erosion, more usable land for crop production, lower energy costs, more windows for planting and harvesting, better use of soil water and lower machinery investment. Despite the positives, no-till or reduced tillage has several drawbacks for an agricultural system's sustainability. According to Phillips et al. (1980), no-tillage systems have a number of drawbacks, such as increased disease and insect pressure, a higher level of management expertise needed, a slower rate of soil warming in the spring and a 50% increase in pesticide use. Although there is no denying that the sustainability advantages of no-tillage, the systems' usage naturally removed one of the farmers' most useful mechanical weed management tools. Globally, the number of cases of distinct herbicide-resistant weeds increased rapidly at the same period, rising from 25 in 1979 to 128 species in 1990 (Heap, 2021). There is no causal link between the rise in herbicide resistance and the rise in no-tillage adoption, despite the fact that it would be simple to infer that they are. While no-tillage acreage adoption had only started at that time, herbicide use on corn and soybean acreage peaked and plateaued in the early 1980s (Fernandez-Cornejo et al., 2014; Arshad et al., 2025e).

Leguminous cover crops (*Mucuna deeringiana* (Bort) Merr., *Canavalia ensiformis* (L.) DC., *Leucaena leucocephala* (Lam.) de Wit, *Lysiloma latisiliquum* (L.) Benth.) utilized both as living cover crops and as dead mulch (integrated into the soil surface) have demonstrated a reduction in weed biomass. Notably, the most significant decrease in weed biomass (68%) was observed with *M. deeringiana* functioning as a living cover crop in maize cultivation. The suppressive impact of these legumes on weed growth and development can be attributed to their allelopathic characteristics. The aqueous leachates from all four leguminous species showed pronounced phytotoxic effects on the root development of *E. crus-galli* and *Amaranthus hypochondriacus* (L.) (Caamal-Maldonado et al., 2001). Furthermore, aqueous leachates derived from fresh foliage and the volatile compounds of *Tephrosia vogelii* Hook. inhibited the germination and growth of *Festuca arundinacea Schreb., Cynodon dactylon* (L.) Pers. and *Digitaria sanguinalis* (L.) Scop. In addition, the application of mulch from this leguminous cover crop led to a reduction in weed biomass (15.8%) within maize cultivation (Wang et al., 2011; Akbar et al., 2025a). The allelopathic influence observed in legumes is dependent on the specific variety and may possess a genetic foundation. The suppressive effect of various *M. sativa* cultivars on weed populations was found to be directly correlated with the quantity and concentration of growth inhibitors (phenolic compounds) that demonstrated significant allelopathic activity. Consequently, the suppression of weeds by leguminous cover crops may be directly proportional to their allelopathic intensity (Xuan et al., 2005). When *M. sativa* was incorporated into the soil (as mulch) for the purpose of weed management, the phenolic acids present in the soil reached peak concentrations within 10 to 15 days and remained effective for a duration of 20 to 25 days. The compounds released from allelopathic plants incorporated into the soil are toxic and can inhibit specific species, suggesting their potential application as a biological strategy for weed management (Xuan et al., 2005). Importantly, these organic inputs not only suppress weeds but also add carbon and nutrients to the soil, stimulating microbial communities and enhancing soil fertility over time. This dual function directly connects weed control with improved soil quality and plant nutrition, which is essential for sustainable farming systems.

5.4 Dead mulches and synthetic mulches

One of the most often used management techniques that can reduce weed problems is "mulching," which is the process of covering the soil with plant wastes or residues or synthetic materials. This can either stop weed seeds from germinating at all or stop the growth of emerging seedlings. Additionally, it encourages biodiversity and water management that is sustainable (ADVID -2019). The control of temperature variations and enhanced physical, chemical and biological properties of the soil are other benefits of mulching. Importantly, organic mulches decompose over time, contributing to soil organic matter buildup, which improves soil structure, cation exchange capacity and nutrient-holding ability. There are several types of mulches, including synthetic mulches like plastic and natural mulches like straw, sawdust, weeds, paper and plant waste (Mia et al., 2020). The application of plant residues, organic waste or synthetic substances to the soil surface, commonly termed "mulching," represents one of the most widely employed agronomic practices that can mitigate weed proliferation, either by inhibiting the germination of weed seeds or by obstructing the development of nascent seedlings. Additionally, mulching fosters the sustainable conservation of water resources and enhances biodiversity (Gnanavel, 2015). By reducing soil erosion and improving moisture retention, mulches create a favorable environment for root growth and nutrient uptake, ultimately enhancing crop nutrition. Various forms of mulch are available, encompassing natural options such as straw, sawdust, unwanted vegetation, paper and plant remnants as well as synthetic alternatives like plastic (Mia et al., 2020). Materials such as black polyethylene have been utilized for weed management across diverse agricultural production systems, particularly in horticultural crops (e.g., strawberries, tomatoes, eggplants, muskmelons, watermelons, etc.) (Pannacci et al. 2017). Innovative plastic mulches have been engineered to filter out photosynthetically active radiation while allowing infrared light to penetrate, thereby warming the soil. These infrared-permeable mulches have demonstrated efficacy in weed control (Korresa et al., 2019). However, unlike organic mulches, synthetic mulches do not directly contribute to soil nutrient cycling and long-term reliance on them may reduce soil organic matter unless supplemented with organic amendments. It is noteworthy that mulching tends to be more efficacious against annual weeds as opposed to perennial varieties (e.g., *Cyperus spp*., *Elymus repens* (L.) Gould., *Cynodon dactylon* (L.), *Sorghum halepense* (L.) Pers.) due to their substantial capacity to penetrate plastic (Schonbeck 2011; Nawaz et al., 2025). Overall, the integration of mulches into cropping systems not only suppresses weeds but also sustains soil fertility, promotes microbial activity and ensures balanced nutrient cycling—key drivers of soil quality and sustainable plant nutrition.

6. Chemical control: benefits and limits

Population growth and other reasons are driving an increase in the demand for food worldwide (Dijk et al., 2021). As a result, farming practices like controlling agricultural weeds are becoming more and more important in ensuring food security. Reducing the adverse environmental effects of agricultural production is similarly significant, considering that there are around 5 billion hectares of farmland and pastures in the globe (FAOSTAT 2020). Regretfully, it's possible that the majority of the weed management methods used now are not sustainable. But herbicides remain widely used due to cost-effectiveness and ease of application, particularly in large-scale commodity crops. Herbicides account for a large share of pesticide volumes and farmer expenditure in many countries (Gianessi et al., 2007). However, their extensive use has led to many negative consequences including herbicide resistance, environmental contamination and impacts on non-target organisms. Continuous herbicide applications may also disrupt soil microbial communities, which play a central role in nutrient mineralization and organic matter turnover, thereby indirectly reducing soil fertility and nutrient availability to crops. Best practice for chemical control includes rotation of herbicide modes of action, tank-mix or sequence strategies when appropriate, targeted application (spot-spraying), reduced rates combined with cultural tactics and strict adherence to label recommendations and buffer rules to protect water and non-target habitats. Farmers are switching from destructive traditional agriculture that relies heavily on chemicals to more environmentally friendly and sustainable farming methods in order to meet the growing demand from customers. Minimizing reliance on herbicides not only protects biodiversity but also helps maintain balanced nutrient cycling by preserving beneficial soil organisms such as nitrogen-fixing bacteria and mycorrhizal fungi. As a result of this evolution, new ecologically friendly and sustainable weed management options have emerged. The core tenet of sustainable weed management is to stop weeds from spreading instead than trying to control them after they have grown and begun to pose a threat (Sims et al., 2018; Arshad et al., 2025d). A variety of weed control techniques, including crop rotation, intercropping, crop competitiveness tillage, mulching, biological control agents and green/bioherbicides, which avoid the use of chemical herbicides, are included in sustainable weed management. Biological weed management is a method that uses biotic agents, natural enemies, or natural compounds to inhibit weed population growth and germination to an economic threshold level. The application techniques for bioherbicides and traditional herbicides are comparable; however, in the case of mycoherbicides, the pathogenic fungus are "inoculated" by spraying the pathogens onto the target weeds. Bioherbicides have recently been recognized as an essential component of weed management (Hoagland et al., 2007), albeit they should not be used in place of conventional herbicides (Singh et al., 2009). Compared to synthetic herbicides, bioherbicides are less disruptive to soil enzyme activity and nutrient dynamics, thereby helping preserve soil quality and supporting sustainable plant nutrition. Herbicide resistance and environmental hazards are linked to intensive tillage and herbicide usage. To decrease the use of herbicides and soil tillage while preserving agricultural productivity, ecosystem service supply and biodiversity, new weed control techniques must be developed. The ecological interactions between weeds and crops, which differ based on the morpho-functional characteristics of the crops and weeds, should be reflected in these techniques. Weed management efforts can be scaled down and certain weeds preserved for the provision of ecosystem services and biodiversity maintenance if a weed community does not significantly impact agricultural output or quality (MacLaren et al., 2019). Maintaining a balanced weed community can also reduce soil nutrient depletion by limiting aggressive nutrient-demanding weeds while allowing beneficial species to improve organic matter inputs and soil nutrient cycling. Therefore, encouraging neutral weed communities is a good way to improve agricultural systems' long-term sustainability and production. We provide two methods for establishing weed communities that are neutral. While the second strategy depends on choosing certain weed species for conservation or eradication, the first strategy aims to increase weed biodiversity. According to (Liebman et al., 2001), one of the main goals of ecological weed management is to change the makeup of weed communities from unwanted to desirable plant species. Both tactics will aid in this effort. Ultimately, the careful integration of chemical and ecological approaches to weed management is essential not only for weed suppression but also for sustaining soil fertility, nutrient availability and overall soil quality that underpin long-term agricultural productivity.

6.1 Mechanisms of Herbicide Resistance

Over time, weed populations have evolved several mechanisms of herbicide resistance (such as target site resistance, cross and multiple resistance, metabolic resistance, sequestration, etc.) (Powles et al., 2001; Gaines et al., 2020; Arshad et al., 2025c). Consequently, herbicide resistance has been documented in 266 species of weeds (comprising 153 dicots and 113 monocots) across 21 out of the 31 recognized modes of action, in response to 164 distinct herbicides, within 96 different crops (Heap-2022). The widespread reliance on herbicides not only selects for resistant weed biotypes but can also disrupt soil microbial diversity, which is critical for nutrient cycling and organic matter decomposition, ultimately influencing plant nutrient uptake efficiency. Additional adverse ramifications of herbicide application manifest (1) directly through environmental degradation (notably soil and groundwater contamination and the accumulation of heavy metals) and (2) indirectly affecting the health and welfare of both humans and animals. Soil contamination with herbicide residues can alter enzyme activity, reduce beneficial microbial populations such as nitrogen-fixers and mycorrhizal fungi and thereby impair soil fertility and long-term nutrient availability to crops. Therefore, in order to meet market demands and ensure a greater focus on improving the current and developing new non-chemical methods for safe and successful weed control in agriculture, Jabran et al. (2018) ensuring a more precise ecological integrated weed management (EIWM), Monteiro et al. (2022) reported modern agricultural production necessitates a shift in producers' awareness. Integrating resistance management with ecological practices not only delays resistance evolution but also helps sustain soil quality by reducing chemical loads, preserving nutrient cycling processes and maintaining soil-plant health relationships. By implementing the current (conventional/modern) management choices in a progressive way (Swanton et al., 1991), EIWM generally seeks to maintain the advantage of crops over weeds throughout the season (Sullivan et al., 2003).

7. Allelopathy: opportunities and caveats

Allelopathy — chemical interference among plants — offers potential tools (cover crops, extracts, allelopathic cultivars) for weed suppression. Many compounds (phenolics, terpenoids, benzoxazinoids) have shown phytotoxic effects (MacLaren et al., 2019). However, allelopathic effects are context-dependent, can affect non-target crops or soil biota and are influenced by soil processes (adsorption, degradation), so field validation at scale is essential before large-scale adoption. Since many allelochemicals interact with soil microorganisms, they can alter nutrient mineralization and organic matter turnover, thereby directly linking allelopathy to soil fertility and nutrient dynamics. Breeding or engineering crops for allelopathy is a potential avenue but requires careful ecological risk assessment because allelochemicals may reduce beneficial plant-plant interactions and soil biodiversity. For instance, excessive accumulation of allelochemicals in soil can suppress not only weeds but also beneficial microbes such as nitrogen fixers and mycorrhizal fungi, leading to reduced nutrient availability for crops. Conversely, moderate and well-managed allelopathic effects may improve soil quality by reducing weed pressure, conserving soil moisture and enhancing nutrient-use efficiency of crops. Any negative or positive impact, direct or indirect, that one plant (donor) has on another (target) by the release of chemical compounds into the environment is known as allelopathy, a biochemical phenomenon having ecological ramifications (Rice, 1984). Both conspecific (autoallelopathy or autotoxicity) and heterospecific (heterotoxicity) species may suffer adverse consequences from allelochemicals, or the protective secondary metabolites engaged in allelopathic interactions. Phenolic compounds (simple phenols, flavonoids, quinones, coumarins, etc.), terpenoids (mono-, di- and triterpenes, sesquiterpenes and steroids) and compounds with a nitrogen atom (e.g., benzoxazinoids) are the most representative of their vast array of chemical classes. Given that the obvious effects on target plants (such as reduced seedling growth or inhibition of seed germination) are frequently secondary indicators of primary changes (such as inhibition of cell division and elongation, interference with cell membrane permeability, enzymatic activities, respiration and photosynthesis, etc.), allelochemicals have the most diverse mechanisms of action. (Scavo et al., 2018). These biochemical interferences not only reduce weed competitiveness but also shape soil enzymatic activities, which in turn affect nutrient cycling and soil structural stability. Additionally, in field conditions, mixtures of allelochemicals typically work together to produce allelopathic effects. Allelochemicals have been reviewed and studied for their potential as biopesticides to control weeds, insects and illnesses in agriculture (Khanh et al., 2005, Farooq et al., 2011; Arshad et al., 2025b). Only the negative impacts of allelopathy and plant-plant interactions will be examined in this study, with particular attention paid to allelopathic interference between crops and weeds. Since allelopathy is a polygenetic trait that has a poor correlation with yield, it is necessary to modify many genes in order to encode the production of allelochemicals. In the case of benzoxazinoids like DIMBOA and DIBOA among Poaceae members, this feature has been noted (Frey et al., 1997). Recombinant DNA, polymerase chain reaction, metabolic engineering, overexpression of genes and other Genitivally engineered technologies are being evaluated to better understand the metabolic pathways, enzymes and genes involved in the manufacture of allelochemicals in order to solve these challenges (Tesio and Ferrero, 2010; Soltys et al., 2013). With significant allelopathic potential, Brassica is a crucial genus within the Brassicaceae family. *Brassica oleifera* L. and *Brassica napus* L., commonly referred to as the oilseed crop, are among its about 100 species (Siemens et al., 2002). Numerous techniques, including cover crops, crop rotations, water extract application, mulching, intercropping and crop residue integration, have been used to employ a number of brassica species (Farooq et al., 2013). In addition to weed suppression, the glucosinolate breakdown products of Brassica species can improve soil organic matter decomposition and nutrient release, thereby contributing to soil quality enhancement. The roots, stems, leaves and flowers of the black mustard (*B. nigra* L.) plant contain water derivatives that prevent radish, oat, lentil and alfalfa seedlings from germinating and growing (Turk and Tawaha, 2002 and 2003). The use of rye mulch reduced weed biomass and enhanced soybean yield, according to a field research by (Smith et al., 2011; Arshad et al., 2025e).

Thus, despite the undesirable side effects, the use of synthetic pesticides for efficient weed control has become essential. Organic fruits, vegetables, dairy products and drinks have gained popularity recently worldwide, especially in industrialized nations. Although they only make up a small portion of the food sector, organic products have attracted a lot of attention from academics, businesspeople and consumers due to their rapid rise. Nearly two million products were produced in 2013 and Asia accounts for 36% of all organic farmers worldwide, with Africa coming in second at 29% and Europe at 17%. Over the past few decades, sales of organic products have continuously risen (Willer and Yussefi, 2005)

8. Conservation agriculture, no-till and weed dynamics

Conservation tillage and no-till systems conserve soil moisture and reduce erosion, but they change weed community dynamics and may increase reliance on non-inversion strategies (Carr et al., 2006). Transitioning to conservation systems should be paired with diversified rotations, cover crops and targeted non-chemical tactics to avoid simple substitution of tillage with herbicide dependence. Historical increases in herbicide resistance coincided with many changes in cropping systems, but causation is complex and context-specific; conservation agriculture brings both soil benefits and new weed management challenges that must be managed adaptively. In addition to weed suppression, conservation tillage improves soil organic carbon, enhances nutrient cycling and strengthens soil structure, which collectively foster sustainable soil fertility and plant nutrition.

The enhancement of agricultural yield and the amelioration of soil conditions may be achieved through the transition from traditional or conventional tillage methods to conservation tillage systems, which are broadly characterized as any array of techniques that mitigate soil or water erosion in contrast to a conventional system that relies on soil inversion (Lal et al., 1994). In this broad context, minimum tillage and reduced tillage are frequently utilized interchangeably with conservation tillage. More specifically, conservation tillage is delineated as any array of practices that maintains a minimum of 30% of the soil surface covered by crop residues post-seeding (Lal et al., 1994). Zero tillage, also known as no tillage, direct seeding and direct drilling, encompasses cropping systems wherein soil disruption is confined to that which occurs during seeding, employing disk openers that may be preceded by narrow cutting coulters affixed to the planting apparatus. Zero tillage represents the conservation tillage methodology that preserves the highest quantities of crop residues on the soil surface, with the advantages being particularly evident in arid regions following the implementation of zero tillage, where the conservation of soil moisture is a notable benefit (Carr et al., 2006). Crop residue retention in no-till also adds organic matter that acts as a slow-release nutrient source, thereby improving nitrogen availability, cation exchange capacity and microbial-mediated nutrient transformations essential for long-term soil fertility. Cover crops constitute a fundamental element of organic zero tillage systems. These cover crops provide numerous ecosystem services when integrated into rotations with commercial crops, encompassing enhancements in soil and water quality and benefits in nutrient cycling (Snapp et al., 2005, Cherr et al., 2006). Nevertheless, the principal application of cover crops in organic zero tillage is to generate vegetative mulch aimed at suppressing weed growth. Beyond weed suppression, cover crops fix atmospheric nitrogen (in the case of legumes), reduce nutrient leaching and promote rhizosphere microbial activity, which together enhance soil quality and improve nutrient availability for subsequent crops.

9. Technological innovations and digital tools

In order to increase the relative competitive ability of crops, this suggests that using non-chemical ways to suppress weed germination and reduce weed density in crops (Pardo et al., 2010). By reducing the detrimental effects of agrochemicals (herbicides) on human health, the environment, invasive weed spread, weed resistance and weed shifts, the ultimate objective is to achieve a long-term weed management approach. With the advent of new cultivation methods, digital agriculture, new food chains, improved labeling, carbon emission monitoring and sustainable use of chemicals and water, the once common and conventional crop and food production systems have been modernized. Ecologically friendly procedures that support safe products and guarantee human health are the next step in the Union's "greening," albeit the outcomes are still up for discussion. However, because agricultural systems rely so significantly on outside inputs, they continue to be quite susceptible. Precision agriculture, remote sensing for weed mapping, camera-based weeding robots, variable-rate applicators and decision-support systems (including mobile apps) can improve timeliness and spatial targeting of weed control, reduce herbicide volumes and help manage resistance. By minimizing excessive herbicide applications through site-specific technologies, the risk of chemical accumulation in soil is reduced, thereby protecting soil microbial communities that are vital for organic matter decomposition and nutrient cycling. Including farmer-accessible decision-support tools (simple threshold charts, region-specific weed identification guides) as part of extension services increases the chance of adoption, especially among smallholders (Arshad et al., 2025a). Furthermore, digital innovations that integrate weed mapping with soil fertility monitoring can help farmers optimize fertilizer placement, reduce nutrient losses and promote balanced plant nutrition while sustaining long-term soil quality.

10. Integrated Weed Management: Principles and Global Adoption

Integrated Weed Management (IWM) is instrumental in the weed control strategies employed within the advanced agricultural systems of developed nations, particularly within the European Union, whereas its adoption remains insufficient in developing regions (Scavo et al., 2022). The effective implementation of IWM necessitates a synergistic application of diverse weed management techniques (including agronomic, physical, mechanical and chemical approaches) within a comprehensive system, rather than dependence on a singular method. This multi-layered approach is critical in mitigating the selection pressure that contributes to the emergence of resistance against any sole weed control strategy. Moreover, the implementation of non-chemical weed management approaches in minor crop production is essential due to the limited availability of chemical herbicides (Pannacci et al., 2017). In contrast to conventional methodologies, IWM incorporates a variety of agro-ecological practices, such as understanding the effects of conservation tillage and crop rotation on weed seed bank dynamics, forecasting the critical period of weed interference alongside crop competition and defining specific thresholds for crop/weed interactions (Sims et al., 2018; Nath et al., 2024; Arshad et al., 2025). Beyond weed suppression, IWM plays a vital role in maintaining soil structure, protecting beneficial soil biota and enhancing organic matter turnover, all of which are central to sustaining soil fertility. By minimizing herbicide dependency and incorporating cultural and biological practices, IWM reduces chemical residues in soils, thereby improving nutrient availability and fostering balanced plant nutrition.

11. Recommendations for practice and policy

Weed management has implications not only for crop yields but also for soil fertility, nutrient cycling and environmental sustainability. Effective weed control enhances soil nutrient availability by reducing competition for nitrogen, phosphorus and other essential elements, while preserving soil structure and microbial activity that support long-term fertility. Translating research findings into actionable practices and supportive policy measures is essential for scaling up integrated approaches. The following recommendations elaborate on practical steps for farmers and guidance for policymakers:

1. **Adopt prevention-first strategies.** Preventing weeds from entering the production system is the most cost-effective and sustainable approach. Farmers should prioritize the use of certified clean seed, sanitation of farm machinery to prevent weed seed dispersal and preparation of weed-free seedbeds. Regular monitoring of irrigation channels, bunds and field margins also helps reduce the introduction of invasive weed species. By minimizing early weed pressure, preventive measures allow

crops to access more soil nutrients, improving growth and yield while reducing the depletion of soil organic matter caused by excessive weed-crop competition. Preventive measures reduce the weed seedbank and lessen the burden on subsequent control measures.

2. **Design diversified rotations and incorporate cover crops.** Monocropping fosters weed species that are adapted to specific cropping systems, whereas diversified rotations interrupt weed life cycles. Including legumes, cereals and cover crops not only suppresses weeds but also improves soil organic matter, enhances nutrient availability and promotes biological activity. Leguminous cover crops, in particular, contribute to soil nitrogen fixation, while deep-rooted species improve nutrient cycling and soil structure, thereby sustaining plant nutrition for subsequent crops. Cover crops such as rye, clover or vetch provide ground cover, reducing weed emergence while contributing to soil fertility.
3. **Use monitoring and thresholds.** Instead of relying on calendar-based herbicide sprays, farmers should adopt scouting-based approaches to assess weed density and species composition. Extension agents should train farmers to use economic thresholds and critical periods of weed competition to decide whether interventions are necessary. Targeted interventions reduce the overuse of chemicals, preventing negative impacts on soil microbial communities and maintaining nutrient mineralization processes critical for plant nutrition. This reduces unnecessary chemical inputs, lowers production costs and minimizes ecological damage.
4. **Rotate herbicide modes of action and use targeted application technologies.** Where herbicides remain necessary, they should be used judiciously. Rotating modes of action, using tank mixtures and employing precision technologies such as spot sprayers or shielded sprayers can slow resistance evolution. These practices also reduce herbicide residues in the soil, protecting soil microbial diversity and nutrient cycling functions that are essential for crop growth. These measures help maintain herbicide efficacy and reduce off-target contamination.
5. **Invest in research and extension for alternative approaches.** Emerging technologies such as bio herbicides, allelopathic crop cultivars and robotic or mechanical weeders show promise but require locally adapted research. Public and private research institutions, in collaboration with extension services, should focus on improving formulations, delivery systems and farmer-friendly tools to increase adoption at scale. Developing and promoting bioherbicides and allelopathic cultivars can suppress weeds while simultaneously supporting soil health, enhancing

organic matter turnover and maintaining essential nutrient availability for crops.

6. **Promote supportive policies and incentives.** Policy interventions are vital for encouraging sustainable practices. Governments and development agencies should provide subsidies for cover crop seeds, tax incentives for purchasing precision weeding tools and payments for ecosystem services to reward farmers who adopt soil- and biodiversity-friendly weed management. Certification schemes and market premiums for sustainably produced crops can further stimulate adoption. Policies that incentivize soil- and nutrient-friendly weed management ultimately strengthen soil fertility, enhance plant nutrition and ensure the long-term sustainability of cropping systems.

By combining preventive measures, diversified farming practices, modern technologies and enabling policies, weed management can shift from reactive control toward proactive, sustainable ecosystem management (Nath et al., 2024; Arshad et al., 2020, 2024, 2025a). This integrated approach ensures that weed management not only protects crop yields but also sustains soil quality and optimizes nutrient availability for future crop productivity.

12. Research gaps and future directions

High-priority research needs include:

- Long-term field trials comparing combinations of IWM tactics on soil health indicators and crop nutrient-use efficiency. Such studies should quantify how integrated weed management strategies influence soil organic matter, microbial diversity, nutrient mineralization and the availability of essential nutrients like nitrogen and phosphorus for crop uptake.
- Improved formulations and delivery systems for bio-herbicides and crop-derived extracts. Research should also assess how these biologically based products interact with soil microbial communities and nutrient cycling, ensuring that weed suppression does not compromise soil fertility or plant nutrition.
- Socio-economic studies to identify barriers to adoption of IWM in smallholder and resource-limited contexts. These studies can incorporate evaluation of soil and crop nutrient benefits from adopting sustainable weed management practices, which can strengthen the economic case for IWM adoption.
- Development and validation of farmer-friendly decision-support tools for threshold-based management and resistance monitoring. Tools should integrate information on soil fertility status and nutrient availability,

allowing farmers to make informed decisions that optimize both weed control and plant nutrition.

13. Conclusions

Weed management is central to sustaining plant nutrition and soil quality. A shift from single-tool dependence (often herbicides) to diversified, ecology-based strategies will reduce negative environmental impacts and preserve soil functions while maintaining agricultural productivity. Effective weed management enhances nutrient availability by reducing competition for essential nutrients like nitrogen, phosphorus and potassium, while maintaining soil organic matter and microbial activity that are critical for soil fertility. Implementing such strategies requires integrated research, farmer training, practical decision-support tools and supportive policies. Moreover, adopting cover crops, mulches, crop rotations and allelopathic cultivars not only suppresses weeds but also improves soil structure, water retention and nutrient cycling, creating a more resilient and productive agroecosystem.

References

Abbas, A., Wang, Y., Muhammad, U., & Fatima, A. (2021a). Efficacy of different insecticides against gram pod borer (Helicoverpa armigera) and their safety to the beneficial fauna. *International Journal of Biosciences, 18*, 82-88.

Abbas, R. N., Arshad, M. A., Iqbal, A., Iqbal, M. A., Imran, M., Raza, A., & Hefft, D. I. (2021). Weeds spectrum, productivity and land-use efficiency in maize-gram intercropping systems under semi-arid environment. *Agronomy, 11*(8), 1615.

Akbar, B. A., Arshad, M. A., Khalid, B., Baloch, R., Ahmad, A., Rouf, S., ... & Maqbool, R. (2025). Chloroplast engineering and RNA interference: A dual-technology approach for insect pest control. *Journal of Pure and Applied Agriculture*, *10*(1), 1-20.

Akbar, B. A., Arshad, M. A., Mahmood, M. H., Iqbal, N., & Faisal, M. (2025a). The Expression of Cry1ac in Gossypium Hirsutum Against Chewing Insects via Agrobacterium Mediated Genetic Transformation. *J Agri Horti Res*, *8*(1), 01-10.

Akhter, M. J., Abbas, R. N., Waqas, M. A., Noor, M. A., Arshad, M. A., Mahboob, W. M., & Gull, U. G. (2017). Adjuvant improves the efficacy of herbicide for weed management in maize sown under altered sowing methods.

Aleem, S. (2024). Advancements in Mutation Breeding in Phalsa (Grewia asiatica L.) Crop Improvement: A Comprehensive Review of Radiation and Chemical Induced Mutagenesis Studies. *Haya Saudi J Life Sci*, *9*(5), 158-171.

Arshad, M, A., Mahmood, M, H., Ishaq, M, W., Hayat, M, U., Khan, S., et al. (2025a). Smart Farming Evolution: Integrating AI Precision Agriculture for Advanced Weed Management. J Agri Horti Res, 8(1), 01-13.

Arshad, M. A. (2021b). A review on wheat management, strategies, current problems and future perspectives. *Haya: Saudi Journal of Life Sciences, 6*, 14-18.

Arshad, M. A., Abbas, R. N., Baloch, R., Ahmad, A., Zulfiqar, U., El-Beltagi, H. S., Alomran, M. M., & Vara Prasad, P. V. (2025e). Assessing herbicide efficacy and selectivity for weed management and enhancing the production of non-GMO soybean cultivation. Archives of Agronomy and Soil Science, 71(1), 1–23. https://doi.org/10.1080/03650340.2025.2554157

Arshad, M. A., Abbas, R. N., Khaliq, A., & Ahmed, Z. (2024a). Assessing herbicide efficacy and susceptibility for weed management and enhancing production of non-GMO soybean cultivation.

Arshad, M. A., Abbas, R. N., Khaliq, A., & Ahmed, Z. (2025). Ecological approaches to sustainable soybean production with sequential herbicide applications and their impact on weed dynamics and crop yield. *Journal of Ecological Engineering*, *26*(2).

Arshad, M. A., Akbar, B. A., Jawad, A., Mahmood, M. H. (2025c). Integrating Environmental Health and Food Security: The Agronomist's Role in Advancing Sustainable Agriculture and Achieving UN Sustainable Development Goals. Plant, 13(2), 53-75. https://doi.org/10.11648/j.plant.20251302.13

Arshad, M. A., Akbar, B. A., Shehzadi, N., Iqbal, N., Mushtaq, M. Z., Rouf, S., & Jawad, A. (2025b). Nanoparticles in Plant Genetic Engineering: Innovative Tools and Future Prospects for Enhanced Crop Traits and Agricultural Sustainability. *Journal of Plant Sciences*, *13*(2), 38-58.

Arshad, M. A., Ishaq, M. W., Siddique, M. B., & Mahmood, M. H. (2025d). Organic Weed Management in Soybean (Glycine Max L.), Recent Trends, Challenges and Future Predictions. *International Journal of Agricultural Sciences and Technology (IJAGST)*, *5*(1).

Arshad, M. A., Rouf, S., Abbas, R. N., Aleem, K., Sarwar, A., Shahbaz, Z., Baloch, R., Rehman, H. u., & Masood, M. T. (2024). Environmental benefits and risks of herbicides use in forestry– Review. *Haya: Saudi Journal of Life Sciences, 9*(2), 23-35.

Arshad, M. A., Rouf, S., Abbas, R. N., Shahbaz, Z., Aleem, K., Shahbaz, H., Pervaiz, R., Sarwar, A., & Rehman, H. u. (2024c). Navigating synergies: A comprehensive review of agroforestry system and agronomy crops. *Haya: Saudi Journal of Life Sciences, 9*(4), 97-112.

Babalola, O. O., Truter, J. C., & Van Wyk, J. H. (2021). Lethal and teratogenic impacts of imazapyr, diquat dibromide and glufosinate ammonium herbicide formulations using frog embryo teratogenesis assay-Xenopus (FETAX). *Archives of Environmental Contamination and Toxicology, 80*(4), 708–716. https://doi.org/10.1007/s00244-020-00820-7

Ball, K. R., Baldock, J. A., Penfold, C., Power, S. A., Woodin, S. J., Smith, P., & Pendall, E. (2020). Soil organic carbon and nitrogen pools are increased by mixed grass and legume cover crops in vineyard agroecosystems: Detecting short-term management effects using infrared spectroscopy. *Geoderma, 379,* 114619. https://doi.org/10.1016/j.geoderma.2020.114619

Bone, J., Head, M., Barraclough, D., Archer, M., Scheib, C., Flight, D., & Voulvoulis, N. (2010). Soil quality assessment under emerging regulatory requirements. *Environment International, 36*(6), 609–622. https://doi.org/10.1016/j.envint.2010.04.010

Brooker, R. W., Bennett, A. E., Cong, W.-F., Daniell, T. J., George, T. S., Hallett, P. D., Hawes, C., Iannetta, P. P. M., Jones, H. G., Karley, A. J., Li, L., … Zhang, C. (2015). Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. *New Phytologist, 206*(1), 107–117. https://doi.org/10.1111/nph.13132

Bulluck, L. R. III, Brosius, M., Evanylo, G. K., & Ristaino, J. B. (2002). Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. *Applied Soil Ecology, 19*(2), 147–160. https://doi.org/10.1016/S0929-1393(01)00187-1

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry, 120,* 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Caamal-Maldonado, J. A., Jiménez-Osornio, J. J., Torres-Barragán, A., & Anaya, A. L. (2001). The use of allelopathic legume cover and mulch species for weed control in cropping systems. *Agronomy Journal, 93*(1), 27–36. https://doi.org/10.2134/agronj2001.93127x

Carr, P. M., Martin, G. B., & Horsley, R. D. (2006). Impact of tillage and crop rotation on spring wheat: I. Tillage effect. *Crop Management, 5*(1), 1–11. https://doi.org/10.1094/CM-2006-0227-01-RS

Cherr, C. M., Scholberg, J. M. S., & McSorley, R. (2006). Green manure approaches to crop production: A synthesis. *Agronomy Journal, 98*(2), 302–319. https://doi.org/10.2134/agronj2005.0035

Dick, R. P. (1997). Soil enzyme activities as integrative indicators of soil health. In C. E. Pankhurst, B. M. Doube, & V. V. S. R. Gupta (Eds.), *Biological indicators of soil health* (pp. 121–156). CAB International.

Doran, J. W., & Jones, A. J. (Eds.). (1996). *Methods for assessing soil quality*. Soil Science Society of America.

Doran, J. W., & Parkin, T. B. (1994). Defining and assessing soil quality. In J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart (Eds.), *Defining soil quality for a sustainable environment* (pp. 3–21). Soil Science Society of America. https://doi.org/10.2136/sssaspecpub35.c1

Elhakeem, A., van der Werf, W., Ajal, J., Lucà, D., Claus, S., Vico, R. A., & Bastiaans, L. (2019). Cover crop mixtures result in a positive net biodiversity effect irrespective of seeding configuration. *Agriculture, Ecosystems & Environment, 285,* 106627. https://doi.org/10.1016/j.agee.2019.106627

Farooq, M., Bajwa, A. A., Cheema, S. A., & Cheema, Z. A. (2013). Application of allelopathy in crop production. *International Journal of Agriculture and Biology, 15*(6), 1367–1378.

Farooq, M., Jabran, K., Cheema, Z. A., Wahid, A., & Siddique, K. H. M. (2011). The role of allelopathy in agricultural pest management. *Pest Management Science, 67*(5), 493–506. https://doi.org/10.1002/ps.2091

Fernandez-Cornejo, J., Nehring, R., Osteen, C., Wechsler, S., Martin, A., & Vialou, A. (2014). *Pesticide use in U.S. agriculture: 21 selected crops, 1960–2008* (Economic Information Bulletin No. 124). U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=43854

Food and Agriculture Organization of the United Nations (FAO). (2020). *FAOSTAT*. https://www.fao.org/faostat/en/#data/RL

Frey, M., Chomet, P., Glawischnig, E., Stettner, C., Grün, S., Winklmair, A., Eisenreich, W., Bacher, A., Meeley, R. B., Briggs, S. P., Simcox, K., & Gierl, A. (1997). Analysis of a chemical plant defense mechanism in grasses. *Science, 277*(5326), 696–699. https://doi.org/10.1126/science.277.5326.696

Gaines, T. A., Duke, S. O., Morran, S., Rigon, C. A. G., Tranel, P. J., Küpper, A., & Dayan, F. E. (2020). Mechanisms of evolved herbicide resistance. *Journal of Biological Chemistry, 295*(30), 10307–10330. https://doi.org/10.1074/jbc.REV120.013572

Gianessi, L. P., & Reigner, N. P. (2007). The value of herbicides in U.S. crop production. *Weed Technology, 21*(3), 559–566. https://doi.org/10.1614/WT-06-130.1

Gnanavel, I. (2015). Eco-friendly weed control options for sustainable agriculture. *Science International, 3*(1), 37–47.

Heap, I. (2021). *The international herbicide-resistant weed database*. Retrieved September 1, 2021, from http://www.weedscience.org

Heap, I. (n.d.). *The international herbicide-resistant weed database*. Retrieved February 20, 2022, from http://www.weedscience.org

Hemathilake, D., & Gunathilake, D. (2022). Agricultural productivity and food supply to meet increased demands. In D. Barling (Ed.), *Future foods* (pp. 247–265). Academic Press. https://doi.org/10.1016/B978-0-323-91001-9.00016-5

Hoagland, R. E., Boyette, C. D., Weaver, M. A., & Abbas, H. K. (2007). Bioherbicides: Research and risks. *Toxin Reviews, 26*(3), 313–342. https://doi.org/10.1080/15569540701623192

Jabran, K., & Chauhan, B. S. (2018). *Non-chemical weed control*. Academic Press.

Khanh, T. D., Chung, M. I., Xuan, T. D., & Tawata, S. (2005). The exploitation of crop allelopathy in sustainable agricultural production. *Journal of Agronomy and Crop Science, 191*(3), 172–184. https://doi.org/10.1111/j.1439-037X.2005.00162.x

Korres, N. E., Burgos, N. R., Travlos, I., Vurro, M., Gitsopoulos, T. K., Varanasi, V. K., Duke, S. O., Kudsk, P., Brabham, C., Rouse, C. E., Salas-Perez, R., ... & Norsworthy, J. K. (2019). New directions for integrated weed management: Modern technologies, tools and knowledge discovery. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 155, pp. 243–319). Academic Press. https://doi.org/10.1016/bs.agron.2019.01.004

Koudahe, K., Allen, S. C., & Djaman, K. (2022). Critical review of the impact of cover crops on soil properties. *International Soil and Water Conservation Research, 10*(3), 343–354. https://doi.org/10.1016/j.iswcr.2022.05.004

Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities and trade-offs. *Ecology and Society, 17*(4), 40. https://doi.org/10.5751/ES-05035-170440

Lal, R., Logan, T. J., Eckert, D. J., & Dick, W. A. (1994). Conservation tillage in the Corn Belt of the United States. In M. R. Carter (Ed.), *Conservation tillage in temperate agroecosystems* (pp. 73–114). Lewis Publishers.

Las Casas, G., Ciaccia, C., Iovino, V., Ferlito, F., Torrisi, B., Lodolini, E. M., Giuffrida, A., Catania, R., Nicolosi, E., & Bella, S. (2022). Effects of different inter-row soil management and intra-row living mulch on spontaneous flora, beneficial insects and growth of young olive trees in southern Italy. *Plants, 11*(4), 545. https://doi.org/10.3390/plants11040545

Liebman, M., Mohler, C. L., & Staver, C. P. (Eds.). (2001). *Ecological management of agricultural weeds*. Cambridge University Press.

Lithourgidis, A. S., Dordas, C. A., Damalas, C. A., & Vlachostergios, D. N. (2011). Annual intercrops: An alternative pathway for sustainable agriculture. *Australian Journal of Crop Science, 5*(4), 396–410. Retrieved from https://cropj.com/anastasios_5_4_2011_396_410.pdf

MacLaren, C., Bennett, J., & Dehnen-Schmutz, K. (2019). Management practices influence the competitive potential of weed communities and their value to biodiversity in South African vineyards. *Weed Research, 59*(1), 93–106. https://doi.org/10.1111/wre.12347

Mia, M. J., Massetani, F., Murri, G., & Neri, D. (2020). Sustainable alternatives to chemicals for weed control in the orchard — A review. *Horticultural Science (Prague), 47*, 1–12. https://doi.org/10.17221/29/2019-HORTSCI

Monteiro, A., & Santos, S. (2022). Sustainable approach to weed management: The role of precision weed management. *Agronomy, 12*(1), Article 118. https://doi.org/10.3390/agronomy12010118

Nath, C. P., Singh, R. G., Choudhary, V. K., Datta, D., Nandan, R., & Singh, S. S. (2024). Challenges and alternatives of herbicide-based weed management. *Agronomy, 14*(1), Article 126. https://doi.org/10.3390/agronomy14010126

Nawaz, H., Ishaq, M. W., Qadeer, S., Mahmood, M. H., Adeel, M., Anwar, I., & Zaheer, M. (2025). Assessing the threat: *Parthenium* adverse effects on biodiversity, human communities and environmental integrity. *Scholars Bulletin, 11*(3), 21–41. https://saudijournals.com/articles/11224/ *(Publisher page / PDF available; verify journal title abbreviation with publisher if you require exact formatting.)*

Ngwira, A. R., Aune, J. B., & Mkwinda, S. (2012). On-farm evaluation of yield and economic benefit of short-term maize–legume intercropping systems under conservation agriculture in Malawi. *Field Crops Research, 132*, 149–157. https://doi.org/10.1016/j.fcr.2012.03.004

Pannacci, E., Lattanzi, B., & Tei, F. (2017). Non-chemical weed management strategies in minor crops: A review. *Crop Protection, 96*, 44–58. https://doi.org/10.1016/j.cropro.2017.02.021

Pardo, G., Riravololona, M., & Munier-Jolain, N. M. (2010). Using a farming system model to evaluate cropping system prototypes: Are labour constraints and economic performances hampering the adoption of Integrated Weed Management? *European Journal of Agronomy, 33*, 24–32. https://doi.org/10.1016/j.eja.2010.01.003

Pervaiz, R., et al. (2024). Herbicide strategies for weed control in rice cultivation: Current practices and future directions. *Haya: Saudi Journal of Life Sciences, 9*(4), 114–129. *(Article metadata from journal issue; DOI not listed — please confirm with publisher if DOI required.)*

Phillips, R. E., Thomas, G. W., Blevins, R. L., Frye, W. W., & Phillips, S. H. (1980). No-tillage agriculture. *Science, 208*, 1108–1113. https://doi.org/10.1126/science.208.4448.1108

Powles, S. B., & Shaner, D. L. (2001). *Herbicide resistance and world grains* (1st ed.). CRC Press.

Rafeeq, H., Arshad, M. A., Amjad, S. F., Ullah, M. H., Imran, H. M., Khalid, R., & Ajmal, H. (2020). Effect of nickel on different physiological parameters of *Raphanus sativus*. *International Journal of Scientific Research Publications, 10*, 9702. *(Confirm issue/page formatting with journal's website; DOI not provided.)*

Rasheed, H. U. (2024). Adaptation and agricultural significance of *Syzygium cumini* L. in saline environments: A global perspective on jamun cultivation and salt stress resilience. *Haya: Saudi Journal of Life Sciences, 9*(5), 172–187. *(Confirm DOI / publisher page if required.)*

Rice, E. L. (1984). *Allelopathy* (2nd ed.). Academic Press.

Ryan, M. R., Wayman, S., Pelzer, C. J., Peterson, C. A., Menalled, U. D., & Rose, T. J. (2021). Winter wheat (*Triticum aestivum* L.) tolerance to mulch. *Plants, 10*(10), Article 2047. https://doi.org/10.3390/plants10102047

Scavo, A., Fontanazza, S., Restuccia, A., Pesce, G. R., Abbate, C., & Mauromicale, G. (2022). The role of cover crops in improving soil fertility and plant nutritional status in temperate climates: A review. *Agronomy for Sustainable Development, 42*, Article 93. https://doi.org/10.1007/s13593-022-00777-3

Scavo, A., Restuccia, A., & Mauromicale, G. (2018). Allelopathy: General principles and basic aspects for agroecosystem control. In S. Gaba, B. Smith, & E. Lichtfouse (Eds.), *Sustainable Agriculture Reviews* (Vol. 28, pp. 47–101). Springer. https://doi.org/10.1007/978-3-319-90426-0_2

Schonbeck, M. (2011). *Principles of sustainable weed management in organic cropping systems* (3rd ed.). Workshop for Farmers and Agricultural Professionals on Sustainable Weed Management, Clemson University.

Schonbeck, M., & Tillage, B. (2011). Principles of sustainable weed management in organic cropping systems. In *Workshop for Farmers and Agricultural Professionals on Sustainable Weed Management* (Vol. 3, pp. 1–24). Clemson, SC: Clemson University. *(This appears to be the same workshop material as #69 — consider keeping one entry to avoid duplication.)*

Seelan, S., Laguette, S., Casady, G. M., & Seielstad, G. A. (2003). Remote sensing applications for precision agriculture: A learning community approach. *Remote Sensing of Environment, 88*(1–2), 157–169. https://doi.org/10.1016/j.rse.2003.04.007

Siemens, D. H., Garner, S. H., Mitchell-Olds, T., & Callaway, R. M. (2002). Cost of defense in the context of plant competition: *Brassica rapa* may grow and defend. *Ecology, 83*(2), 505–517. https://doi.org/10.1890/0012-9658(2002)083[0505:CODITC]2.0.CO;2

Sims, B., Corsi, S., Gbehounou, G., Kienzle, J., Taguchi, M., & Friedrich, T. (2018). Sustainable weed management for conservation agriculture: Options for smallholder farmers. *Agriculture, 8*(8), 118. https://doi.org/10.3390/agriculture8080118

Singh, S., Chhokar, R. S., Gopal, R., Ladha, J. K., Gupta, R. K., Kumar, V., & Singh, M. (2009). Integrated weed management: A key to success for direct-seeded rice in the Indo-Gangetic Plains. In J. K. Ladha, Y. Singh, O. Erenstein, & B. Hardy (Eds.), *Integrated crop and resource management in the rice–wheat system of South Asia* (pp. 261–278). International Rice Research Institute.

Smith, A. N., Reberg-Horton, S. C., Place, G. T., Meijer, A. D., Arellano, C., & Mueller, J. P. (2011). Rolled rye mulch for weed suppression in organic no-tillage soybeans. *Weed Science, 59*(2), 224–231. https://doi.org/10.1614/WS-D-10-00112.1

Smith, J., Pearce, B. D., & Wolfe, M. S. (2013). Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? *Renewable Agriculture and Food Systems, 28*(1), 80–92. https://doi.org/10.1017/S1742170512000170

Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J., & O'Neil, K. (2005). Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal, 97*(1), 322–332. https://doi.org/10.2134/agronj2005.0322

Soltys, D., Krasuska, U., Bogatek, R., & Gniazdowska, A. (2013). Allelochemicals as bioherbicides—Present and perspectives. In A. J. Price & J. A. Kelton (Eds.), *Herbicides—Current research and case studies in use*. IntechOpen. https://doi.org/10.5772/56185

Statista Research Department. (2023, August 7). *Forecast: Global agricultural consumption volume of herbicides 2023–2027*. Statista. https://www.statista.com/statistics/1403196/global-agricultural-use-of-herbicidesforecast/

Sullivan, P. (2003). *Principles of sustainable weed management for croplands* (ATTRA Publication No. IP139). National Sustainable Agriculture Information Service. http://www.attra.org/attra-pub/weed.html

Swanton, C. J., & Weise, S. F. (1991). Integrated weed management: The rationale and approach. *Weed Technology, 5*(3), 657–663. https://doi.org/10.1017/S0890037X00027512

Tahir, M., Arshad, M. A., Akbar, B. A., Bibi, A., Ain, Q. U., Bilal, A., & Pervaiz, R. (2024). Integrated nitrogen and irrigation management strategies for sustainable wheat production: Enhancing yield and environmental efficiency. *Journal of Pharmacognosy and Phytochemistry, 13*(4), 209–222.

Tesio, F., & Ferrero, A. (2010). Allelopathy, a chance for sustainable weed management. *International Journal of Sustainable Development & World Ecology, 17*(5), 377–389. https://doi.org/10.1080/13504509.2010.498933

The Business Research Company. (2021). *Herbicides global market report 2025–2034: By type (synthetic, bio-based), by mode of action (selective, non-selective), by application (grains and cereals, pulses and oilseeds, commercial crops, fruits and vegetables, turf and ornamentals) – Market size, trends and forecast*. The Business Research Company. https://www.thebusinessresearchcompany.com/report/herbicides-global-market-report

Turk, M. A., & Tawaha, A. M. (2002). Inhibitory effects of aqueous extracts of black mustard on germination and growth of lentil. *Pakistan Journal of Agronomy, 1*(1), 28–30.

Turk, M. A., & Tawaha, A. M. (2003). Allelopathy effect of black mustard (*Brassica nigra* L.) on germination and growth of wild oat. *Crop Protection, 22*(4), 673–677. https://doi.org/10.1016/S0261-2194(02)00236-X

van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food, 2*(7), 494–501. https://doi.org/10.1038/s43016-021-00322-9

Vandermeer, J. H. (1989). *The ecology of intercropping.* Cambridge University Press. https://doi.org/10.2307/2404385 *(Note: The citation "Simmonds, N.W.; Vandermeer, J." was likely misattributed. The correct author of The Ecology of Intercropping is John H. Vandermeer.)*

Wang, A., Zhang, W., & Wei, X. (2019). A review on weed detection using ground-based machine vision and image processing techniques. *Computers and Electronics in Agriculture, 158*, 226–240. https://doi.org/10.1016/j.compag.2019.02.005

Wang, R., Yang, X., Song, Y., Zhang, M., Hu, L., Su, Y., & Zeng, R. (2011). Allelopathic potential of *Tephrosia vogelii* Hook. f.: Laboratory and field evaluation. *Allelopathy Journal, 28*(1), 53–62.

Westwood, J., Charudattan, R., Duke, S., Fennimore, S., Marrone, P., Slaughter, D., Swanton, C., & Zollinger, R. (2018). Weed management in 2050: Perspectives on the future of weed science. *Weed Science, 66*(3), 275–285. https://doi.org/10.1017/wsc.2017.78

Willer, H., & Yussefi, M. (2005). *The world of organic agriculture 2005—Statistics and emerging trends.* International Federation of Organic Agriculture Movements.

Xuan, T. D., Shinkichi, T., Khanh, T. D., & Min, C. I. (2005). Biological control of weeds and plant pathogens in paddy rice by exploiting plant allelopathy: An overview. *Crop Protection, 24*(3), 197–206. https://doi.org/10.1016/j.cropro.2004.08.004

Xuan, T. D., Tawata, S., Khanh, T. D., & Chung, I. M. (2005). Decomposition of allelopathic plants in soil. *Journal of Agronomy and Crop Science, 191*(3), 162–171. https://doi.org/10.1111/j.1439-037X.2005.00127.x

10

PERFORMANCE EVAULATION OF DIFFERENT SOLID WASTE MANAGEMENT METHODS: HYBRID AHP-CoCoSo MODEL

Naci Yılmaz[1], Korkmaz Bellitürk[2], Ahmet Çelik[3], Zubair Aslam[4]

1.Introduction

Organic solid waste management is the effective, economical and safe management of the process by minimizing the negative impact of organic solid wastes on society and environmental health. Organic solid waste management is of great importance. Because organic waste produces strong greenhouse gases such as methane as it decomposes. Additionally, proper management plays an important role in combating climate change, and the efficient use of resources is critical for environmental health. Today, the concept of "integrated organic solid waste management", which refers to the use of more than one method together, is frequently mentioned. Integrated organic solid waste management, which refers to the use of different waste disposal methods such as waste reduction, recycling, incineration and landfill, etc., is accepted as the best viable option (Tekin, 2020). Sustainable and integrated organic solid waste management adopted by the public and using advanced technology will make a great contribution to meeting the needs of future generations (Palabıyık, 1999; Tekin, 2020).

2. Literature

Seo et al. (2004) conducted an evaluation of the environmental impacts associated with various solid waste treatment methods used in Korea. Among the methods analyzed, incineration and anaerobic digestion emerged as the most environmentally friendly options, whereas landfilling was found to have the greatest negative impact. When examining the life cycle of these treatment methods, the primary treatment stage was identified as the dominant contributor to environmental impact—accounting for between 46% and 94% of the total impact, depending on the method. Wastewater treatment also contributed to the overall environmental burden, with respective shares of 6.2%, 0.2%,

1 Assoc. Prof. Dr., Doğuş Üniversitesi, İktisadi ve İdari Bilimler Fakültesi, İktisat Bölümü (İngilizce), ORCID: 0000-0003-0107-6448. E-mail: nyilmaz@dogus.edu.tr
2 Prof. Dr., Tekirdağ Namık Kemal Üniversitesi, Ziraat Fakültesi, Toprak Bilimi ve Bitki Besleme Bölümü, ORCID: 0000-0003-4944-3497. E-mail: kbelliturk@nku.edu.tr
3 Prof. Dr., Adıyaman Üniversitesi, Ziraat Fakültesi, Toprak Bilimi ve Bitki Besleme Bölümü, ahmetcelik@adiyaman.edu.tr, ORCID: 0000-0001-8958-4978
4 Professor, Plant and Microbial Ecology lab., Department of Agronomy, University of Agriculutre, Faisalabad, ORCID: 0000-0002-3094-9175. E-mail: zubair.aslam@uaf.edu.pk

4.1%, and 9.0% for landfilling, incineration, composting, and anaerobic digestion. Among the various environmental impact categories considered, global warming, eutrophication, and acidification were the most significant, collectively representing between 53% and 91% of the total impact depending on the treatment method. Of these, global warming was the most dominant factor. Other impact categories—such as photochemical oxidant formation, abiotic resource depletion, and ozone layer depletion—were found to have minimal influence on the overall environmental footprint. These findings provide a foundation for constructing comprehensive environmental datasets and enable a more informed assessment of the life cycle impacts of different waste treatment strategies, thereby supporting effective decision-making in solid waste management.

In their study, Demirarslan & Başak (2018) investigated the solid waste amounts and management of 7 provinces in the Eastern Black Sea Region. The waste amounts of the provinces, the ratio of the municipal population to which waste service is provided to the total municipal population, the ratio of the municipal population to which waste service is provided to the total population, the population of municipalities to which waste service is provided, the number of municipalities to which waste service is provided, the amount of municipal waste collected (tons/year), the average amount of municipal waste per capita (kg/person-day) and waste disposal methods were examined. When the amount of waste per capita is compared, it is seen that as of 2016, it is seen that Giresun > Rize > Artvin > Ordu > Gümüşhane >Trabzon > Bayburt, respectively.

In their study, Negiz & Yalçın (2023) examined the circularity of cities in Turkey. They used the circularity ratio in their studies. This rate; It is the ratio of circular materials (recycled resources) to the total materials (inputs) entering the economy that year. The universe of the research is the cities of Izmir, Aydın, Gaziantep, Malatya, Ordu and Şanlıurfa, which have different levels of development in Turkey. Circularity rates were calculated for solid waste in these cities. As a result of the study, although the circularity rate is not very high in the world; It has been determined that the circularity status of cities in Turkey is far below the world average. In 2025, Wang conducted a study aimed at identifying an organic solid waste treatment method that is efficient, environmentally sustainable, and cost-effective. The research compared three approaches—landfilling, incineration, and biosynthesis technology—based on resource utilization, economic feasibility, and environmental impact. The findings revealed that biosynthesis technology presents a mixed profile in terms of resource use and cost, offering both strengths and limitations when compared to conventional methods like landfilling and incineration. However, in terms of environmental performance, biosynthesis technology stands out significantly. Its advantages stem from its mild reaction conditions, absence of secondary pollutants, and its ability to enhance soil quality while reducing greenhouse gas emissions. In contrast, landfilling poses risks of soil and groundwater contamination, and incineration can lead to the release of harmful gases. Overall, biosynthesis technology demonstrates clear superiority in environmental aspects. For resource efficiency and cost, each method has its own trade-offs, suggesting that the optimal choice may depend on the specific priorities of the waste management strategy.

3. Solid Waste Management Methods

Organic solid waste management is a critical process for protecting the environment and using resources efficiently. Here are the main methods for managing this type of waste sustainably: composting, biogas production, use as animal feed, incineration for energy recovery (prolysis), waste reduction strategies, landfill.

Composting is the controlled breakdown of organic waste, such as food scraps and garden debris, into nutrient-rich soil amendments known as humus. Recognized as a recovery method, composting can be implemented at both household and industrial scales. It significantly reduces reliance on chemical fertilizers by transforming organic solid waste into a valuable soil conditioner through aerobic (oxygen-rich) decomposition (Hoornweg & Bhada-Tata, 2012). The composting process involves extracting organic components from solid waste, adding moisture, reducing volume, stabilizing the material under aerobic conditions, and preparing it for agricultural use. With its long-standing history, composting requires relatively simple technology and is especially effective for managing kitchen and yard waste in an environmentally beneficial way. (Palabıyık, 2001).

Biogas production involves extracting methane gas from organic waste through anaerobic digestion. This process takes place in sealed, oxygen-free containers where organic materials are broken down biologically. The resulting methane can be harnessed to produce heat and electricity, making it a valuable renewable energy source. Anaerobic digestion is commonly integrated with wastewater treatment facilities and is considered a key method for recycling organic solid waste. Unlike composting, which is aerobic and generally less expensive, anaerobic digestion is more costly due to its infrastructure and operational requirements. However, methane is the primary and intended product of this process, offering significant energy potential. (Hoornweg & Bhada-Tata, 2012). Countries like South Korea widely use this method.

Food waste can be treated properly and used as animal feed. It is especially suitable for waste from restaurants and supermarkets. Utilizing food waste as animal feed is an important practice in terms of both environmental sustainability and economic efficiency. This process includes the appropriate collection, classification, processing and use of residues generated in food production and consumption processes. In particular, plant-based wastes such as vegetable and fruit pulp, bakery product residues, dairy product by-products and sugar beet pulp are rich in nutritional value and can be beneficial for animals. This method both reduces food waste and lowers feed costs. It also contributes to the circular economy and minimizes negative impacts on the environment. When applied correctly, it offers a safe and effective alternative for feeding farm animals.

In the context of recovery and reuse, certain organic materials—such as paper and wood—are recycled and reintegrated into production cycles. Additionally, some non-organic items, like glass bottles, can be reused directly without undergoing any transformation. Reuse refers to the repeated utilization of solid waste in its original form, requiring no processing beyond basic cleaning. This approach involves simple collection and sanitation, making it an efficient and low-tech method of waste management (Palabıyık and Altunbaş, 2004). The reuse of organic solid waste is very difficult.

The process of burning organic solid wastes for energy recovery (Prolysis) includes the transformation of solid wastes into solid, liquid and gaseous products by chemical oxidation and obtaining heat (Steiner and Wiegel, 2009). Solid waste incineration / gasification process, also called thermal conversion, is the process of converting commemorable wastes into an inert residue such as ash and slag at high temperatures. With waste incineration, the volume and weight of waste are reduced and its effects on the environment and public health are minimized (Öztürk and Alp, 2015). Incinerating waste for energy recovery can also reduce the volume of waste to be stored by up to 90%. However, it should be noted that such a reduction in the volume of waste is only seen in relatively bulky waste streams, which contain large amounts of packaging materials, paper, cardboard, plastic and garden waste. The recovery of the energy value embedded in the waste before storage, which is the last stage of waste disposal, is also considered a preferred process for direct soil filling. Because the recovery of this energy is necessary for the appropriate handling of process costs, as well as for the pollution control of the waste that will go to the ground. Typically, incineration without energy recovery is not a preferred option due to costs and pollution. Open combustion of waste is particularly discouraged due to severe air pollution associated with low-temperature combustion (Hoornweg and Bhada-Tata, 2012).

Waste Reduction Strategies can be implemented by not buying excess food and preventing waste. Individual contributions such as markets and restaurants selling or donating excess products at a discount and composting at home can also be considered in this context. Waste reduction or reduction at source initiatives aim to reduce the amount of waste at waste generation points by redesigning products or changing production and consumption patterns

(Hoomweg and Bhada-Tata, 2012).

As a last resort, the Landfill method can be applied. It is the storage of organic wastes in controlled areas in a way that does not harm the environment. This method should be preferred when other options are not possible. Storage is one of the first applications used by human beings to remove garbage from living spaces. The method applied in the form of leaving the wastes on a land outside the residential areas causes discomfort in terms of the damage of solid wastes to the environment. For this reason, more organized storage methods have been developed over time. In the modern solid waste management approach, the control of landfills gains importance. Regular and sanitary storage areas are built using a number of engineering methods. Although it is aimed to be used less and less in the disposal of solid waste, landfill stands out as the most used method in the world. Storage is the collection of collected wastes in a certain place by removing them from the areas where people live. An integrated and sustainable solid waste management envisages the regular storage of solid waste. However, it is still a fact that in some countries, solid wastes are dumped irregularly in open areas outside residential areas. In this respect, two types of storage can be mentioned: Wild storage and landfill (Tekin, 2020).

4. Solid Waste Processing Processes

4.1. Mechanical operation

Mechanical processing involves size reduction, separation, and compaction operations. These units can function as standalone facilities or serve as pre- or post-treatment stages alongside thermal or biological waste treatment systems. When the mechanical process emphasizes the separation or recovery of recyclable materials, the facility is typically referred to as a Material Recovery Facility (MRF). Fundamentally, mechanical processing alters the physical characteristics of waste without affecting its chemical composition. (Christensen, 2011b).

4.2. Pyrolysis

Thermal treatment methods include combustion, pyrolysis, and gasification. When waste is subjected to high temperatures, either partially or fully, it undergoes significant changes in both its chemical and physical properties. Incineration refers to combustion with an excess supply of air, resulting in the near-complete oxidation of organic carbon. Pyrolysis involves partial oxidation and internal heating, which raises the temperature and generates pyrolysis gas. Gasification, on the other hand, occurs at high temperatures through external heating, producing reduced gases with high energy content. These processes release gas or flue gas (commonly referred to as smoke), which must be treated, and leave behind a solid residue known as bottom ash or slag. (Christensen, 2011b; Tekin, 2020).

4.3. Biological process

Composting encompasses both aerobic and anaerobic digestion processes, as well as combinations of the two. Aerobic composting is a biological process that uses oxygen to break down easily degradable organic waste into carbon dioxide and stable organic matter. The resulting solid residues are typically converted into fertilizer or disposed of, though additional treatment may be necessary. Anaerobic digestion, in contrast, occurs in the absence of oxygen and involves the decomposition of organic waste. This process generates methane and carbon dioxide, with the methane content making the gas suitable for use as an energy source. The remaining residues—either liquid or solid—are further processed depending on their quality. They may be incorporated into soil as fertilizer or buried. In addition to managing composting operations, it is essential to control the waste gases produced during anaerobic digestion to minimize environmental impact. (Christensen, 2011b; Tekin, 2020).

5. Research Method:

5.1. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a robust decision-making tool used to evaluate and prioritize alternatives based on multiple criteria. Developed by Thomas Saaty in 1980, AHP is a widely adopted Multi-Criteria Decision Making (MCDM) method across various disciplines. One of its key strengths lies in its simplicity and accessibility. In AHP, alternatives are ranked according to the importance of criteria selected by the decision-maker. The method accommodates both qualitative and quantitative factors, allowing for a comprehensive evaluation. Moreover, it integrates human judgment into the decision-making process, enhancing its relevance and applicability. The procedural steps of AHP are outlined below. (Saaty, 1980; Saaty, 1994):

Step 1. The Hierarchical Relation Structure is created. The AHP evaluates the problem in a hierarchical order consisting of at least one criterion at every level. There is an assumption that a criterion below has an effect on a criterion above. For this reason, the goal is to find out the extent to which a lower criterion affects a higher criterion by making pairwise comparisons. The hierarchy should be established at least three levels. While the upper level contains the goal, the lower one consists of decision alternatives.

Step 2. A Bidirectional Comparison Matrix is created. When creating pairwise comparison, criterion at one level in the hierarchical relation structure are compared in pairs with other criteria at the higher level. The benchmarking of alternatives is done to each criterion separately, and as a result, there will be as many bidirectional comparisons as there are criteria. The Comparison Scale designed by Saaty, shown in the following table, is used in the construction of these matrices. Intermediate values (2, 4, 6, and 8) can also be used (Saaty, 2007).

Table 1: Pairwise Comparison Scale

Severity	Definition	Description
1	Equal importance	Both activities serve the purpose equally.
3	Moderate importance	Experience and judgments make one activity a little more preferable than another.
5	Strong importance	Experiences and judgments make one activity more strongly preferred than another.
7	Very strong importance	One activity is strongly preferred over the other. Its superiority is seen in practice.
9	Extreme importance	Evidence of preference for one activity over another is confirmed to the highest possible level.

$$\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \cdots & 1 & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix}, \quad a_{ji} = \frac{1}{a_{ij}}, \quad i,j = 1,\dots,n \tag{1}$$

Step 3. Decision matrix is normalized. The bidirectional comparison matrix set up by the equation above is normalized by the equation below.

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{2}$$

Step 4. Criterion weights are calculated. Criterion weights (W_i) are calculated by the equation below.

$$w_i = \frac{1}{n} \sum_{i=1}^{n} a'_{ij}, \quad i,j = 1,2,..,n \tag{3}$$

Step 5. Coherence Index (CI) and Consistency Ratio (CR) are calculated. The consistency of the matrix of bidirectional comparisons should be checked. If the CR is above 0.10, it means that the matrix is inconsistent. When this ratio is exceeded, the pairwise comparison matrix should be revised with different values (Saaty, 1980). To determine whether the matrix is consistent, CI value should be found. It can be calculated by Equation 5. To calculate it, first the max value (known as the eigenvalue) must be calculated. The max value is calculated by Equation 4. Also, the Random Index (RI) value should be present to assess consistency. The RI values depending to the size of each matrix is given in the table below. Once the RI and CI are calculated, the CR can be found by Equation 6 (Özbek, 2015; Özbek, 2017).

Table 2: RI Values of Matrices

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57

(Özbek, 2017: 93)

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{\sum_{j=1}^{n} a_{ij}\ x\ w_j}{w_i} \quad (4)$$

$$\text{CI} = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \quad (6)$$

5.2.CoCoSo Method

The CoCoSo ranking method, introduced by Yazdani et al. (2019), is one of the prominent techniques in Multi-Criteria Decision Making (MCDM). CoCoSo, short for COmbined COmpromise SOlution, is designed to evaluate alternatives based on a consensus-driven approach, ultimately identifying the most favorable option among them. This method integrates multiple decision-making strategies to balance compromise and optimality, making it particularly effective in complex evaluation scenarios. The procedural steps for applying the CoCoSo method are outlined below. (Akbulut & Hepşen, 2021; Akgül, 2021; Deveci, Pamucar & Gokasar, 2021; Ecer and Pacamur, 2020; Özdağoğlu, Ulutaş & Keleş, 2020; Ulutaş, Karakuş, & Topal, 2020; Yazdani et al., 2019).

Step 1. An initial matrix is designed. Matrix K is built by Equation below. In the equation, m indicates the number of alternatives (options), the symbol n indicates the number of evaluation criteria, and the term x_{ij} indicates the performance of alternative i according to criterion j.

$$K = [x_{ij}]_{mxn} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Step 2. The matrix is normalized by the equations 2 and 3 below. For benefit-oriented criteria equation 2 and for cost-oriented criteria equation 3 are applied. The term r_{ij} refers to the normalized value in these equations.

$$r_{ij} = \frac{x_{ij} - \min x_{ij}}{\text{mak}\, x_{ij} - \min x_{ij}}. \quad (2)$$

$$r_{ij} = \frac{\text{mak}\, x_{ij} - x_{ij}}{\text{mak}\, x_{ij} - \min x_{ij}}. \quad (3)$$

Step 3. The values of weighted matrix are built by the equation below.

$$S_i = \sum_{j=1}^{n} (r_{ij}\ x\ w_j) \quad (4)$$

In the equation above, S_j is the weighted value of alternative i. And w_j is the criterion weight of criterion j.

Step 4. The weight power (Pi) of each alternative is calculated by Eq-5.

$$P_i = \sum_{j=1}^{n} (rij)^{wj} \quad (5)$$

There are 3 aggregation strategies. The aggregation strategies are illustrated by equations 6, 7 and 8 below:

k_{ia}: The alternative is the a-addition strategy for i.

$$k_{ia} = \frac{P_i + S_i}{\sum_{j=1}^{m}(P_i + S_i)} \quad (6)$$

k_{ib}: The alternative is the b-addition strategy for i.

$$k_{ib} = \frac{Sj}{\min Si} + \frac{Pj}{\min Pi} \quad (7)$$

k_{ic}: The alternative is the c-addition strategy for i.

$$k_{ic} = \frac{\lambda S_i + (1-\lambda) P_i}{\lambda\, maxi\, S_i + (1-\lambda)\, maxi\, P_i} \quad (8)$$

In the equation above, term λ denotes the equilibrium value. This value falls between 0-1. It is generally accepted as 0.5 in theory.

Step 5. Final ranking among the alternatives is built by the equation below.

$$k_i = {}^{3}\sqrt{k_{ia} k_{ib} k_{ic}} + \frac{k_{ia} + k_{ib} + k_{ic}}{3} \quad (9)$$

In the equation above, term k_i shows the final performance value of alternative i.

According to the CoCoSo method, the alternative having the biggest ki value is accepted the best performing alternative among the others.

6. Research Findings

The advantages and disadvantages of different organic solid waste disposal methods are shown in the table below.

Table 3. Advantages and disadvantages of methods

Method	Advantages	Disadvantages
Composting	➢ Improves soil quality ➢ Reduces the need for chemical fertilizers ➢ Low cost ➢ It creates economic value.	➢ Time-consuming ➢ Odor and pest risk ➢ Space requirement
Biogas Production	➢ Provides energy production ➢ Reduces greenhouse gas emissions ➢ Evaluates waste ➢ Creates economic value ➢ Separation and processing cost can be high ➢ Complex logistics	➢ High investment cost ➢ Requires technical knowledge
Animal Feed	➢ Rapid evaluation of food waste ➢ Contributes to animal husbandry	➢ Hygiene and safety risk ➢ Not all types of waste are suitable
Waste Reduction	➢ Lowest cost method ➢ Reduces direct environmental impact	➢ Hygiene and safety risk ➢ Requires behavior change ➢ The effect is seen in the long term
Landfill	➢ Easy solution in the short term ➢ Its infrastructure is widespread	➢ Greenhouse gas production is high ➢ Space consumption is high ➢ Least sustainable method

The organic solid waste disposal methods (alternatives) examined in the comparative analysis are shown in the table below:

Table 4. Solid Organic Waste Management Methods (Alternatives)

Code	**Alternative Name**
A1	Composters
A2	Biogas production
A3	Use as Animal Feed
A4	Waste Reduction
A5	Landfill

The main pollutants that are the basis for the performance of the organic solid waste disposal methods examined in the comparative analysis are shown in the table below:

Table 5. Main Criteria Table

Code	**Main Criteria Name**	**Main Criterion Weight (AHP)**
S	Sustainability	0,6325
E	Economic Efficiency	0,2981
U	Applicability	0,0694
	SUM	1,000

In the first stage of the AHP method, the importance weights of the main criteria were calculated based on the pairwise comparison scale. The main criterion of sustainability has the highest weight with a weight of 63.25 percent; we see that environmental, social and long-term impacts are prioritized in the decision process. Economic efficiency was determined as the second most important criterion with a weight of 29.81 percent. Thus, economic factors such as cost, profitability and resource use are taken into account in the secondary degree. The main criterion of applicability had the lowest weight with a weight of 6.94 percent. This result means that the practical feasibility or technical difficulties of the decision are less prioritized.

In the calculation made to determine whether the results were consistent or not, it was seen that the Consistency Ratio was 0.0873. Since this value is less than 0.10, the results have proven to be consistent.

After finding the importance weights of the main criteria by AHP method, the importance weights of the sub-criteria related to each main criterion were determined by the AHP method. In the table below, the initial and final weights of the sub-criteria depending on the main criteria of economic efficiency (Code=E) are shown.

Table 6. Group E Criteria Table

E				W_0	W_1
C1	It is low cost.	E	Mak	0,7500	0,2235
C2	It creates economic value.	E	Mak	0,2500	0,0745
			SUM	1,0000	0,2981

The C1 (Low cost) sub-criterion is of the highest importance under the heading of economic efficiency. The weight of the sub-criterion is 75% and its contribution to the general decision process is 22.36%. This shows that low cost is the most economically decisive factor. The C2 (Creates economic value) sub-criterion has a sub-criterion weight of 25% and an overall contribution of 7.45%. This indicates that value creation is important, but cost is considered a more dominant factor.

In the calculation made to determine whether the results were consistent or not, it was seen that the Consistency Ratio was 0.000. Since this value is less than 0.10, the results have proven to be consistent.

In the table below, the initial and final weights of the sub-criteria depending on the main criteria of Sustainability (Code=S) are shown.

Table 7. Group S Criteria Table

S				W_0	W_1
C3	It provides energy production.	S	Mak	0,15	0,0935
C4	*It has a space requirement.*	*S*	*Min*	0,06	0,0397
C5	It improves soil quality.	S	Mak	0,25	0,1558
C6	It reduces the need for chemical fertilizers.	S	Mak	0,17	0,1057
C7	Greenhouse gas emissions are low.	S	Mak	0,30	0,1882
C8	It evaluates waste quickly.	S	Mak	0,05	0,0288
C9	*There is a risk of odor and pests.*	*S*	*Min*	0,03	0,0204
			SUM	1,0000	0,6325

According to the table, C7 (low greenhouse gas emissions) has the highest overall contribution (18.82%). This shows that reducing environmental impacts is the most critical element for sustainability. C5 and C6 are high priorities, criteria that provide direct environmental benefits, such as improving soil quality and reducing the need for fertilizers. C3 (Energy production) was considered moderately important; Energy recovery contributes to the environmental cycle. C4 and C9 are criteria to minimize negative effects and are evaluated with low weight. This suggests that while one is aware of the risks, a benefit-oriented approach is being taken. While C8 (Rapid assessment of waste) is beneficial, it is not as much of a priority as other environmental impacts.

In the calculation made to determine whether the results were consistent or not, it was seen that the Consistency Ratio was 0.0557. Since this value is less than 0.10, the results have proven to be consistent.

In the table below, the initial and final weights of the sub-criteria depending on the main criteria of ease of application (Code=U) are shown.

Table 8. Group U Criteria Table

U				W_0	W_1
C10	Its infrastructure is suitable.	U	Mak	0,31	0,021455
C11	*It is time-consuming.*	*U*	*Min*	0,58	0,04034
C12	*It requires complex logistics.*	*U*	*Min*	0,11	0,007605
			SUM	1,0000	0,0694

According to the table, the C11 (Time-consuming) criterion stands out as the most critical element in terms of applicability. This suggests that decision-makers are highly sensitive to the time cost of the process. C10 (Infrastructure suitability) was considered an important advantage, but its overall contribution was low because the total weight of the applicability criterion was already low (0.0694). C12 (Complex logistics) is the lowest importance sub-criterion. This suggests that while one is aware of the logistical challenges, they do not play a decisive role in the decision-making process.

In the calculation made to determine whether the results were consistent or not, it was seen that the Consistency Ratio was 0.0032. Since this value is less than 0.10, the results have proven to be consistent.

The aggregated version of the last three tables above is shown below.

Table 8a. Table of Criteria

Code	Name	Main Criteria Group	Optimal	W_{AHP}
C1	It is low cost.	E	Mak	0,224
C2	It creates economic value.	E	Mak	0,075
C3	It provides energy production.	S	Mak	0,094
C4	*It has a space requirement.*	*S*	*Min*	0,040
C5	It improves soil quality.	S	Mak	0,156
C6	It reduces the need for chemical fertilizers.	S	Mak	0,106
C7	Greenhouse gas emissions are low.	S	Mak	0,188
C8	It evaluates waste quickly.	S	Mak	0,029
C9	*There is a risk of odor and pests.*	*S*	*Min*	0,020
C10	Its infrastructure is suitable.	U	Mak	0,021
C11	*It is time-consuming.*	*U*	*Min*	0,040
C12	*It requires complex logistics.*	*U*	*Min*	0,008
			TOTAL	1,000

In the table, the sub-criterion with the highest weight was the C1 coded "Low cost" criterion with a weight coefficient of 22.4 percent. The one with the lowest weight coefficient was the C12 coded "Requires complex logistics" sub-criterion with a weight of 0.8 percent. In general, economic criteria (C1, C2) have a strong effect in total, especially the cost reduction criterion is dominant. Among the sustainability criteria (C3–C9), greenhouse gas emissions, soil quality improvement and chemical fertilizer reduction stand out. This suggests that environmental impacts are being seriously considered. Applicability criteria (C10–C12) had lower weights in the overall decision process. Thus, it is seen that technical and operational difficulties are kept in the background.

After the determination of the criterion weights by the AHP method, firstly, the initial decision matrix was prepared in order to rank the performance of the organic solid waste disposal methods among themselves. While creating the matrix, the answers of the expert in the field were obtained through face-to-face interviews. In the face-to-face interview, the evaluation of the 5 methods compared from the expert on the basis of 12 criteria according to the 5-point Likert scale was noted. Here, for example, the C1 coded "It is low cost." For the criterion, "5. I strongly agree", "4. I agree", "3. I am undecided", "2. I disagree", "1. I strongly disagree". The expert expressed his opinion in this way for 12 criteria.

The initial decision matrix, created with expert opinion, consists of 12 criteria and 5 alternatives and is shown in the table below:

Table 9. Decision Matrix

	C1	C2	C3	*C4*	C5	C6	C7	C8	*C9*	C10	*C11*	*C12*
A1	4	4	1	2	5	5	3	2	4	3	4	1
A2	2	5	5	4	2	1	1	3	1	1	3	4
A3	4	4	1	2	4	3	2	4	3	3	2	3
A4	5	1	1	1	2	1	3	2	1	3	2	1
A5	4	1	1	5	1	1	1	1	4	2	2	4
MAK	*5*	*5*	*5*	*5*	*5*	*5*	*3*	*4*	*4*	*3*	*4*	*4*
MIN	*2*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*2*	*1*

In the matrix above, each of the alternatives (A1–A5) represents a different solid waste disposal method. Criteria (C1–C12) show the evaluation criteria covering the dimensions of economic efficiency, sustainability and applicability. MAK/MIN values show the maximum and minimum values for each criterion. This is used in methods such as normalizing or comparing with the ideal solution. For example, the A1 alternative in the matrix received the highest scores on sustainability criteria such as C5 (Soil quality) and C6 (Manure reduction). It is also strong in terms of C1 (Low cost) and C2 (Economic value). Weak criteria; C3 (Energy production) and C12 (Logistical complexity) criteria.

In the second step of the CoCoSo method, the above initial matrix was normalized. Normalized matrix can be seen below.

Table 10. Normalized Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	0,6667	0,7500	0,0000	0,7500	1,0000	1,0000	1,0000	0,3333	0,0000	1,0000	0,0000	1,0000
A2	0,0000	1,0000	1,0000	0,2500	0,2500	0,0000	0,0000	0,6667	1,0000	0,0000	0,5000	0,0000
A3	0,6667	0,7500	0,0000	0,7500	0,7500	0,5000	0,5000	1,0000	0,3333	1,0000	1,0000	0,3333
A4	1,0000	0,0000	0,0000	1,0000	0,2500	0,0000	1,0000	0,3333	1,0000	1,0000	1,0000	1,0000
A5	0,6667	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,5000	1,0000	0,0000

This normalized matrix shows how decision alternatives are positioned between the best (maximum) and worst (minimum) values in terms of each criterion. The normalized values range from 0 to 1, with 1 representing the best performance and 0 representing the lowest performance.

In the third step of the CoCoSo method, the values of the normalized matrix were weighted with the criterion weights we calculated earlier. Then, the Si values showing the totals on the basis of alternatives were calculated. The weighted matrix and Si values are shown in the table below.

Table 11. Weighted Matrix and Si Values

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Si
A1	0,1491	0,0559	0,0000	0,0298	0,1559	0,1057	0,1882	0,0096	0,0000	0,0215	0,0000	0,0076	0,7233
A2	0,0000	0,0745	0,0936	0,0099	0,0390	0,0000	0,0000	0,0193	0,0204	0,0000	0,0202	0,0000	0,2769
A3	0,1491	0,0559	0,0000	0,0298	0,1169	0,0529	0,0941	0,0289	0,0068	0,0215	0,0403	0,0025	0,5987
A4	0,2236	0,0000	0,0000	0,0398	0,0390	0,0000	0,1882	0,0096	0,0204	0,0215	0,0403	0,0076	0,5900
A5	0,1491	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0107	0,0403	0,0000	0,2001

This table shows the weighted decision matrix and the total utility value (Si) of each alternative. The Si value refers to how well each alternative performs on the basis of all criteria. The higher this value, the better the overall level of success of the alternative.

In the fourth step of the CoCoSo method, the exponential weighted matrix is obtained. Then the Pi values are found on the basis of the alternative. The exponential weighted matrix and Pi values are given in the table below.

Table 12. Exponentially Weighted Matrix and Pi Values

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Pi
A1	0,9133	0,9788	0,0000	0,9886	1,0000	1,0000	1,0000	0,9688	0,0000	1,0000	0,0000	1,0000	8,8495
A2	0,0000	1,0000	1,0000	0,9463	0,8057	0,0000	0,0000	0,9884	1,0000	0,0000	0,9724	0,0000	6,7128
A3	0,9133	0,9788	0,0000	0,9886	0,9562	0,9293	0,8777	1,0000	0,9778	1,0000	1,0000	0,9917	10,6134
A4	1,0000	0,0000	0,0000	1,0000	0,8057	0,0000	1,0000	0,9688	1,0000	1,0000	1,0000	1,0000	8,7744
A5	0,9133	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,9852	1,0000	0,0000	2,8986

This table contains the Exponentially Weighted Decision Matrix and the P_i values that show the final value of the alternatives. The P_i value expresses the relative superiority of each alternative over the criteria. The biggest the value, the higher the overall success of the alternative.

Finally, in the last step of the CoCoSo method, the total performance scores (K) of the alternatives are found. The K value is the sum of the values of K_a, K_b and K_c. The total scores achieved by the alternatives are shown below.

Table 13. Total Scoring and Ranking

Alternatives	K_a	Ranking	K_b	Ranking	K_c	Ranking	K	Final Rank
A1	0,2379	2	6,6672	1	0,8444	2	3,6855	2
A2	0,1737	4	3,6993	4	0,6166	4	2,2310	4
A3	0,2786	1	6,6532	2	0,9890	1	3,8642	1
A4	0,2327	3	5,9754	3	0,8260	3	3,3920	3
A5	0,0770	5	2,0000	5	0,2733	5	1,1313	5

This table shows the final evaluation (K) and final ranking, which is created by combining the scores and rankings obtained by three different methods (Ka, Kb, Kc) used in the multi-criteria decision-making process. Each method scored the alternatives with different perspectives, then these scores were combined to obtain the overall success ranking.

According to the results of the AHP-based CoCoSo analysis, A3 is the strongest alternative. Ranked first or second in all subtotals. It stood out especially with its Kc (0.9890) and Ka (0.2786) values. The A3 alternative has drawn a balanced, versatile and consistent success profile.

According to the AHP-based CoCoSo analysis results, A1 is the second best alternative. It received the highest score in the KB method (6.6672) and ranked second in other methods. It is a strong alternative, especially in terms of economy and sustainability.

A4 is in third place. It ranked 3rd in all subtotals. It is stable but has not achieved scores as high as A1 and A3. It is a successful alternative in applicability and environmental risk management.

A2 is in fourth place. It ranks 4th in all subtotals. While it is strong in certain criteria, overall success is low. It is economical and energy-oriented but provides limited contribution.

The A5 alternative is the weakest alternative. It ranks last in all subtotals. There are low scores, limited contribution, and low overall achievement. It is an option that must be eliminated.

According to the results of AHP-based CoCoSo analysis, the Priority Ranking (in terms of Sustainability and Effectiveness) of organic solid waste management methods is as follows;

1. Use as animal feed. It is practical for the evaluation of food waste; however, it should be managed carefully.

2. Composting. It provides direct benefits in agriculture and horticulture. It can be applied individually and collectively.

3. Waste Reduction. It is the most effective and low-cost solution; Preventing waste is the beginning of everything.

4. Biogas Production. It provides environmental benefits through energy production; ideal for large-scale systems.

5. Landfill. It should be preferred last. It should only be used if other methods are not possible.

7. Conclusion

For a sustainable world, it is extremely important to manage organic solid waste management without harming human health and the environment. In this context, it is necessary to evaluate the strengths and weaknesses of different methods applied together. In this book chapter, the importance weights of the main methods in integrated organic solid waste management and the performance ranking among these methods in terms of sustainability, economic efficiency and ease of application were made based on this.

In the study, organic solid waste disposal methods, use as animal feed, composting, waste reduction, biogas production and landfill methods were compared in terms of sustainability, economic efficiency and ease of application.

In this study, AHP method and CoCoSo method, which are multi-criteria decision making techniques (MCDM), were applied while comparing the disposal methods. While the importance weights of the criteria were analyzed with the AHP method, the performance ranking of the alternative disposal methods was made with the CoCoSo method.

Alternative methods were evaluated on the basis of 12 sub-criteria depending on the main criteria of sustainability, economic efficiency and ease of application. Among these 12 criteria evaluated, there are factors such as low cost, economic value creation capacity, energy generation potential, space requirement, impact on soil quality, impact on chemical fertilizer needs, impact on greenhouse gas emissions, contribution to rapid utilization of waste, exposure to odor and pest risk, infrastructure suitability, time dimension, complex logistics requirement. As a result of the four-level AHP method application, it was seen that the main criterion of sustainability had the highest weight. Economic efficiency has been determined as the second most important criterion. The main criterion of applicability was the lowest weight. Among the 12 sub-criteria examined, the sub-criterion with the highest weight was the C1 coded “Low cost” criterion. The one with the lowest weight was the C12 coded “Requires complex logistics.” sub-criterion.

According to the results of the CoCoSo performance ranking method, the use as animal feed ranked first in the performance ranking of organic solid waste management methods. The composting method came in second. The waste reduction method ranked third. The landfill alternative came in last place.

As a limitation of the study, the opinion of the expert was consulted for weight determination in the study rather than statistical data on the compared methods. Therefore, it involves a certain degree of personal judgment and subjectivity. In order to eliminate this limitation of the research, new studies using other weighting methods based on more objective data are needed in the future.

References

Akbulut, O. Y. & Hepşen, A. (2021). Finansal Performans ve Pay Senedi Getirileri Arasındaki İlişkinin Entropi ve CoCoSo ÇKKV Teknikleriyle Analiz Edilmesi. *Ekonomi Politika ve Finans Araştırmaları Dergisi,* 6(3), 681-709.

Akgül, Y. (2021). Borsa Istanbul'da Işlem Gören Ticari Bankaların Finansal Performansının Bütünleşik CRITIC Cocoso Modeliyle Analizi. *Ekonomi ve Finansal Araştırmalar Dergisi,* 3(2), 71-90.

Arslan, M.H. (2017). AHP-ARAS Hibrit Yöntemi Ile Lojistik Işletmelerinin En Uygun Araç Seçimi. *Alphanumeric Journal The journal of Operations Research, Stattistics, Econometrics and Management Information Systems*, 5(2), 271-282.

Christensen, H. T. (2011a). Introduction to Waste Management, (Edited by Thomas H. Christensen). Solid Waste Technology & Management, Vol. 1: 1-16, Wiley, Chichester, U.K.

Christensen, H. T. (2011b). Inroduction to Waste Engineering, (Edited by Thomas H. Christensen). Solid Waste Technology & Management, Vol. 1: 17-28, Wiley, Chichester, U.K.

Çilek, A. (2022). Bütünleşik SV-Cocoso Teknikleriyle Etkinlik Analizi: Mevduat Bankaları Gruplarında Bir Uygulama. Karadeniz Sosyal Bilimler Dergisi, 14 (26), 52-69.

Deveci, M., Pamucar, D. & Gokasar, I. (2021). Fuzzy Power Heronian Function Based Cocoso Method For The Advantage Prioritization Of Autonomous Vehicles in Real-Time Traffic Management. Sustainable Cities and Society, 69: 102846.

Demirarslan, K.O.& Başak, S. (2018). Doğu Karadeniz Bölgesi İlleri Katı Atık Yönetimi. Ulusal Çevre Bilimleri Araştırma Dergisi, Sayı 1(3):117-132.

Ecer, F. & Pamucar, D. (2020). Sustainable Supplier Selection: A Novel Integrated Fuzzy Best Worst Method (F-BWM) And Fuzzy CoCoSo with Bonferroni (CoCoSo'b) Multi-Criteria Model. *Journal of Cleaner Production*, 266: 121981

Hoornweg, D., & Bhada-Tata, P. (2012). WHAT A WASTE: A Global Review of Solid Waste Management. Urban Development Series Produced by the World Bank's Urban Development and Local Government Unit of the Sustainable Development Network, No. 15.

Negiz, N., & Yalçın, Ö. (2023). Türkiye'de Farklı Gelişmişlik Düzeyine Sahip Kentlerin Döngüsellik Durumu: Katı Atıklar Üzerinden Bir İnceleme. Kent Akademisi, 16(2), 862-878. https://doi.org/10.35674/kent.

Özbek, A. (2015). Performance Analysis of Public Banks in Turkey, International Journal of Business Management and Economic Research (IJBMER), 6 (3), 178-186.

Özbek, A. (2017). Çok Kriterli Karar Verme Yöntemleri ve Excel ile Problem Çözümü Kavram-Teori_ Uygulama, Seçkin Yayıncılık, 1. Baskı, Ankara.

Özdağoğlu, A., Ulutaş, A. & Keleş, M. K. (2020). The Ranking of Turkish Universities with CoCoSo and MARCOS. *Economics Business and Organization Research*, 2(Special Issue): 374-392.

Reza S.& Majid A. (2013). Ranking Financial Institutions Based on Trust In Online Banking Using ARAS And ANP Method, *International Research Journal of Applied and Basic Sciences*, 6(4), 415-423.

Saaty, T.L. (1980). *The Analytic Hierarchy Process*. McGraw-Hill: New York.

Saaty, T.L. (1994). *Fundamentals of Decision Making and Priority Theory with the Analytical Hierarchy Process*. RWS Publication: Pittsburg.

Saaty, T.L. (2007). The Analytic Hierarchy and Analytic Network Measurement Process: Applications to Decision Under Risk. *European Journal of Pure and Applied Mathematics*, 1(1), 122-196.

Seo, S., Aramaki, T., Hwang, Y.& Hanaki, K. (2004). Environmental Impact of Solid Waste Treatment Methods in Korea. Journal of Environmental Engineering, 130(1).81. https://doi.org/10.1061/(ASCE)0733-9372(2004)130:1(81)

Tekin, Ö.F. (2020). Evsel Katı Atık Yönetimi ve Geri Dönüşüm. Ankara: Nobel Yayıncılık. ISBN: 978-625-406-958-1.

Ulutaş, A., Karakuş, C. B. & Topal, A. (2020). Location selection for logistics center with fuzzy SWARA and CoCoSo methods. *Journal of Intelligent & Fuzzy Systems*, 38(4): 4693-4709.

Ulutaş, A.& Topal, A. (2020). *Bütünleştirilmiş Çok Kriterli Karar Verme Yöntemlerinin Üretim Sektörü Uygulamaları*. Ankara: Akademisyen Kitabevi.

Wang, Y. (2025). Comparative Study of Biosynthesis Technology And Traditional Methods for Organic Solid Waste. E3S Web of Conferences. http://dx.doi.org/10.1051/e3sconf/202560603009

Yazdani, M., Zarate, P., Zavadskas, E. K. & Turksis, Z. (2019). A Combined Compromise Solution (CoCoSo) Method for Multi-Criteria Decision-Making Problems. *Management Decision*, 57(9): 2501-2519.

11 BIOCONVERSION OF AGRO-WASTES INTO ECO-FRIENDLY PRODUCTS USING LIGNINOLYTIC FUNGI

Dheeraj Kumar Santhosh Kumar[1], Abinaya Sri Sivakumar[2], Rajalakshmi Govindaraju[3], Janaranajani Dhanapal[4], Antony Godson Siluvaipichai Gnanaprakasm[5]

1. Introduction

Global Agro-Waste Generation and Challenges

Agricultural residues are generated worldwide in enormous quantities due to the cultivation and processing of cereals, sugarcane, legumes, and oilseeds. According to FAO (2022), more than 5 billion tons of crop residues are produced annually, with Asia contributing nearly 50% of the global share. Major residues include rice straw, wheat straw, sugarcane bagasse, maize stover, and oilseed husks (Matamba, 2023). The improper management of these wastes, such as open-field burning, contributes to air pollution, greenhouse gas emissions, and soil nutrient loss (Singh *et al.,* 2021). Therefore, sustainable valorization strategies are urgently required to mitigate environmental challenges while promoting a circular bioeconomy (Figure 1).

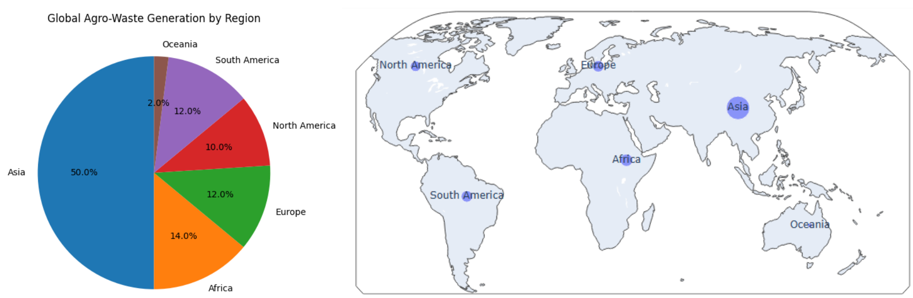


Figure 1. Global agro-waste generation (by region)

1 M. Sc Biotechnology, Department of Biotechnology, Hindusthan College of Arts & Science, Coimbatore, Tamilnadu, India. 24mbt014@hicas.ac.in https://orcid.org/0009-0002-7311-4554
2 M. Sc Biotechnology, Department of Biotechnology, Hindusthan College of Arts & Science, Coimbatore, Tamilnadu, India. 24mbt003@hicas.ac.in https://orcid.org/0009-0001-4239-6504
3 Professor and Head, Department of Biotechnology, Hindusthan College of Arts & Science (Autonomous), Coimbatore, India. raajeerajan@gmail.com https://orcid.org/0000-0002-0851-5055
4 Assistant Professor, Department of Biotechnology, Hindusthan College of Arts & Science (Autonomous), Coimbatore, India. janaranjani.d@hicas.ac.in https://orcid.org/0009-0005-3361-9066
5 Assistant Professor, Department of Biotechnology, Hindusthan College of Arts & Science (Autonomous), Coimbatore, India. antonygodson.sg@hicas.ac.in https://orcid.org/0000-0003-4469-896

Composition and Recalcitrance of Lignocellulosic Biomass

Lignocellulosic agro-residues consist mainly of cellulose (30–50%), hemicellulose (20–40%), and lignin (10–25%) (Sun et al., 2018). While cellulose and hemicellulose provide fermentable sugars, lignin confers recalcitrance, hindering enzymatic hydrolysis and microbial accessibility. This complexity necessitates pretreatment strategies to disrupt the lignin barrier and enhance bioconversion efficiency (Table 1).

Table 1. Comparative Composition of Major Agro-Residues (wt%)

Residue	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Rice straw	32–47	19–27	5–24	Sun et al., 2018
Wheat straw	33–45	20–30	12–16	Matamba, 2023
Sugarcane bagasse	40–50	25–35	18–24	Singh et al., 2021
Corn stover	35–40	25–30	15–19	Thakur et al., 2022

Role of Ligninolytic Fungi in Biomass Valorization

Ligninolytic fungi, primarily white-rot fungi such as *Phanerochaete chrysosporium* and *Trametes versicolor*, are nature's most efficient lignin degraders. They produce oxidative enzymes such as laccases, lignin peroxidases (LiP), and manganese peroxidases (MnP), which enable the breakdown of the complex lignin polymer into smaller aromatic compounds (Kirk & Farrell, 1987; Martínez et al., 2005). The unique ability of these fungi to act under mild conditions makes them promising candidates for sustainable biorefinery approaches. Applications include biofuel production, bioremediation, enzyme recovery, and eco-friendly material synthesis (Arora & Sharma, 2010).

Scope and Objectives of Fungal Bioconversion

The scope of fungal bioconversion extends beyond waste management to the creation of value-added products. By integrating ligninolytic fungi into agro-waste valorization chains, industries can achieve:

- Reduction of environmental pollution.
- Recovery of industrially relevant enzymes and bioactive compounds.
- Production of sustainable alternatives (biofuels, mycelium-based materials).
- Contribution to circular bioeconomy frameworks (Thakur et al., 2022).

This chapter aims to (i) provide an overview of agro-waste challenges, (ii) highlight the role of ligninolytic fungi, and (iii) explore their potential in sustainable bioconversion systems.

2. Agro-Wastes as Substrates

Types of Agro-Residues and Their Availability

Agro-residues are generated in massive volumes from food, feed, and fiber production. Major categories include cereal straws (rice, wheat, maize), sugarcane bagasse, oilseed husks (soybean, groundnut, sunflower), fruit and vegetable peels, and legume pod shells (Matamba, 2023; Singh et al., 2021). Globally, cereal residues contribute nearly 70% of all agro-wastes, followed by sugarcane and maize stover (FAO, 2022). These residues often remain underutilized or are discarded through burning, leading to severe environmental concerns. Valorization of such residues provides opportunities for producing biofuels, enzymes, animal feed, bioplastics, and biocomposites (Thakur et al., 2022) (Figure 2).

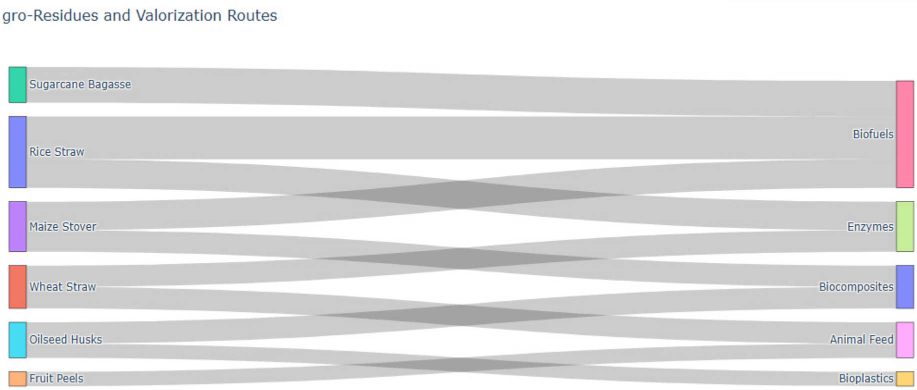


Figure 2: Schematic of common agro-residues and their valorization routes (diagram showing agro-residues (rice straw, wheat straw, sugarcane bagasse, maize stover, fruit peels, oilseed husks) at the center with arrows pointing to valorization routes (biofuels, enzymes, bioplastics, animal feed, biocomposites)

Structural and Chemical Composition of Substrates

Agro-residues are rich in lignocellulosic polymers, with proportions depending on plant type and harvesting conditions. Besides cellulose, hemicellulose, and lignin, they may contain extractives (waxes, resins, phenolics) and inorganic components such as silica (especially in rice husk) (Sun et al., 2018). The C:N ratio plays a crucial role in fungal colonization and enzyme productivity. A balanced ratio (20–30:1) promotes fungal growth, while extremely high ratios may limit nitrogen availability (Kirk & Farrell, 1987) (Table 2).

Table 2: Properties of Agro-Residues (C:N Ratio, Lignin %, Cellulose %)

Residue	C:N Ratio	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Rice straw	60–70:1	32–47	19–27	5–24	Sun et al., 2018
Wheat straw	80–100:1	33–45	20–30	12–16	Matamba, 2023
Sugarcane bagasse	90–100:1	40–50	25–35	18–24	Singh et al., 2021
Maize stover	50–60:1	35–40	25–30	15–19	Thakur et al., 2022
Fruit peels	25–35:1	15–25	10–20	5–10	FAO, 2022

Pretreatment Approaches for Enhanced Bioconversion

Due to their recalcitrant nature, agro-residues require pretreatment before fungal or enzymatic attack. Pretreatments are classified into:

a) Physical: milling, extrusion, steam explosion (reduces particle size, increases surface area).

b) Chemical: alkali, acid, organosolv, ionic liquids (disrupt lignin and hemicellulose bonds).

c) Biological: fungi-based delignification (environmentally friendly, but slower).

An integrated pretreatment strategy is often employed to balance efficiency, cost, and sustainability (Arora & Sharma, 2010; Thakur et al., 2022) (Figure 3).

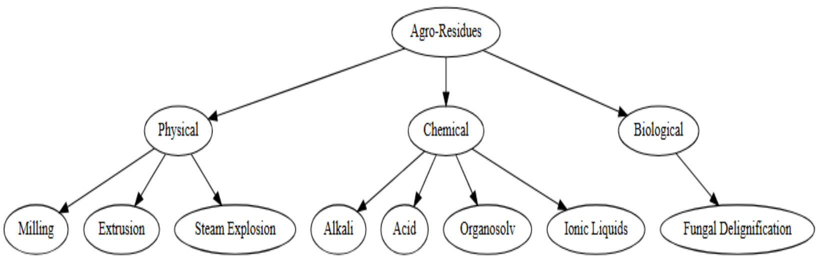


Figure 3: Flowchart of pretreatment methods (physical, chemical, biological)

3. Ligninolytic Fungi: Biology and Mechanisms

Major Functional Groups of Ligninolytic Fungi

Ligninolytic fungi are broadly classified into white-rot, brown-rot, and soft-rot fungi, based on their wood-decaying mechanisms (Kirk & Farrell, 1987; Martínez et al., 2005).

a) White-rot fungi (e.g., *Trametes versicolor*, *Phanerochaete chrysosporium*) completely degrade lignin and leave behind whitish cellulose.

b) Brown-rot fungi (e.g., *Gloeophyllum trabeum*) depolymerize cellulose and hemicellulose, leaving modified lignin residues.

c) Soft-rot fungi (mainly *Ascomycota* and *Deuteromycota*) degrade cellulose within secondary cell walls, forming cavities (Figure 4).

These groups differ in enzymatic machinery, substrate specificity, and ecological distribution.

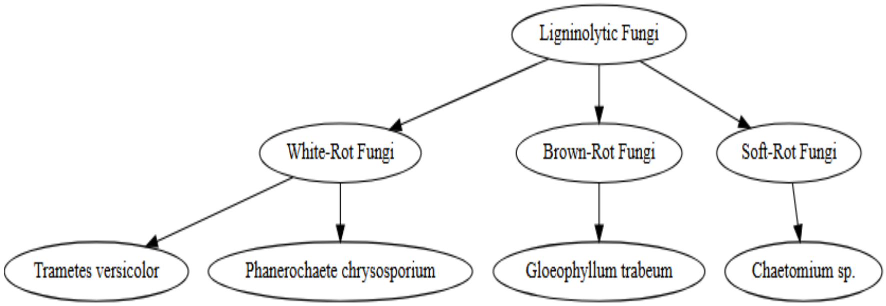


Figure 4: Classification of ligninolytic fungi (white, brown, soft-rot) (Three main branches: White-rot, Brown-rot, Soft-rot, each with representative genera)

Enzymatic Systems: Laccase, LiP, MnP and Auxiliary Enzymes

The ligninolytic enzymatic system consists of:

a) Laccases (Lac): Multicopper oxidases oxidizing phenolic lignin units.

b) Lignin peroxidases (LiP): Oxidize non-phenolic lignin structures using H_2O_2.

c) Manganese peroxidases (MnP): Oxidize Mn^{2+} to Mn^{3+}, which diffuses to oxidize lignin.

d) Versatile peroxidases (VPs): Hybrid enzymes with properties of LiP and MnP.

e) Auxiliary enzymes (aryl-alcohol oxidases, glyoxal oxidases): Generate H_2O_2 required for peroxidases (Wong, 2009; Couto & Herrera, 2006) (Figure 5).

These enzymes act synergistically to depolymerize lignin into smaller aromatic compounds.

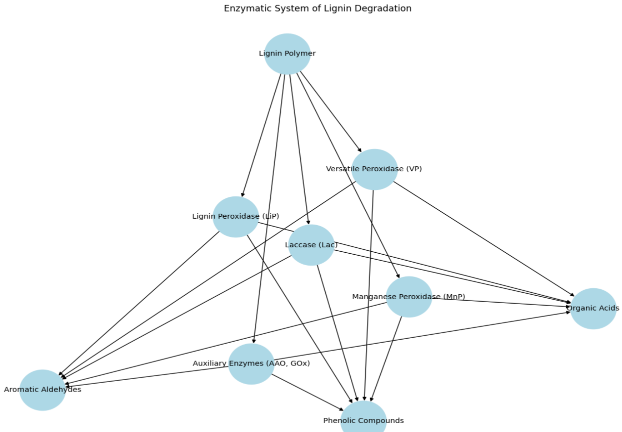


Figure 5: Enzymatic system of lignin degradation (Diagram showing enzymes (Laccase, LiP, MnP, VP, AAO) acting on lignin polymer → depolymerized aromatic compounds)

Mechanistic Pathways of Lignin Degradation

Lignin degradation follows oxidative radical-mediated pathways. Enzymes generate free radicals (phenoxy, cation radicals), which lead to cleavage of β-O-4 linkages, aromatic ring opening, and demethylation (Martínez et al., 2005). The process yields smaller aromatic aldehydes, acids, and alcohols, which can be further metabolized into central carbon pathways.

Influence of Environmental and Physiological Factors

The efficiency of fungal ligninolytic activity depends on environmental and physiological conditions such as:

a) pH: Optimal range 4–6 for laccase and peroxidases.

b) Temperature: Mesophilic fungi prefer 25–35 °C, thermotolerant species up to 45 °C.

c) Moisture & Aeration: High moisture supports SSF, while oxygen availability influences enzyme secretion.

d) Nutrient availability: Nitrogen limitation enhances lignin degradation (Hatakka, 2001).

e) Inducers: Compounds like veratryl alcohol and copper ions stimulate enzyme expression (Table 3).

Table 3: Environmental Factors Influencing Fungal Ligninolytic Activity

Factor	Optimal Range / Effect	Reference
pH	4–6 optimal; extremes reduce enzyme activity	Wong, 2009
Temperature	25–35 °C mesophiles; up to 45 °C for thermotolerant fungi	Hatakka, 2001
Aeration	Essential for peroxidase activity	Arora & Sharma, 2010
Moisture	SSF requires 60–70% moisture	Singh et al., 2021
Nutrient (N, C)	Nitrogen limitation enhances lignin degradation	Kirk & Farrell, 1987
Inducers	Veratryl alcohol, copper ions stimulate enzymes	Couto & Herrera, 2006

4. Bioconversion Processes and Strategies

Bioconversion of lignocellulosic agro-wastes by fungi can be achieved through several fermentation strategies, with solid-state fermentation (SSF) and submerged fermentation (SmF) being the most widely used approaches. SSF involves the growth of fungi on moist solid substrates in the absence of free-flowing water, thereby simulating the organisms' natural habitat and promoting efficient enzyme secretion (Pandey, 2003). Common substrates include wheat bran, rice straw, and sugarcane bagasse, which are inexpensive and readily available. SSF offers several advantages, such as low-cost substrate utilization, higher enzyme titers, and enhanced productivity. However, it also presents limitations, including challenges in process monitoring, uneven moisture distribution, and restricted oxygen diffusion, which can affect fungal metabolism and overall yield. In contrast, submerged fermentation (SmF) is carried out in liquid nutrient media, allowing microorganisms to grow under controlled environmental conditions (Singhania et al., 2009). SmF provides benefits such as easier scale-up, superior process control, and high reproducibility, making it suitable for industrial-scale enzyme and metabolite production. Nevertheless, this method is associated with higher operational costs, diluted product concentrations, and increased risks of contamination. Both SSF and SmF are essential bioprocessing platforms, and the choice between them depends on the type of substrate, target product, and industrial requirements (Figure 6).

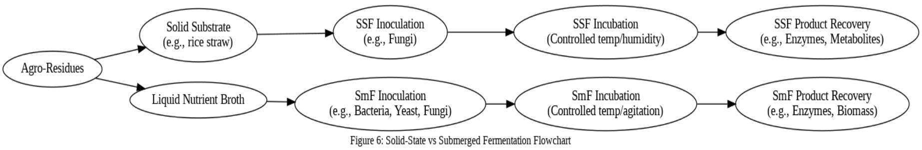


Figure 6: Comparative schematic of SSF vs. SmF (Side-by-side comparison — solid substrate (SSF) vs. liquid broth (SmF)

Co-Cultivation and Synergistic Interactions

Co-cultivation involves the simultaneous or sequential use of two or more fungi (or microbes) to enhance lignocellulosic degradation. One species may secrete hydrolytic enzymes, while another enhances oxidative breakdown (Elisashvili & Kachlishvili, 2009). Synergism improves substrate utilization, enzyme diversity, and product yields.

Hybrid and Emerging Bioprocesses

Hybrid strategies combine features of SSF and SmF, or integrate membrane bioreactors, immobilized cell systems, or biorefinery models (Singh et al., 2021). Emerging technologies include: Biofilm reactors for enhanced enzyme productivity. Membrane-assisted fermentation for in-situ product recovery. Digital twins and AI-based optimization for predictive control (Table 4).

Process Optimization and Scale-Up

Optimization strategies include statistical approaches (RSM, factorial designs), omics-guided strain improvement, and bioreactor engineering (Singhania et al., 2009). Scaling-up requires balancing oxygen transfer, agitation, and substrate loading.

Table 4: Advantages and Limitations of Different Fermentation Strategies

Strategy	**Advantages**	**Limitations**	**References**
SSF	Utilizes low-cost agro-residues; mimics natural fungal habitat; high enzyme yield	Difficult to monitor; scale-up challenges	Pandey (2003)
SmF	Easy scale-up; better process control; reproducible	High water demand; dilute products; costly	Singhania et al. (2009)
Co-culture	Enzyme diversity; synergistic effects; higher biomass utilization	Complex interactions; risk of dominance of one strain	Elisashvili & Kachlishvili (2009)
Hybrid	Combines SSF and SmF benefits; improved yields	Technically challenging; higher initial cost	Singh et al. (2021)

5. Eco-Friendly Products via Ligninolytic Fungi

Biodegradable Packaging and Biocomposites

Agro-waste reinforced with fungal mycelium can be molded into biodegradable packaging foams and biocomposites. These materials replace single-use plastics while offering structural durability and compostability (Attias et al., 2020) (Figure 7).

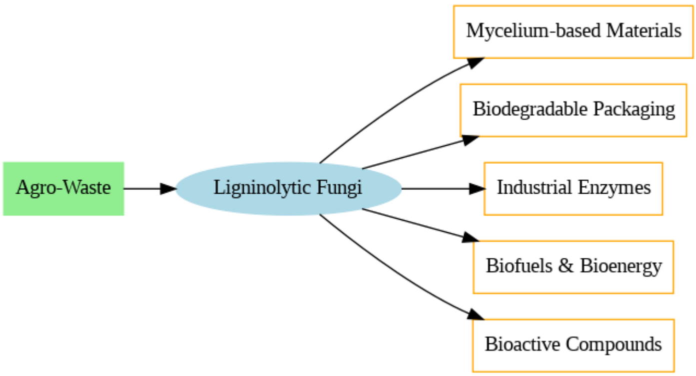


Figure 7: Product Pipeline – Agro-Waste to Eco-Friendly Products

Industrial Enzymes and Biocatalysts

Ligninolytic fungi are excellent producers of industrial enzymes such as laccases, manganese peroxidases, and cellulases. These enzymes are widely used in pulp and paper bleaching, textile processing, bio-remediation, and bioethanol production (Couto & Herrera, 2006).

Biofuels and Bioenergy Applications

Fungi contribute to second-generation biofuels through lignocellulosic biomass hydrolysis and fermentation. Products include bioethanol, biogas, and hydrogen (Kumar et al., 2009). Mycelium residues can also serve as solid biofuels or feedstock for anaerobic digestion.

Bioactive and High-Value Compounds

Fungi synthesize bioactive molecules such as antibiotics (penicillin), statins (lovastatin), immunomodulators, pigments, and nutraceuticals. Agro-waste-based cultivation offers a low-cost route to produce high-value pharmaceuticals and cosmeceuticals (Zhu et al., 2016) (Table 5).

Table 5: Fungal Strains and Their Applications in Product Development

Fungal Strain	**Product/Application**	**Reference**
Ganoderma lucidum	Mycelium leather, biocomposites	Couto & Herrera (2006)
Pleurotus ostreatus	Packaging foams, bioplastics	Couto & Herrera (2006)
Trametes versicolor	Laccase production for textile/paper industries	Couto & Herrera (2006)
Aspergillus niger	Citric acid, enzymes, biocatalysts	Kumar et al. (2009)
Penicillium chrysogenum	Antibiotics (penicillin)	Zhu et al. (2016)
Monascus purpureus	Pigments and nutraceuticals	Zhu et al. (2016)

Figure 8. Representative fungal-derived eco-products from agro-waste bioconversion: (a) bioactive pigments and antibiotics, (b) mycelium-based construction bricks and panels, (c) biodegradable packaging foams, (d) bioethanol and bioenergy products, (e) industrial enzyme formulations, and (f) mycelium-based leather alternatives. These examples demonstrate the broad industrial potential of ligninolytic fungi in producing sustainable materials, chemicals, and fuels.

6. Case Studies and Recent Advances

In recent years, remarkable progress has been achieved in advancing fungal lignocellulose bioconversion from laboratory-scale demonstrations to pilot-scale processes and commercial applications. These advancements fall broadly into three thematic areas: (1) enzyme and process optimization, (2) development of novel bio-based product platforms, and (3) integration of fungi into multi-stage bioprocess systems.

Enzyme and Process Optimization

Significant research efforts have focused on enhancing the yield, stability, and activity of key ligninolytic enzymes such as laccase, manganese peroxidase (MnP), and lignin peroxidase (LiP). Strategies including the use of metal ion inducers (e.g., copper) and innovative immobilization techniques have led to improved enzyme titers and broader industrial applicability in areas such as textile effluent treatment, bioremediation, and paper pulping (Sharma & Kumar, 2025). For instance, *Pleurotus sajor-caju* has shown enhanced laccase production under optimized solid-state fermentation (SSF) conditions, significantly improving dye decolorization capabilities (Sharma & Kumar, 2025).

Biological Pretreatment and Delignification

Fungal pretreatment has emerged as a promising alternative to conventional chemical delignification methods. White-rot fungi, in particular, can selectively degrade lignin while preserving polysaccharide components, thereby improving subsequent saccharification yields. Although biological pretreatment often requires longer residence times, its low-energy demand and environmental sustainability make it an attractive option for integration into biorefinery processes (Gupta & Banerjee, 2025).

Commercialization of Mycelium-Based Materials

Beyond enzyme production, fungal biotechnology has been successfully applied to develop innovative materials. Companies such as MycoWorks and Ecovative have commercialized mycelium-based leather, biodegradable packaging, and food ingredients, demonstrating strong market potential for fungal-derived products (Jakubczyk, 2020; Vogue Business, 2025). These advancements illustrate how fungal bioprocessing can bridge laboratory research and industrial manufacturing.

Co-Culture and Integrated Bioprocesses

Emerging approaches focus on co-cultivation strategies and hybrid bioprocesses, which combine SSF and submerged fermentation (SmF) or immobilized systems. These strategies enhance enzyme diversity, improve substrate degradation efficiency, and expand the range of valorized products (Morales & Zhang, 2025). Such systems are increasingly recognized as essential for scaling ligninolytic processes in industrial settings (Table 6).

Table 6. Summary of Representative Case Studies in Fungal Lignocellulose Bioconversion

Case ID	Substrate Type	Fungal Strain / Consortium	Process Type	Product / Outcome	Reference
1	Sawdust / Wheat bran	*Pleurotus sajor-caju*	SSF – laccase production optimization	High laccase titers; textile effluent decolorization	Sharma & Kumar (2025)
2	Tea residues	*Trametes versicolor*	Optimized SSF	Enhanced laccase production and lignin degradation	Li et al. (2025)
3	Corn straw	*Aspergillus oryzae*	SSF / SmF hybrid	Increased laccase yield and enzyme activity	Ahmed et al. (2025)

4	Mixed lignocellulosic feedstocks	White-rot basidiomycetes co-culture	Co-culture SSF / hybrid	Improved delignification and enzyme complementarity	Morales & Zhang (2025)
5	Mixed agro- and food waste	Fungal pretreatment consortia	Biological pretreatment	Enhanced saccharification with lower chemical input	Gupta & Banerjee (2025)
6	Agro-waste-derived mycelium feedstock	*Ganoderma / Pleurotus* (industrial strains)	Controlled mycelium cultivation	Mycelium-based leather and packaging prototypes (commercial pilots)	Jakubczyk (2020)

Outlook and Research Trends

The field is evolving rapidly, with increasing emphasis on integrated systems, sustainability assessments, and scale-up studies. Future research will likely focus on metabolic engineering of fungal strains, systems biology-guided process optimization, and development of circular bioeconomy models that integrate fungal bioconversion with other biomass valorization technologies (Figure 9).

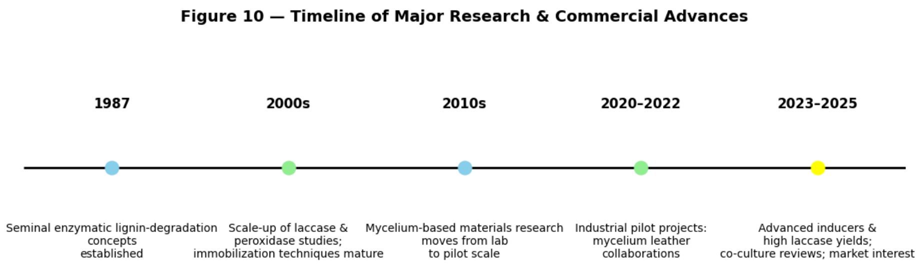


Figure 9 — Timeline of major research & commercial advances

7. Environmental and Economic Perspectives

Bioconversion of agro-wastes using ligninolytic fungi must be evaluated not only for technical feasibility but also for environmental performance and economic viability. This section outlines integration into circular bioeconomy frameworks, approaches to life cycle assessment (LCA), and socio-economic considerations for commercialization.

Integration into the Circular Bioeconomy

Integrating fungal bioconversion into a circular bioeconomy emphasizes closing material loops, minimizing waste, and creating value-added products from residues (Thakur et al., 2022). A circular model positions ligninolytic fungi at multiple nodes: as biological pretreatment agents to enable downstream saccharification and fermentation, as direct producers of enzymes and high-value metabolites, and as manufacturers of mycelium-based materials that re-enter product lifecycles through composting or recycling. Policy incentives, supply-chain coordination (feedstock collection, transport, pretreatment hubs), and modular biorefinery designs support scalable integration (Singh et al., 2021) (Figure 10).

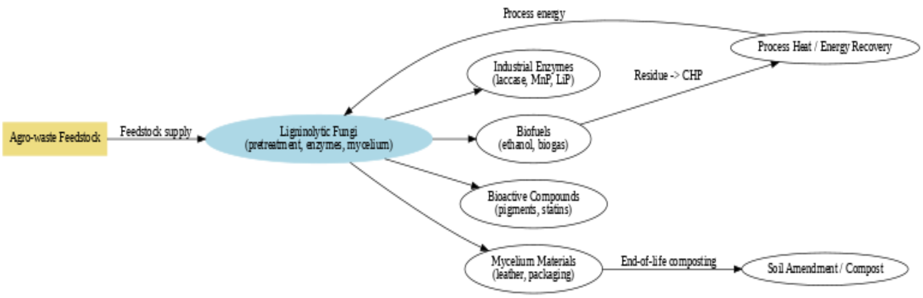


Figure 10: Circular bioeconomy model integrating ligninolytic fungi

Life Cycle Assessment (LCA) of Fungal Bioconversion

LCA provides a standardized framework to quantify environmental impacts (global warming potential, cumulative energy demand, land use, water use, eutrophication) from cradle to grave (ISO 14040:2006) (Figure 11). When comparing fungal bioconversion with conventional disposal (open burning, landfilling), typical LCA endpoints to examine include:

a) Global Warming Potential (GWP) — kg CO_2-eq per tonne of feedstock processed.

b) Fossil Energy Use — MJ per tonne.

c) Eutrophication / Water Use — kg PO_4-eq, m^3 water.

d) Land Use — m^2·year.

e) Human Health / Particulate Emissions — relative weights (important where burning is common).

f) Net Energy Ratio / Energy Return on Investment (EROI).

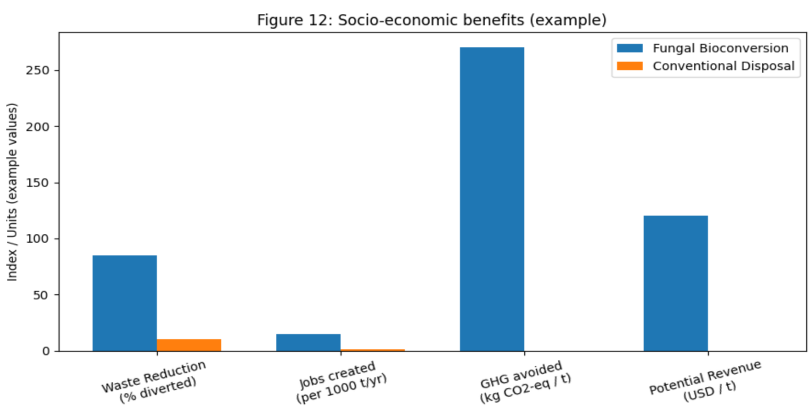


Figure 11: LCA comparison of fungal bioconversion vs conventional disposal

8. Conclusion and Future Outlook

Conclusion

Ligninolytic fungi present a versatile, eco-friendly solution for the valorization of agro-waste into high-value products, contributing to sustainable bioeconomy strategies. The chapter has highlighted several key points:

1. Global agro-waste challenge: Millions of tons of lignocellulosic residues are generated annually, causing environmental issues when left unmanaged or improperly disposed. Fungal bioconversion provides an alternative to open burning or landfilling, reducing greenhouse gas emissions and pollution (Thakur et al., 2022).
2. Substrate suitability and pretreatment: Agro-residues like rice straw, sugarcane bagasse, wheat straw, and corn stover are abundant and rich in cellulose and hemicellulose but require pretreatment to overcome recalcitrance. Fungal pretreatment, chemical, and physical strategies are complementary in optimizing substrate digestibility (Singh et al., 2021).
3. Fungal mechanisms and enzymatic pathways: White-rot fungi, brown-rot fungi, and soft-rot fungi employ oxidative enzymes such as laccases, manganese peroxidases, and lignin peroxidases. Co-cultivation and hybrid strategies enhance enzyme diversity and substrate utilization efficiency (Elisashvili & Kachlishvili, 2009).
4. Bioconversion processes and products: Solid-state and submerged fermentations, along with co-culture and hybrid systems, allow production of industrial enzymes, biofuels, bioactive compounds, and mycelium-based materials. The optimization of these processes is critical for scalability and economic feasibility.
5. Environmental and economic impact: Integration into circular bioeconomy models shows significant potential in waste reduction, job creation, and energy-efficient production. LCA studies suggest fungal bioconversion can substantially lower environmental impacts compared to conventional disposal methods. Socio-economic assessments confirm market viability for bio-based products, including mycelium materials, enzymes, and biofuels (Cherubini, 2010; Göransson et al., 2019).

Future Outlook

Despite the advances, several challenges and opportunities exist:

a) Strain improvement and synthetic biology: Advances in molecular biology, omics, and genetic engineering could create fungal strains with higher enzyme titers, broader substrate specificity, and faster growth rates, making industrial-scale bioconversion more efficient.

b) Integrated biorefinery approaches: Combining fungal pretreatment with downstream chemical or microbial processing can enable full valorization of lignocellulosic biomass, producing fuels, chemicals, and materials in a zero-waste biorefinery model.

c) Digitalization and AI in process optimization: Application of AI and machine learning for predictive modeling, process monitoring, and optimization can reduce experimental costs, improve reproducibility, and accelerate scale-up.

d) Commercial scaling and market acceptance: While mycelium-based materials and bio-based chemicals have entered niche markets, broader adoption requires regulatory frameworks, consumer education, and consistent quality standards.

e) Environmental and policy integration: Policies incentivizing low-carbon, circular processes, carbon credits for sustainable material production, and reduced landfill use will further drive fungal bioconversion adoption.

f) Emerging applications: Future research may expand into food security (protein-rich fungal biomass), bioremediation of persistent pollutants, and production of high-value nutraceuticals and pharmaceuticals.

9. Summary Statement

Overall, ligninolytic fungi represent a biotechnological cornerstone for transforming agro-waste into eco-friendly, economically viable products. With ongoing research, technological optimization, and policy support, fungal bioconversion is poised to play a central role in the circular bioeconomy, contributing simultaneously to environmental sustainability, industrial innovation, and socio-economic development.

References

Ahmed, S., Patel, R., & Singh, V. (2025). Dual-phase fermentation of *Aspergillus oryzae* for enhanced ligninolytic enzyme production from corn straw. *Bioresource Technology*, 404, 125643. https://doi.org/10.1016/j.biortech.2025.125643

Arora, D. S., & Sharma, R. K. (2010). Ligninolytic fungal laccases and their biotechnological applications. *Applied Biochemistry and Biotechnology, 160*(6), 1760–1788. https://doi.org/10.1007/s12010-009-8676-y

Attias, N., Danai, O., Ezov, N., Tarasiuk, A., Borenstein, A., Grobman, Y. J., & Borenstein, S. (2020). Mycelium bio-composites in industrial design and architecture: Comparative review and experimental analysis. *Journal of Cleaner Production, 246*, 119037. https://doi.org/10.1016/j.jclepro.2019.119037

Cherubini, F. (2010). The biorefinery concept: Using biomass instead of fossil fuels. *Energy Conversion and Management, 51*(7), 1412–1421. https://doi.org/10.1016/j.enconman.2010.01.015

Couto, S. R., & Herrera, J. L. T. (2006). Industrial and biotechnological applications of laccases: A review. *Biotechnology Advances, 24*(5), 500–513. https://doi.org/10.1016/j.biotechadv.2006.04.003

Elisashvili, V., & Kachlishvili, E. (2009). Physiological regulation of laccase and manganese peroxidase production by white-rot basidiomycetes. *Journal of Biotechnology, 144*(1), 37–42. https://doi.org/10.1016/j.jbiotec.2009.04.009

FAO. (2022). *FAOSTAT statistical database*. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/

Göransson, E., Moberg, Å., & Hansson, P.-A. (2019). Environmental assessment of biobased materials: Methodological issues and LCA case studies. *Journal of Cleaner Production, 239*, 118085. https://doi.org/10.1016/j.jclepro.2019.118085

Gupta, N., & Banerjee, S. (2025). Biological pretreatment of lignocellulosic biomass using fungal consortia: Progress and prospects. *Green Chemistry*, 27(8), 2045–2063. https://doi.org/10.1039/D5GC00456H

Hatakka, A. (2001). Biodegradation of lignin. In *Biopolymers Online* (pp. 129–180). Wiley-VCH.

Jakubczyk, D., & Dussart, F. (2020). Selected fungal natural products with antimicrobial properties. *Molecules*, *25*(4), 911. https://doi.org/10.3390/molecules25040911

Kirk, T. K., & Farrell, R. L. (1987). Enzymatic "combustion": The microbial degradation of lignin. *Annual Review of Microbiology, 41*(1), 465–505. https://doi.org/10.1146/annurev.mi.41.100187.002341

Kumar, P., Barrett, D. M., Delwiche, M. J., & Stroeve, P. (2009). Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. *Industrial & Engineering Chemistry Research, 48*(8), 3713–3729. https://doi.org/10.1021/ie801542g

Li, Y., Chen, X., & Wu, Z. (2025). Laccase production and lignin degradation by *Trametes versicolor* using tea residues under optimized SSF conditions. *Journal of Environmental Biotechnology*, 32(2), 115–128.

Martínez, A. T., Speranza, M., Ruiz-Dueñas, F. J., Ferreira, P., Camarero, S., Guillén, F., & Martínez, M. J. (2005). Biodegradation of lignocellulosics: Microbial, chemical, and enzymatic aspects of the fungal attack of lignin. *International Microbiology, 8*(3), 195–204.

Matamba, T. (2023). A review on biomass as a substitute energy source. *Renewable and Sustainable Energy Reviews*, *170*, 113197. https://doi.org/10.1016/j.rser.2023.113197

Morales, G., & Zhang, H. (2025). Fungal co-cultures and hybrid fermentation systems for improved lignocellulose valorization. *Applied Microbiology and Biotechnology*, 109(5), 1923–1938. https://doi.org/10.1007/s00253-025-11587-4

Pandey, A. (2003). Solid-state fermentation. *Biochemical Engineering Journal, 13*(2–3), 81–84. https://doi.org/10.1016/S1369-703X(02)00121-3

Sharma, P., & Kumar, A. (2025). Enhanced laccase production by *Pleurotus sajor-caju* under solid-state fermentation for textile effluent decolorization. *Bioprocess and Biosystems Engineering*, 48(3), 451–462. https://doi.org/10.1007/s00449-025-01987-3

Singh, R., Kumar, A., & Pandey, A. (2021). Agro-residue management for sustainable agriculture and environment. *Renewable and Sustainable Energy Reviews, 135*, 110236. https://doi.org/10.1016/j.rser.2020.110236

Singhania, R. R., Patel, A. K., Soccol, C. R., & Pandey, A. (2009). Recent advances in solid-state fermentation. *Biochemical Engineering Journal, 44*(1), 13–18. https://doi.org/10.1016/j.bej.2008.10.019

Sun, J., Li, J., Zhao, H., & Zhao, B. (2018). Pretreatment and enzymatic hydrolysis of lignocellulosic biomass. *BioResources, 13*(2), 2996–3012.

Thakur, I. S., Kumar, M., Varjani, S., & Wong, J. W. C. (2022). Lignocellulosic biomass-based biorefineries for circular bioeconomy. *Bioresource Technology, 360*, 127560. https://doi.org/10.1016/j.biortech.2022.127560

Vogue Business. (2025, June 12). Mycelium leather and packaging enter mainstream markets: A biotech revolution. *Vogue Business*. Retrieved from https://www.voguebusiness.com

Wong, D. W. S. (2009). Structure and action mechanism of ligninolytic enzymes. *Applied Biochemistry and Biotechnology, 157*(2), 174–209. https://doi.org/10.1007/s12010-008-8279-z

Zhu, L. P., Yang, X., Chao, R., & Li, C. F. (2016). Secondary metabolites from fungi: Chemistry and biotechnological applications. *Critical Reviews in Biotechnology, 36*(2), 245–258. https://doi.org/10.3109/07388551.2014.961402

12

CLIMATE SMART SOIL QUALITY MANAGEMENT STRATEGIES FOR RESILIENT AGRICULTURE

Muhammad Sajjad[1], Bader Ijaz[2], Muhammad Hur[3]

1. Introduction

Climate change is one of the greatest threats to global agriculture directly affecting soil health, crop productivity and food security. Sustainable soil management has therefore become central to climate smart agriculture (CSA), which integrate adaptation, mitigation and productivity goals. By addressing food security and climate change, CSA aims to increase sustainable agricultural output. CSA minimizes and reduces post-harvest losses while increasing agricultural productivity and resource efficiency (Olarewaju et al., 2025). By lowering losses and ensuring food security CSA also aids farmers in adapting to climate change.

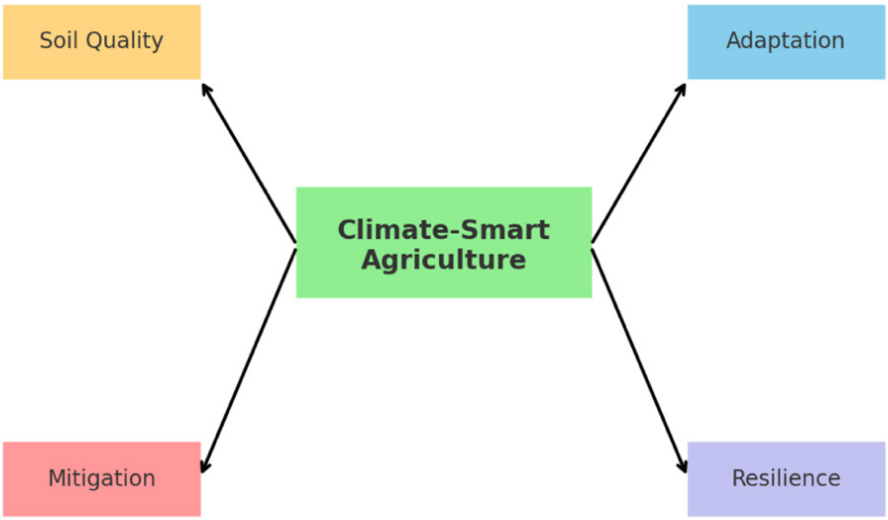
By enhancing fertilizer application and manure management, it reduces greenhouse gas emissions. A popular approach to agricultural management, CSA considers the relationships between soil, water, crops, animals and climate including stakeholders and the agricultural community in decision-making to guarantee that methods are technically feasible, economically feasible and culturally appropriate (Prentice et al., 2024). Examples of CSA operations include improved livestock management, water-saving irrigation technology, integrated pest control, crop diversification and agroforestry (Yang et al., 2024). Climate change has a profound impact on agriculture worldwide, creating enormous challenges to food security and rural communities.

2. Soil quality: indicators and assessment

Assessing soil quality requires the use of measurable indicators that capture chemical, physical and biological dimensions of soil functioning. In the following subjection, the concept of soil quality is defined and the main categories of soil indicators are reviewed with special emphasis on role of soil organic carbon.

1 Department of Agronomy, Faculty of Agriculture, University of Agriculture Faisalabad, Pakistan. muhammadsajjaduaf@gmail.com, ORCID 0000-0002-4064-4076.
2 Department of Agricultural Sciences, University of Sassari, Viale Italia 39/A, 07100 Sassari, Italy, baderzaildar@gmail.com, ORCID 0000-0002-6298-0644.
3 Department of Agronomy, Faculty of Agriculture, University of Agriculture Faisalabad, Pakistan. muhammadhur@gmail.com

Figure 1. CSA concept



2.1. Urbanization and the Emerging Imperative for Sustainable Food Systems

Soil quality refers to "the capacity of soil to carry out its functions." Soil quality affects basic soil functions including moderating and partitioning the movement and availability of water and solutes to plants, storing and cycling nutrients, filtering, buffering, immobilizing and detoxifying inorganic and organic materials, enhancing root growth and protecting against erosion (Ahmed et al., 2025). Selecting appropriate soil quality indicators is often challenges, as they must be sensitive to ecosystem changes and capable of reflecting structural compositional and functional dynamics. Indicators should remain simple practical and relevant to management goals (Daunoras et al., 2024).

2.2. Soil quality indicators

Soil quality indicators assess how effectively soil functions, which is difficult to measure directly. Measuring soil quality entails identifying soil qualities that respond to management, influence or correlate with environmental outcomes and can be precisely quantified within specified technological and budgetary limits. Soil indicators must be qualitative or quantitative (Chaudhry et al., 2024). Chemical indicators include pH, electrical conductivity, nutrient cycling, nitrate, nutrient cycling. Physical indicators deal with Bulk density, physical stability and support, infiltration, water relations, habitat. Biological indicators followed by earthworms, biodiversity, enzymes and soil organic carbon filtering

2.3. Role of soil organic carbon

Soil organic carbon (SOC) is fundamental for soil fertility and resilience. On average, greater than 40% of global carbon (C) is in soil associated with forests, shrub lands and grasslands across the globe (Zhang and Wu, 2024). Soil organic carbon has an important role in soil organic matter (SOM), engaging adhesion to hold soil particles together, while concurrently promoting microorganisms and stabilizing the soil microbial community (Huang et al., 2024). Soil organic matter reduces erosion, while promoting plant nutrition and water uptake. The reduction of soil organic carbon can have dire consequences, such as increased risk of erosion (Li et al., 2024).

3. Climate-induced soil degradation

Climate change reinforces processes of soil degradation through changing rainfall patterns, increasing temperatures and severe weather events because these changes accelerate revision, mitigation and desertification while altering soil moisture dynamics. The combined effect reduces soil fertility, carbon storage and resilience posing serious risk to food security and ecosystem stability.

3.1. Climate change and world soils

Climate change has extensive implications for water supplies and plant availability. Nevertheless, rising temperatures and declining effective rainfall develop significant positive feedback that accelerates soil organic carbon (SOC) decomposition and increases atmospheric CO2 (Elbasiouny et al., 2022). In addition to the effects of climate change, long-term, persistent poor management by extractive industries is another factor contributing to soil degradation and desertification. Constant bad management can replace the natural plant life in a certain area because the soil becomes worse over time (Srivastava et al., 2024). Additionally, the GHG emissions from these fragile and environmentally sensitive places may change because of desertification. Wind erosion one of the primary degrading activities in dryland environments may potentially increase because of protected climate change in desert places (Han et al., 2023).

3.2. Drought and desertification

In already dry areas, water resources are limited (Kim et al., 2023). Sandy land which covers 41% of the earth's area and are home to 42% of its people, are already the most at risk from desertification and drought. But they are expected to face even worse impacts from future climate changes including the loss of the top layer of soil, the selective removal of clay and soil organic matter, the breakdown of soil structure and a decline in plant life (Horel et al., 2022). Planting trees in irrigated areas of the Sahara and the Australian outback could help stop global warming (Ornstein et al., 2009). Climate change intensifies desertification through rising temperature, altered isolation and higher evapotranspiration, leading to vegetation loss (Don et al., 2024).

3.3. Impacts of extreme weather events on soil

The most frequent occurrences of extreme weather events include landslides, floods and snow slides. At the same time, areas in the subtropical drylands are expected to face even more severe reductions in water flow (Furtak et al., 2023). Floods and droughts have significant negative social and economic effects, particularly when it comes to agricultural supply networks. Extreme weather events pose a severe danger to food security as populations rise, and soil degradation continues (Qu et al., 2023).

3.4. Soil moisture, drought and floods under climate change

Climate change-related extreme weather events such as droughts and floods are having an impact on soil fertility and quality (Schmitt et al., 2022). Human land use changing such as sealing floodplains, often cause drought conditions to be followed by a sudden flooding event (Clarke et al., 2022). The carbon and nutrient cycle and soil biology are impacted by increased CO2 concentrations, warming temperatures, changes in atmospheric nitrogen deposition, seasonal variations and extreme events like floods and droughts. Soil characteristics including biological, chemical and physical factors are important indicators of soil health and climate change (Xu et al., 2023). Numerous human and environmental variables influence the variety and activity of microbial consortia (Wang et al., 2024). Several physiological processes including gas exchange, photosynthesis, chlorophyll content and membrane stability are adversely affected by fluctuations in water status along the soil-root-leaf continuum (Xiao et al., 2023). Drought can increase soil osmotic pressure by accumulating solvents in residual water clusters and forming a hypertonic solution, which causes microbial cells to desiccate and limit their activity and development (Lal et al., 2023).

4. Soil management strategies

The amount and quality of soil organic carbon (SOC) and humus (decayed organic matter) are crucial markers of crop output and soil quality. When the concentration of SOC goes below a particular level, critical soil qualities are negatively impacted, impeding plant development. Increasing the quantity of humus and soil organic carbon (SOC) requires the supply of nitrogen (N) and other essential nutrients, such as phosphorus (P) and sulfur (S), to facilitate the conversion of biomass carbon into SOC (Keesstra et al., 2024).

Zero tillage is most suited for the soils which are prone to crusting and erosion, soils which are subjected to intervallic drought, soils having low water holding capacity and humid and sub humid climate (Kumari et al., 2023). Minimum tillage ensures correct seeding, excellent seed germination and successful crop establishment. Better soil conditions, greater water intake from vegetation, better plant root development, better stand establishment and reduced soil compaction (Adam and Abdulai, 2023).

Cover crops provide soil cover during the fallow period, releasing small compounds through their roots as they grow and driving the development of microbes, which stimulates higher biodiversity within the farming system. The dead plant materials from cover crops will contribute organic matter to the soil that can be a source of carbon and nitrogen for future crops (Adam and Abdulai, 2023). Crop rotation is an ancient farming method in which several crops are grown in a particular region throughout time in a specified order. Implementing different crops within the systems, such as cash crops, food crops and cover crops can mitigate economic risks, increase diversity of nutrition and improve the ecosystem services within agricultural systems (Abdalla et al., 2022).

5. Organic amendments and soil enhancers

Recently, organic farming has gained popularity as a sustainable food alternative that lessens the environmental impact of traditional farming (Adam and Abdulai, 2023). Farmyard manure (FYM) is made up of excrement, urine, blood and straw. Per ton, FYM comprises around 5-6 kg nitrogen, 1.2 - 2.0 kg phosphorus and 5-6 kg potassium. A large amount of the organic fraction in dung is made up of complex lignin and protein, resulting in a sluggish release of plant nutrients (Abdalla et al., 2022). Composting is the process of decomposing plant and animal leftovers before spreading them onto fields. Crop wastes applied/incorporated in raw form into the soil produce severe N immobilization, resulting in temporary N deficiency conditions in the soil. To speed the decomposition process, organic leftovers are heaped up, wet, sometimes turned to aerate and held for an appropriate duration (Priyambada and Wardana, 2018).

Biochar produced at 400-450 °C retains more oxygenated functional groups, enhancing solubility, germination, microbial activity and water-holding capacity compared to biochar made at higher temperatures. Biochar improves soil quality, reduces pollutants and is critical for lowering carbon emissions, so mitigating global climate change. Biochar can replace for soil’s hydraulic qualities (Bo et al., 2023).

6. Integrated nutrient and fertilizer management

Integrated nutrient management (INM) workflow combines organic resources (e.g., compost, green manure) with appropriate amounts of chemical fertilizers as well as site-specific soil management measures to increase nutrient usage efficiency. By the twenty-first century, INM was recognized as a cornerstone of sustainable agriculture, backed by worldwide programs and management methods that encourage farmers to embrace holistic nutrient management strategies that maintain soil health, minimize pollution and increase crop resilience (Bragina et al., 2024).

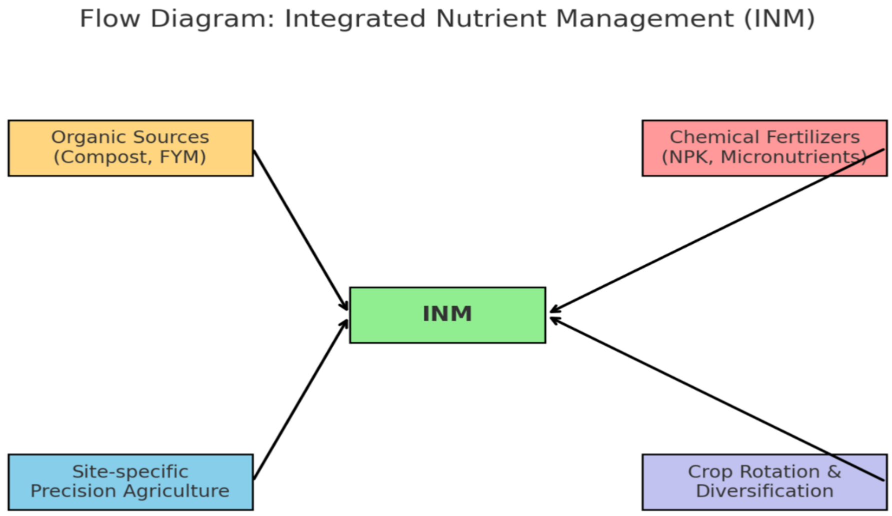
6.1. Integrated Nutrient management (INM)

The primary components of integrated nutrient management include:

- **Soil Fertility Assessment:** Regular soil testing to determine nutrient status and pH levels.
- **Balanced Fertilization:** Application of macronutrients (N-P-K) and micronutrients based on crop requirements.
- **Organic Amendments:** implement of compost, green manure and bio-fertilizations to increase soil organic matter.
- **Crop Rotation and Diversification:** Growing different crops in succession to improve nutrient cycling and reduce pest pressures.

Precision Agriculture: Using technology to enhance fertilizer rates through site-specific nutrient management

Figure 2. Integrated nutrient management



6.2. Site-specific fertilizer application

Precision agriculture is an innovative and effective practice that utilizes modern technology and data-driven solutions to inform decisions and optimize crop production (Costa et al., 2022). Site-specific nitrogen management (SSNM) is a central strategy in the emerging practice of precision agriculture that attempts to achieve these goals. SSNM is the process of matching N delivery to the needs of each field, based on soil characteristics, crop needs and environmental conditions. Farmers may increase the efficiency of nitrogen utilization, save input costs, and preserve natural resources by employing this precise nutrient targeting (Sajjad et al., 2024; Khaliq et al., 2023). When applied in proper quantity and at the correct time, nitrogen application has the potential to increase crop yield and quality while minimizing unutilized N to the environment.

6.3. Slow-release and climate-responsive fertilizers

Using slow-release nitrogen-based fertilizers increases productivity while decreasing environmental risk to the agro-ecosystem. Nitrogen is a macronutrient and essential plant nutrient that supports crop growth, development and grain quality. Phosphorus and potassium are also macronutrients that play a variety of roles in crops development under abiotic stress. Soil nitrogen fertilizer application is delicate and must be managed to meet crop requirements. Potassium helps maintain cell turgidity through osmoregulation and stomatal regulation in plants (Zuma et al., 2023). The efficiency of slow-release fertilizers can be enhanced by balanced application, proper maintenance and good fertilizer quality. Higher crop production depends on scientifically recommended NPK levels, application rates and timing (Paramesh et al., 2023).

7. Soil moisture conservation techniques

The goal of soil moisture conservation is to reduce the quantity of water that evaporates from the soil through transpiration the process by which plants absorb water and release it into the atmosphere and evaporation the process by which water changes into vapor and departs the soil directly (Sajjad et al., 2025b).

7.1. Mulching

Mulch is a coating of organic (or inorganic) material that is applied to the root zone of plants. Mulching is best suited for low to medium rainfall areas and less suited for locations with highly rainy circumstances.

7.2. Conservation tillage

Cutting back on tilling or stopping it completely in tough situations, helps keep the soil's organic matter in good shape, which makes the soil better at holding and soaking up water. Crop residue is left on the soil during conservation tillage, a technique that reduces evapotranspiration and covers the soil surface from the impacts of wind, sunlight, and heavy rain.

7.3. Crop rotation

Every season, growing a variety of crops enhances the soil's structure and in turn its ability to retain water. Since plants draw water from different depths inside the soil, rotating crops with deep and shallow roots allows them to take advantage of previously utilized soil moisture. Plant materials are grown only for the aim of improving soil organic matter and nutrients. Improved soil quality leads to increased water retention capacity.

7.4. Strip cropping and rainwater harvesting

Growing erosion-tolerant crops with erosion-resistant crops in alternate strips. Rainwater harvesting is another way to conserve soil moisture by lowering runoff and storing water for on-site consumption.

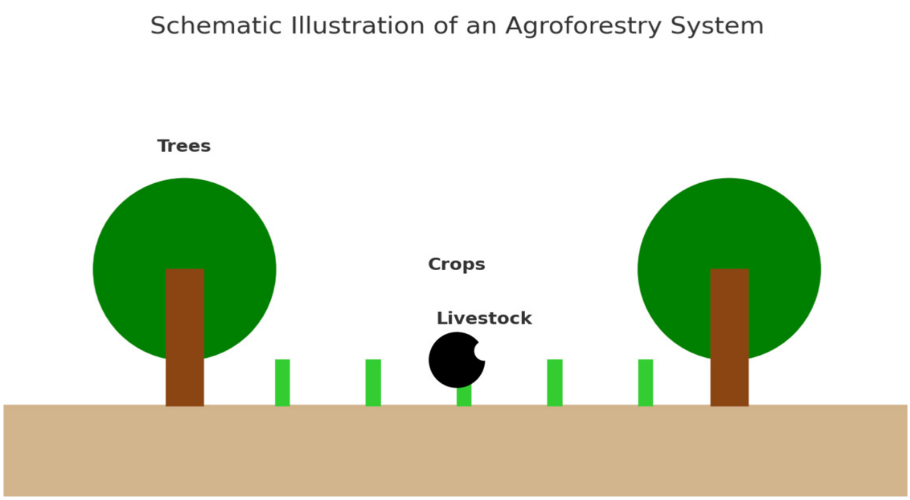
8. Agroforestry soil biodiversity and innovation

8.1. Agroforestry for sustainable health

Agroforestry is a land-use strategy that integrates trees, shrubs or perennial vines with agricultural crops and/or livestock. It offers two primary advantages for farmers: adding perennial components to the farm, which creates additional long-term revenue streams and generating a more diversified system of plants that more closely replicates a natural environment (Quandt et al., 2023).

One of the primary goals in developing sustainable agricultural systems is to increase soil health. Protecting and promoting soil health is necessary since soil is one of the most important resources for future generations (Gupta et al., 2023). Agroforestry is a form of sustainable agriculture that follows natural ecological principles. It works by mixing trees with crops, which can help make farming more productive and environmentally friendly in the long run (Rolo et al., 2023).

Figure 3. Schematic illustration of an agroforestry system



8.2. Role of Soil Microbial Communities

Microorganisms found in soil including bacteria, fungus, viruses, protozoa and tiny algae are crucial for maintaining the fertility and health of the soil. These microorganisms play a key role in many soil processes such as decomposing organic matter, cycling nitrogen and combating plant pathogens. The diversity of soil microorganisms is important to sustaining healthy agricultural systems that produce nutritious crops with good yields (Tiedje et al., 2022). Any loss of microbial diversity can lead to a loss of ecosystem multifunctionality and can negatively affect ecosystem services important to soil fertility, food production and the production of fiber crops (Kumari et al., 2023).

8.3. Technological Interventions and innovations

Researchers and agricultural experts are always looking at new strategies for sustainable soil management, relying on progress in product development and agriculture innovation. New technologies including charcoal and microbial inoculants offer potential solutions ranging from improving soil health, resilience and productivity.

8.3.1. Soil Sensors and Monitoring Systems

Real-time information on soil temperature, moisture content and nutrient levels is provided by soil sensors and monitoring systems, empowering farmers to make better decisions on crop management, fertilization and irrigation. These devices improve resource efficiency, reduce waste and promote precise soil management methods. Additionally, ongoing research and innovation in agricultural technology and product development leads to new approaches to sustainable soil management, ensuring an economic and sustainable agricultural future (Sun et al., 2023).

8.3.2. Precision agriculture and digital soil mapping

To meet food demand, both industrialized and developing countries must increase crop output through agricultural intensification. The introduction of new technologies such as precision agriculture (PA) will have a substantial influence on our ability to increase agricultural output in a sustainable way on a global scale. Pennsylvania defines the term as "the science of improving crop productivity and assisting management decisions using high technology sensor and analysis tools" Mostly PA management, combined with genetic advancements in agricultural qualities, might play a major role today and in the future in satisfying global demands for food, feed, fiber and fuel (Pande et al., 2023). Digital soil maps may illustrate the visual variety of soil nutrients at a finer resolution, allowing landowners to detect high and low nutrient distributions within their crops. As a result, there is a need to gather digitized soil data to provide exact nutrition recommendations (Talaat, 2023).

8.3.3. Remote sensing and GIS tools in soil monitoring

Remote sensing (RS) has emerged as an encouraging approach to these difficulties with effective and extensive means to acquire information about soils, a variety of tools or technologies including satellites, aerial photographs, GPS, LiDAR, ground-based sensors, radar systems, crowdsourcing, social media and historical records are employed for gathering RS data (Lenton et al., 2024). Remote sensing is still evolving and with advancements in technology, additional sources of data will continue to emerge (Zhao et al., 2023).

Soil zonation holds great importance for assessing options for fertilization in digital agriculture. Management zones (MZs), which are defined as homogenous geographical units grounded in soil and landscape characteristics have gained popularity as a way of improving field operations and chemical applications in agriculture. MZs support approaches that are specific to traits of the soil, such as texture and cation exchange capacity (Balasundram et al., 2023). The integration of RS and GIS has greatly advanced the definition of MZs in that it captures spatial and temporal variability in soil and vegetation parameters, which inform data-driven decisions (Gumbi et al., 2023).

8.3.4. Decision support systems for soil management

Agricultural decision support systems (DSSs) tend to raise the level of a specific soil function for example soil health with a focus on primary productivity or nutrient cycling while neglecting other important soil functions such as climate regulation, carbon sequestration and water purification and regulation (Arena et al., 2022). A recent review of agricultural DSS systems illustrates that there a need and potential benefit for systems that address specific farm management issues to reach sustainability objectives (Gupta et al., 2022).

Studies often concentrate on the technical characteristics of these tools and fewer studies evaluate their practical utility in different agro-ecological contexts. In order for digital technologies to support the agro-ecological transition and foster agro-ecological agriculture systems, these gaps need to be addressed.

8.4. Policy and Institutional Support

Farmers and a broader variety of other stakeholders including civil society, land planners and politicians at various scales are impacted by soil management, which has multiple consequences ranging from soil biodiversity to global climate change (Hou et al., 2020). Soils provide both private (farmer income) and public goods and services (ecosystem services ES) and it is often not easy to separate these types. A specific management strategy may improve soil quality for both types of values or it can promote one type of value and potentially compromise another. There are various examples of these trade-offs, particularly those related to the long-term effects of behaviors. For example, using farmyard manure in the continental climatic zone improves soil biological and physical quality while also contributing to soil carbon stores (Sparkman et al., 2022).

Extension professionals work directly with farmers, giving information, expertise and practical skills. Their responsibilities include promoting new agricultural technology and providing information, skills and strategies to help farmers enhance their resilience to short-term climate-related external shocks that endanger food security. The goal of this study is to understand extension personnel's perspectives of their role in extension service delivery, the subjects and material they cover, the tactics they support and how they improve sustainable agricultural systems (Fairbrother, 2022).

This aim is addressed through three research objectives:

1. Identify the extension advisory services commonly provided in the main study area.
2. Determine the common modes of dissemination of those services and
3. Identify the challenges and opportunities of the extension advisory services across differing perspective and discuss implications for future.

The above three objectives assist us in examining key areas that can be monitored to close the widening knowledge gap between farmers by examining the experiences of extension sector in the agricultural extension system as mentioned earlier in the above introduction section. Seeking the experiences and perceptions of extension personnel is important because they are the frontline workers interacting with and providing information, knowledge and practical skills to farmers (Suprayitno et al., 2024).

8.5. Application of the ecosystem approach to soil biodiversity management

To preserve crops and soil resources, especially soil biodiversity, VGG encourages and teaches adaptive management. Through resolution V/6 of the Conference of the Parties, the Convention on Biological Diversity (CBD) approved principle 9 of the ecosystem approach, which is in line with this experiential learning methodology. The following methods of producing basic grains are used to improve soil biodiversity:

- Using crop rotations, leguminous cover crops, better local seeds and growing different crops together helps make the farming system more resilient and increases production.
- Using gentle farming methods that disturb the soil less helps keep the soil structure and the organisms living in the soil safe.
- Using leftover crop parts, animal manure and growing green manure helps create natural fertilizers.
- Taking steps to protect the soil helps keep it strong and retains more moisture. This includes:
  - Different types of crops and land uses arranged in patterns.
  - Collecting and storing rainwater for use by plants, animals and people.
  - Bringing back a variety of agricultural plants by growing local crops, useful plants and tree species.

8.5.1. Relevance to the programe of work Agricultural Biological Diversity

Building capacity is the primary benefit of the FAO/CBD relationship, in addition to adaptive management. This entails encouraging responsibility and improving the capacity to manage biological diversity, particularly soil biodiversity.

8.5.2. Outcomes

More than 2000 farmers have adopted soil and water conservation techniques, as well as integrated crop and soil biological management, throughout the past 20 years. The following are some of the group members' primary accomplishments.

- More local farming output has gone up.
- Many farmers who didn't like natural or organic methods have cut back on using strong chemicals.
- More farmers are putting crop leftovers back into the soil.
- There's been a bigger effort to protect soil and water and to make the soil more fertile.
- Farmers are getting better at bringing in money from outside sources to support their work.

9. Challenges and future directions towards soil quality management strategies for resilient agriculture

Climate-smart agriculture (CSA) has become more popular as a promising way to address food poverty especially with the increasing effects of climate change. In countries where farming is the main source of income rising problems like hunger, climate change and reliance on rain for crops are causing lower crop production, less access to food and reduced financial stability. Climate change, along with other structural and institutional issues, has led to food shortages. Current agricultural initiatives are also dealing with diminishing farmland, deteriorating soil health, addressing food insecurity for a rising population and lessening poverty in rural regions (Katherasala et al., 2024). Climate-smart agriculture (CSA) is a regenerative strategy that interlinks context sensitive technologies and practices with sustainable intensification to solve economic and environmental problems (Sajjad et al., 2025a). CSA tools that improved productivity and resilience present a realistic methodology for stabilizing agricultural outputs. Moreover, since many low-income countries should have already adopted CSA technologies and practices, there are observed limitations to farmers' use of CSA (Futa et al., 2024). CSA strategies have been shown to be successful tools to raise awareness of the connection with agricultural climate change and to unify development, agriculture and climate change organizations, all at the same table (Mutengwa et al., 2023).

10. CONCLUSION

Climate change has impacted food security and people's livelihoods across the globe. Climate-smart agriculture (CSA) is quite promising in soil management, increasing food security and also helps in adapting to and mitigating climate change. Addressing climate change is a necessary, cost effective and timely solution to improve resiliency, food security and meet climate change objectives. Moreover, CSA is knowledge-intensive, location-specific and relies on an appropriate enabling environment including technology, skilled human capital, facilities and resources. Thus, each country should identify the context-appropriate CSA packages that are selected and adapted according to its own circumstances and socio-economic needs. There needs to be improved methodologies for better coordination between extension workers, researchers, politicians and other non-state actors to accelerate the adoption of CSA-compatible technology and production systems.

References

Abdalla, K., Sun, Y., Zarebanadkouki, M., Gaiser, T., Seidel, S. and Pausch, J. (2022). Long-term continuous farmyard manure application increases soil carbon when combined with mineral fertilizers due to lower priming effects. *Geoderma*, 428: 116216.

Adam, B. and Abdulai, A. (2023). Minimum tillage as climate-smart agriculture practice and its impact on food and nutrition security. *Plos one*, 18(12): e0287441.

Ahmed, N., Xinagyu, G., Alnafissa, M., Sikder, M. and Faye, B. (2025). Evaluating the impact of sustainable technology, resource utilization, and climate change on soil emissions: A CS-ARDL analysis of leading agricultural economies. *Cleaner Engineering and Technology*, 24: 100869.

Arena, S., Florian, E., Zennaro, I., Orrù, P. F. and Sgarbossa, F. (2022). A novel decision support system for managing predictive maintenance strategies based on machine learning approaches. *Safety Science*, 146: 105529.

Balasundram, S. K., Shamshiri, R. R., Sridhara, S. and Rizan, N. (2023). The role of digital agriculture in mitigating climate change and ensuring food security: an overview. *Sustainability*, 15(6): 5325.

Bo, X., Zhang, Z., Wang, J., Guo, S., Li, Z., Lin, H., ... & Zou, J. (2023). Benefits and limitations of biochar for climate-smart agriculture: A review and case study from China. *Biochar*, 5(1): 77.

Bragina, V., Volodin, E., Chernenkov, A. and Tarasevich, M. (2024). Simulation of climate changes in Northern Eurasia by two versions of the INM RAS Earth system model. *Climate Dynamics*, 62(8): 7783-7797.

Chaudhry, H., Vasava, H. B., Chen, S., Saurette, D., Beri, A., Gillespie, A. and Biswas, A. (2024). Evaluating the soil quality index using three methods to assess soil fertility. *Sensors*, 24(3): 864.

Clarke, B., Otto, F., Stuart-Smith, R. and Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. *Environmental Research: Climate*, 1(1): 012001.

Costa, D., Sutter, C., Shepherd, A., Jarvie, H., Wilson, H., Elliott, J. and Macrae, M. (2022). Impact of climate change on catchment nutrient dynamics: insights from around the world. *Environmental Reviews*, 31(1): 4-25.

Daunoras, J., Kačergius, A. and Gudiukaitė, R. (2024). Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology*, 13(2): 85.

Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S. and Chenu, C. (2024). Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *Global Change Biology*, 30(1): e16983.

Elbasiouny, H., El-Ramady, H., Elbehiry, F., Rajput, V. D., Minkina, T. and Mandzhieva, S. (2022). Plant nutrition under climate change and soil carbon sequestration. *Sustainability*, 14(2): 914.

Fairbrother, M. (2022). Public opinion about climate policies: A review and call for more studies of what people want. *PLoS Climate*, 1(5): e0000030.

Furtak, K. and Wolińska, A. (2023). The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture–A review. *Catena*, 231: 107378.

Futa, B., Gmitrowicz-Iwan, J., Skersienė, A., Šlepetienė, A., & Parašotas, I. (2024). Innovative soil management strategies for sustainable agriculture. *Sustainability*, 16(21): 9481.

Gumbi, N., Gumbi, L. and Twinomurinzi, H. (2023). Towards sustainable digital agriculture for smallholder farmers: A systematic literature review. *Sustainability*, 15: 12530.

Gupta, S. R., Dagar, J. C., Sileshi, G. W. and Chaturvedi, R. K. (2023). Agroforestry for climate change resilience in degraded landscapes. *Agroforestry for sustainable intensification of agriculture in Asia and Africa*, 121-174.

Gupta, S., Modgil, S., Bhattacharyya, S. and Bose, I. (2022). Artificial intelligence for decision support systems in the field of operations research: review and future scope of research. *Annals of Operations Research*, 308(1): 215-274.

Han, Y., Zhao, W., Zhou, A., & Pereira, P. (2023). Water and wind erosion response to ecological restoration measures in China's drylands. *Geoderma*, *435*: 116514.

Horel, Á., Zsigmond, T., Farkas, C., Gelybó, G., Tóth, E., Kern, A., & Bakacsi, Z. (2022). Climate change alters soil water dynamics under different land use types. *Sustainability*, 14 (7): 3908.

Hou, D., Bolan, N. S., Tsang, D. C., Kirkham, M. B., & O'connor, D. (2020). Sustainable soil use and management: An interdisciplinary and systematic approach. *Science of the Total Environment*, 729: 138961.

Huang, X., Ibrahim, M. M., Luo, Y., Jiang, L., Chen, J. and Hou, E. (2024). Land use change alters soil organic carbon: constrained global patterns and predictors. *Earth's Future*, 12(5): e2023EF004254.

Katherasala, S. (2024). Approaches to Sustainable Agriculture: A Retrospective Analysis for Soil Health Improvement: Sustainable Approaches for Soil Health. *SAARC Journal of Agriculture*, 22 (2): 1-13.

Keesstra, S. D., Chenu, C., Munkholm, L. J., Cornu, S., Kuikman, P. J., Thorsøe, M. H. and Visser, S. M. (2024). European agricultural soil management: Towards climate-smart and sustainability, knowledge needs and research approaches. *European Journal of Soil Science*, 75 (1): e13437.

Khaliq, A., Zafar, M., Sajjad, M., Hassan, M. U., Mudassar, M. A., Shakoor, M. A., ... & Niaz, S. (2023). Nitrogen use efficiency in sunflower (*Helianthus annuus* l.) influenced by various fertigation and bed planting techniques. *Pakistan Journal of Biotechnology*, *20* (02): 385-392.

Kim, K. H. and Lee, B. M. (2023). Effects of climate change and drought tolerance on maize growth. *Plants*, 12 (20): 3548.

Kumari, A., Dash, M., Singh, S. K., Jagadesh, M., Mathpal, B., Mishra, P. K. and Verma, K. K. (2023). Soil microbes: a natural solution for mitigating the impact of climate change. *Environmental Monitoring and Assessment*, 195 (12): 1436.

Lal, P., Shekhar, A., Gharun, M. and Das, N. N. (2023). Spatiotemporal evolution of global long-term patterns of soil moisture. *Science of The Total Environment*, 867: 161470.

Lenton, T. M., Abrams, J. F., Bartsch, A., Bathiany, S., Boulton, C. A., Buxton, J. E. and Boers, N. (2024). Remotely sensing potential climate change tipping points across scales. *nature communications*, 15 (1): 343.

Li, S., Delgado-Baquerizo, M., Ding, J., Hu, H., Huang, W., Sun, Y. and Liang, Y. (2024). Intrinsic microbial temperature sensitivity and soil organic carbon decomposition in response to climate change. *Global Change Biology*, 30 (6): e17395.

Mutengwa, C. S., Mnkeni, P. and Kondwakwenda, A. (2023). Climate-smart agriculture and food security in Southern Africa: A review of the vulnerability of smallholder agriculture and food security to climate change. *Sustainability*, 15 (4): 2882.

Olarewaju, O. O., Fawole, O. A., Baiyegunhi, L. J., & Mabhaudhi, T. (2025). Integrating Sustainable Agricultural Practices to Enhance Climate Resilience and Food Security in Sub-Saharan Africa: A Multidisciplinary Perspective. *Sustainability*, 17 (14): 6259.

Ornstein, L., Aleinov, I., & Rind, D. (2009). Irrigated afforestation of the Sahara and Australian Outback to end global warming. *Climatic Change*, 97(3): 409-437.

Pande, C. B. and Moharir, K. N. (2023). Application of hyperspectral remote sensing role in precision farming and sustainable agriculture under climate change: A review. *Climate Change Impacts on Natural Resources, Ecosystems and Agricultural Systems*, 503-520.

Paramesh, V., Mohan Kumar, R., Rajanna, G. A., Gowda, S., Nath, A. J., Madival, Y. and Toraskar, S. (2023). Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. *Frontiers in Sustainable Food Systems*, 7: 1173258.

Prentice, C. M., Vergunst, F. Minor, K. and Berry, H. L. (2024). Education outcomes in the era of global climate change. *Nature Climate Change*, 14 (3): 214-224.

Priyambada, I. B., and Wardana, I. W. (2018). Fast decomposition of food waste to produce mature and stable compost. *Sustinere: Journal of Environment and Sustainability*, 2 (3): 156-167.

Qu, Q., Xu, H., Ai, Z., Wang, M., Wang, G., Liu, G. and Xue, S. (2023). Impacts of extreme weather events on terrestrial carbon and nitrogen cycling: A global meta-analysis. *Environmental Pollution*, 319: 120996.

Quandt, A., Neufeldt, H. and Gorman, K. (2023). Climate change adaptation through agroforestry: opportunities and gaps. *Current Opinion in Environmental Sustainability*, 60: 101244.

Rolo, V., Rivest, D., Maillard, É. and Moreno, G. (2023). Agroforestry potential for adaptation to climate change: A soil-based perspective. *Soil Use and Management*, 39 (3): 1006-1032.

Sajjad, M., Hussain, K., Hakki, E. E., Ilyas, A., Gezgin, S., & Shakil, Q. (2025a). Impact of Irrigation Techniques on Water-Use Efficiency, Economic Returns, and Productivity of Rice. *Sustainability*, 17 (17): 7712.

Sajjad, M., Hussain, K., Wajid, S. A., & Saqib, Z. A. (2024). The impact of split nitrogen fertilizer applications on the productivity and nitrogen use efficiency of rice. *Nitrogen,* 6 (1): 1.

Sajjad, M., Ijaz, B., Khil, A., Ibtahaj, I., Hur, M., Azizi, N., ... & ur Rehman, H. (2025b). Influence of different organic mulches on growth, yield and oil content of maize (*Zea mays* L.) hybrids and soil physical properties. *Journal of Ecological Engineering*, 26 (11): 410-427.

Schmitt, J., Offermann, F., Söder, M., Frühauf, C. and Finger, R. (2022). Extreme weather events cause significant crop yield losses at the farm level in German agriculture. *Food Policy*, 112: 102359.

Sparkman, G., Geiger, N. and Weber, E. U. (2022). Americans experience a false social reality by underestimating popular climate policy support by nearly half. *Nature communications*, 13(1): 4779.

Srivastava, R. K., Purohit, S., Alam, E., and Islam, M. K. (2024). Advancements in soil management: Optimizing crop production through interdisciplinary approaches. *Journal of Agriculture and Food Research*, 18: 101528.

Sun, Q., Granco, G., Groves, L., Voong, J. and Van Zyl, S. (2023). Viticultural manipulation and new technologies to address environmental challenges caused by climate change. *Climate*, 11 (4): 83.

Suprayitno, D., Iskandar, S., Dahurandi, K., Hendarto, T. and Rumambi, F. J. (2024). Public policy in the era of climate change: adapting strategies for sustainable futures. *Migration Letters*, 21 (S6): 945-958.

Talaat, F. M. (2023). Crop yield prediction algorithm (CYPA) in precision agriculture based on IoT techniques and climate changes. *Neural Computing and Applications*, 35(23): 17281-17292.

Tiedje, J. M., Bruns, M. A., Casadevall, A., Criddle, C. S., Eloe-Fadrosh, E., Karl, D. M. and Zhou, J. (2022). Microbes and climate change: a research prospectus for the future. *MBio*. 13 (3): e00800-22.

Wang, M., Zhang, S., Guo, X., Xiao, L., Yang, Y., Luo, Y. and Luo, Z. (2024). Responses of soil organic carbon to climate extremes under warming across global biomes. *Nature Climate Change*, 14 (1): 98-105.

Xiao, J., Yu, C. and Fu, G. (2023). Influences of human activity and climate change on growing-season soil moisture in the Qinghai–Tibet grasslands from 2000 to 2020. *Frontiers in Ecology and Evolution*, 11: 1264870.

Xu, L., Gao, G., Wang, X. and Fu, B. (2023). Distinguishing the effects of climate change and vegetation greening on soil moisture variability along aridity gradient in the drylands of northern China. *Agricultural and Forest Meteorology*, 343: 109786.

Yang, Y., Tilman, D., Jin, Z., Smith, P., Barrett, C. B., Zhu, Y. G. and Zhuang, M. (2024). Climate change exacerbates the environmental impacts of agriculture. *Science*, 385 (6713): eadn3747.

Zhang, Z. and Wu, B. (2024). Soil health and sustainable agriculture: Key research directions and practical pathways. *Geographical Research Bulletin*, 3: 298-301.

Zhao, S., Liu, M., Tao, M., Zhou, W., Lu, X., Xiong, Y. and Wang, Q. (2023). The role of satellite remote sensing in mitigating and adapting to global climate change. *Science of the Total Environment*, 904: 166820.

Zuma, M., Arthur, G., Coopoosamy, R. and Naidoo, K. (2023). Incorporating cropping systems with eco-friendly strategies and solutions to mitigate the effects of climate change on crop production. *Journal of Agriculture and Food Research*, 14: 100722.

13

THE VALUE OF ORGANIC WASTE: MAKING NUTRIENT-RICH VERMICOMPOST FOR SUSTAINABLE AGRICULTURE

Yehya Bouraghda[1], Abderrahim Boutemedjet[2]

1. Introduction

The organic fraction of domestic solid waste (food and yard waste products) is a significant and challenging part of the global waste problem. In many cities worldwide, including those in low- and middle-income countries, organic waste makes up 60-80 percent of all municipal solid waste (MSW) generated (Scheinberg et al., 2010; Sharma et al., 2019). This type of waste includes household food waste, agricultural residue, animal manure, and industrial organic by-products, all with high moisture content and solid density (Mudiyanselage & Herat, 2021).

Landfilling or uncontrolled open dumping are current waste management practices that pose environmental hazards. Decomposition of waste in landfills without aeration is a significant source of the greenhouse gases methane (CH_4; with a global warming potential higher than that of CO_2) and nitrous oxide (N_2O) (Manheim et al., 2021). Additionally, leachate contamination threatens soil and groundwater quality; open dumping causes bad odors, visual pollution, and the spread of pathogens and diseases (Karimi et al., 2024, Sharma et al., 2019).

From an economic perspective, the linear 'take-make-dispose' model has resulted in the loss of valuable resources such as plant nutrients and organic matter, as well as the disposal of large quantities of Rice Husks (RHs) in landfills. The only valorization alternative for these materials has an associated cost related to the collection and transportation (Puyuelo et al., 2019). The Sustainability crisis of Agriculture responds to the environmental crisis. The overuse of chemical fertilizers and pesticides has led to soil degradation, biodiversity loss and water pollution (Karimi et al., 2024).

Nevertheless, the basics of this methodology are important to trace back to at least some of the alternative methods that have assisted farmers in creating some form of environmentally safe, economically viable, and socially responsible

1 University of 8 Mai 1945 Guelma, Faculty of Science and Technology, Department of Process Engineering, Guelam, Algeria, https://orcid.org/0009-0003-4126-0773, bouraghda.yehya@univ-guelma.dz
2 University of Souk Ahras, Faculty of Science and Technology, Department of Process Engineering, Souk Ahras, Algeria, https://orcid.org/0009-0007-9392-3080, *ab.boutemedjet@univ-soukahras.dz*

farming system (Terán-Samaniego et al., 2025; Pandey & Mishra, 2024). The major goal is to ‘close the loop’ in nutrient cycles by shifting the focus from reliance on non-renewable external inputs to techniques that increase and sustain soil fertility over time (Hendrix et al., 1992). Through the increase in organic matter and biological activity, as well as the promotion of good soil structure, this will improve the health of the soil and facilitate the development of more productive and resilient agroecosystems (Giri & Pokhrel, 2022).

Under such circumstances, microbial vermicomposting is an attractive and practical composting strategy which can effectively solve the organic waste problems and satisfy the demands of eco-agriculture. This is through bio-oxidation carried out by earthworms (mostly epigeic species such as *Eisenia fetida*) and micro-organism involved in the process of converting organic waste into vermicompost, a stabilized end product with significant intrinsic value (Karimi et al., 2024).

Moreover, the vermicomposting process is not similar to the traditional composting; the application of colloidal bioreactor process in vermicomposting, which is used to accelerate composting by using the activity of colloidal microorganisms and organic particles that stimulates microbial interactions, the colloidal bioreactor enhances physical, chemical and biological properties of the vermicompost than the conventional compost. Nitrogen, phosphorus, potassium and micronutrients are quite rich in the vermicompost, as compared to other type of composts and raw manure (Karimi et al., 2024).

It contains extreme population of beneficial fungus, bacteria and enzymes, as well as the nutrients beside inhibiting soil-borne pathogens, the chemicals contribute to mineralization of nutrient (Sharma et al., 2019). Also, the usage of vermicompost helps to reinstate the physical characteristics and properties of soil like aeration, porosity and water-holding capacity which in turn is adaptive in enhancing the drought resistance capability of the crop. The transformation of the problematic waste streams into resources that contribute to a more efficient and sustainable soil fertility and less reliance on synthetic fertilizers can also be suitably seen as a part of the idea of the circular bioeconomy, where vermicomposting becomes a significant facilitating technology to approach a more resource-saving and sustainable future (Puyuelo et al., 2019, Hendrix et al., 1992).

2. Organic Waste: A Resource for Agriculture

2.1. Types and characteristics of organic waste relevant to agriculture

suitable organic waste for sustainable agriculture is not a homogenous product but a diverse range of complex and mixed waste flows. All of these streams differ in their source, composition, and regional economic background (Huang, 2024).

Globally, the organic fraction of the Municipal Solid Waste (MSW) is the most dominant part of waste worldwide and also the biggest challenge among the rest. It comprises over 65% of total waste in low-income countries, compared to less than 30% in high-income countries, where dry recyclables such as paper, plastic, and glass are usually dominant (Ragab et al., 2025).

This mixed feedstock comprises of kitchen waste (such as rotten meat, fruit and vegetable peelings, egg shells), yard waste (including leaves, grass clippings, tree pruning), and biodegradable paper products (Nanda & Berruti, 2021). Such a material is associated with high moisture and density, thus being hardly manageable because it has low calorific value when incinerated and is also leachable to some degree as well as releasing a huge amount of greenhouse gas when it is landfilled (Lackner & Besharati, 2025). This stream includes a variety of waste types, such as Food Waste (FW) which is an important subcategory. It is produced at all levels along the food supply chain. This includes both household level and central sources, such as restaurants, markets, food processing industries and large institutions (Mahish et al., 2024; Uhlig et al., 2025).

Universities are potentially one of the best candidates for sustainable management options, such as anaerobic digestion (AD) and composting, this is because food waste generation from aggregative sources can be seen as continuous (steady flow over time) and homogenous. From this perspective, university campuses are ideal “living labs” to test out such creative solutions (Torrijos et al., 2021). Such controlled environments also provide opportunities in early business development for circular models and to test new technologies before their application in more complex urban prototypes where systems are more heterogeneous with associated higher risks of cross-contamination (Maçin et al., 2024).

Unlike urban centred MSW, agricultural waste is a large and often under exploited stream that is created directly during food production. This category includes large amounts of agricultural residues such as, wheat and rice straw, sugarcane bagasse and corn stalks, animal manure and agro-industrial waste products such as slaughter house waste and olive mills effluent (Lackner & Besharati, 2025; Mahish et al., 2024; Mallikarjuna Rao et al., 2024). Such waste is often inappropriately disposed, most commonly through open burning and releases particulate matter and greenhouse gas emissions to the atmosphere (Ravish et al., 2025). However, these organics have a high content of lignocellulose and a large carbon with major nutrients and thus are an ideal candidate for valorisation as feedstock (Ginni et al., 2021).

The organic waste streams produced are of a varied nature but do share one very essential quality, i.e., that they are not waste but are resources that have been underutilised. Because of increased share of organic matter and needed plant nutrients are good substrate for biological conversion process (Adhikari et al., 2013). Technologies such as composting, anaerobic digestion and vermicomposting share the value in returning to use of these materials in the many different products like biofertilizers, biogas and soil amendments. By enhancing soil fertility, and reducing the need for the use of synthetic inputs, the strategy can be applied as part of a circle bio-economy and sustainable agriculture (Lackner & Beschrati, 2025; Mahish et al., 2024; Cucina, 2023).

2.2. Challenges and opportunities in their management

Issues of logistics and technology are paramount to the management of heterogeneous organic streams. The successful valorisation is hindered in many cases by the need to have an efficient source separation, since cross contamination with other materials (plastics, glass, or heavy metals) it should be avoided. This contamination can affect to the quality and safety of finished product (Sharma et al., 2019; Maçin et al., 2024; Thakali et al., 2022). The fact that food and agricultural waste is high in moisture content has been shown to result in difficulties during transportation, affect the performance of thermochemical process and require careful management during biological conversion phase which would prevent loss of nutrient due to leachate as well as bacteria propagation (Lackner & Besharati, 2025; Nanda & Berruti, 2021; Paul et al., 2013). The intense decay of this refuse also presents problems with respect to odours and pest attraction and if poorly managed, a threat to public health (Karimi et al., 2024; Nie et al., 2023).

However, these challenges be weighed against the potential contained within these materials. Organic waste is a major form of organic carbon and some plant nutrients (i.e. short supply to the plant) such as nitrogen, phosphorous and potassium. Moreover, it has significant bioenergy potential (Barros et al., 2020; Lackner & Besharati, 2025; Panagiotis et al., 2025). By appropriate mechanism of waste management, and also technologies like composting, anaerobic digestion and vermi-composting -waste can be converted into products with high value. They include biofertilizers that are rich in nutrients and have been found to improve soil fertility and structure thereby reducing the demand for synthetic chemical fertilizers (Mahish et al., 2024; Li et al., 2020; Ansar et al., 2025).

Additionally, such streams are valued as a major source for production of renewable energy based on biogas (for heat and power) and biofuel apart from the manufacture of new biobased products like bioplastics and biochar (Lackner & Besharati, 2025). These approaches have the potential to reduce environmental impact of agriculture, create new revenue streams, stimulate employment and contribute to a more circular and resilient bio economy.

This bioeconomy would mean closing nutrient loops and serving the ideas of sustainable development (Barros et al., 2020; Hefner et al., 2024).

3. Vermicomposting: The Process of Transformation

3.1. The biological engine: synergies between earthworms and microbes

Vermicomposting is bio-oxidative mesophilic process that uses earthworms and microorganisms to transform organic waste into humus-like product rich on nutrients (Domínguez et al., 2010; Aira et al., 2007).

In contrast to the high temperature required in the conventional composting, the vermicomposting can be achieved at moderate temperature of 15 to 25 °C which are the favourable temperatures of earthworm activity (Edwards & Arancon, 2022; Ramzan et al., 2021). Vermicomposting is an organic degradation that is a mixture between earthworms and microorganisms, where earthworms play a role as decomposer instead of microorganisms such as bacteria and fungi to a more stable and mineralized organic (Domínguez & Edwards, 2011; Sulaiman & Mohamed, 2020). It has a more beneficial effect on the microbiological life than the classic composting process, which enhances the stability product and richness of nutritional elements or biologically complementary compounds (Aira et al., 2007; Mal & Chattopadhyay, 2024).

The nutrients are produced by all vermicomposting earthworms, but especially epigeic (surface-dwelling) species such as *Eisenia fetida*, where the worms physically creating the enormous surface area on which microbes can carry out metabolic activities before food is ingested and digested, a phenomenon, well known as the tread-hill effect (borrows or channels) (Aira et al., 2006). The substance passes through the intestine of the earthworm in which during transit it is mixed and ground down with a large and diverse digestive micro-flora (bacteria and fungi) designed for destruction (Edwards & Arancon, 2022). Such an activity is important to change the microbial community of the waste. It assists the body to destroy the pathogenic microorganisms and nourish on the beneficial microorganisms like actinobacteria and firmicutes (Velásquez-Chávez et al. 2025; Zhang et al., 2020).

Micro-flora of the earthworm gut and in their associated composting media continue to decompose and mineralize the ingested biological matter by the earthworm, bringing about a stable mineral rich nutrient vermicompost (Velásquez-Chávez et al., 2025; Masin et al., 2020).

3.2. Physico-chemical properties relevant to composting

The efficiency of the vermicomposting is related to physico-chemical properties of the substrate for creating a proper habitat for earthworms and associated microorganisms. The process is driven by moisture which should range from 50% to 65% for microbial metabolism, earthworm respiration and nutrient movement (Karimi et al., 2024; Qin et al., 2021). The C/N ratio is important for process performance and the optimum range for the good results is between 25:1 to 30:1, however more recent works demonstrated that a sewage sludge mixture of 18:1 gave high quality gas and tar products (Dume et al., 2023). This balance guaranties the availability of the amount necessary of carbon for energy in comparison with nitrogen compounds available for protein synthesis; High carbon ratio produces slower reduction, and vice versa, excess of nitrogen may induce losses in ammonia and decrease final humus (Karimi et al., 2024; Ravindran & Mnkeni, 2016). In conclusion, an appropriate balance of moisture and C/N in optimal ranges can ensure strong earthworm activity, efficient microbial decomposition and high quality vermicompost.

Furthermore, the biophysical and chemical conditions of the habitat are two primary features that microorganisms associated with earthworms affect. Temperature and pH should be studied with the limit of their suitability in vermicompost. Though earthworms are able to survive at a low pH, which is 4, this is considered to be the limit on their survival in the long period. When the pH is lower than 5.6 over prolonged periods they are not observed to breed. On the other extreme, they will non-functional in a high alkaline environment, of approximately pH 8 and above (Edwards et al., 2020; Qin et al., 2021).

The size of the primary materials also has an important aspect that is smaller particles size gives a larger surface area which can be decomposed by earthworms and increases microbial decomposition is (Ramzan et al., 2021; Peng et al., 2024).

Finally, in the context of pH and particle size, salinity treatments could emerge as strong constraining conditions. High salt concentrations (mostly from food waste produced in restaurants and homes) influence the activity of earthworms; their development is limited manufacturing results in a decrease in vermicompost quality and degradation (Thirunavukkarasu et al., 2023; Xia et al., 2025). It has been stated that more than 0.2% can significantly slow down earthworm growth, therefore pretreatment or dilution of highly saline raw materials must be done before. Consequently, to guarantee to create high quality vermicompost and that the process is running consistently and effectively.

4. Characteristics of Nutrient-Rich Vermicompost

4.1. Physicochemical properties

High quality, mature vermicompost tends to be dark in color and powdery, feels crumbly and has a pleasant earthy smell, all of which are characteristics of high degree of organic matter stabilization (Chen et al., 2018). Vermicompost is a material of high porosity and organic matter content which increases its water-holding capacity (WHC) and enhances the structure of the soil as amendment (Das et al., 2022; Dube et al., 2024; Mahala et al., 2019). This corresponds to the physiological lapse of active microorganisms during which CO_2 and organic acids are picked up, thereby re-buffering the substrate at a pH closer to neutrality for the final product (Zhao et al., 2023; Usta & Guven 2024).

Mature vermicompost will typically be around pH 7.0-7.6, regardless of the initial alkalinity or acidity of the starting raw materials (Das et al., 2022; Chen et al., 2018). This set of physico-chemical characteristics makes vermicompost an efficient biofertilizer and a soil-conditioning agent that contributes to the nutrient supply and long-term health of the soils. Vermicompost maturity. As in sewage sludge compost, the low and constant value of C/N ratio (in general below 20:1 and preferably lower than 15:1) indicates organic carbon mineralization with relative increase in N content into final product (Tang et al., 2023; Rama Lakshmi et al., 2014; Angst et al., 2017). EC is also a significant maturity indicator which expresses the concentration of soluble salt.

Electrical Conductivity (EC) should increase with decay when mineral salts are released, aged vermicompost for agricultural purposes would have an EC of less than 3 dS/m to prevent phytotoxicity of the crops (Katiyar et al., 2023; Chen et al., 2018). All these aspects combined create stability, safety, and agronomic value for the vermicompost.

4.2. Chemical composition (nutrient composition of vermicompost)

In addition to being a soil conditioner, vermicompost is rich in available plant nutrients and biologically active compounds. the macronutrients (N), (P), (K) are available in the vermicompost more than their raw material. This increased supply is due to microbial mineralization realized during the decomposition process where organic nitrogen is transformed in lower forms such as ammonium and nitrate, organically-sequestered phosphorus is solubilized for a plant-available form, and potassium sequestered within organic compounds becomes mobile (Domínguez & Edwards, 2020; Oyege & Bhaskar, 2023).

In addition to the NPK stat alone, vermicompost also includes secondary nutrients (Ca, Mg, S) and trace micronutrients (Fe, Zn, Cu, Mn) which can further enhance soil fertility and plant nutrition (Chen et al., 2018).

The content of humic substances is also noted to be high in vermicompost, which is primarily composed by the humic and fulvic acids which are the products of the humification and mineralization of organic residues. Due to these aromatics complex carbon molecule helps to develop outstanding soil structure and water retention power, soil microbial action is presumably extremely significant. Cation Exchange Capacity (CEC) is the capacity of soil or growing medium to retain the nutrients and to make them available for plant roots through processes such as chelation (Hanc et al., 2019; Filipović et al., 2023).

Moreover, vermicompost is the source of PGRs (plant growth regulators) which perform at very low concentration and stimulate the root elongation, shoot length or vegetative crop yield. The concentration and proportion of these phytohormones in vermicompost has been shown to vary to the raw material source and vermicomposting conditions (Yatoo et al., 2021; Rehman et al., 2023; Pereira et al., 2023) and as such it's not just an alternative to fertilizers but it's also a bio-stimulant, with the double aim of directly encouraging sustainability in farming and keeping the soils healthy.

4.3. Biological properties

Vermicompost is a biofertilizer which contains useful microorganisms. which keep soil and plants healthy. recently studies enounce that vermicompost can add helpful bacteria to the soil. These bacteria can fix nitrogen (like *Azotobacter chroococcum*), dissolve phosphate (such as *Bacillus megaterium* and *Pseudomonas fluorescens*) and make potassium more available.

Such microorganisms enhance nutrient cycling and plant accessibility (Lu et al., 2024; Andrade-Sifuentes et al., 2024). Vermicompost enhances *Arbuscular Mycorrhizal* fungi, that form a symbiotic relationship with plants roots and enhances phosphorus uptake and stress tolerance of the plant. the beneficial microorganisms in the vermicompost significantly enhance soil microbial mass, enzyme activity and nutrient mineralization as well as improve soil fertility and plant growth (Hanc et al., 2019; Yatoo et al., 2021). it observed that *Eisenia fetida*'s action together with rock phosphate and phosphate-solubilizing microorganisms increases enormously the number of Phosphorus assimilable for vermicompost. application of vermicomposting plant wastes with microbial inoculation has been proved that it could increase the level of humic acid and bioavailability of N and P.

Another important biological feature of vermicomposting, is its potential to eliminate human and plant pathogens. Large reductions in pathogenic species such as *Escherichia coli* and *Enterococcus faecalis* occur due to passage through the earthworm gut, microbial antagonism and production of antibiotic metabolites (Karimi et al., 2024; Katiyar et al., 2023). This suppression of the pathogen decreases biohazard of vermicompost for land utilization. In general, the biological complexity of vermicompost surpasses nutrient supply and also acts as a biofertilizer, bio-stimulant and a biological control agent that promotes soil health and sustainability to agricultural production system.

4.4. New approaches to analytical thought

The chemical and structural transformations, which are taking place in the process of vermicomposting, can be described in a comprehensive manner using the modern analytical techniques, which also provide evidence for the stability of the organic waste and formation of the humified substance.

Fourier transform infrared spectroscopy (FTIR)

The techniques of analysis used nowadays make it possible to describe in full detail the chemical and structural changes of vermicomposting processes, as well as the vermicompost products, verify the stability of organic waste, their ability to form dormant compounds. In addition, the FTIR is also widely applied to observe the biological dormancy development during the vermicomposting.

In the mature vermicompost, the peak of aliphatic compounds decreases linearly, while those of the aromatic C=C bonds (1600 cm^{-1}) and carboxylic compounds C=O (1700-1740 cm^{-1}) increase relatively (Rama Lakshmi et al., 2014; Díaz et al., 2021; Filipović et al., 2023). This is explained by safe degradation of carbohydrates and lipids as well as temporary storage of the material in a biologically dormant state in this phase. This change also indicates greater stabilization of the organic matter, as well as the increased ability of the vermicompost to react with minerals and nutrients in the soil.

Scanning electron microscopy (SEM)

SEM is capable of visualizing the micro-structure of vermicompost or raw materials, the original waste is usually fibrous, thick and irregular and the mature vermicompost is in the form of broken, porous and granular structure (Huang et al., 2024; Lim & Wu, 2015). This porous network would be a safe home for beneficial microorganisms, and have the added benefit of increasing water-holding capacity and aeration in the soil. This was also explained by the improvement in the physical structure of soil aggregates and their increased stability after the introduction of vermicompost into arable soils.

Specific surface area (BET analysis)

Reduction of surface area (SSA) of vermicompost is obtained by Brunauer-Emmett-Teller (BET) method. It studies the quantity of nutrients it can hold as well as the quantity of water. According to recent research, SSA is typically 1.0 to 1.6 m^2 g^{-1}, depending on feedstock and its processing (Lim & Wu, 2015). The soil has higher content of nutrients like potassium, phosphate, and ammonium, higher the SSA (soil reaction). These nutrients then are released slowly, which makes the soil more fertile, but also, the microbes are better developed so vermicompost becomes a more active and useful soil supplement, not just a simple fertilizer.

X-ray diffraction (XRD)

The change in mineral content and organic component of compost over time is revealed by X-ray diffraction. During the degradation of organic matter, the amount of crystalline cellulose is decreased by worms. At the same time, the mineral signals of calcite, quartz and clay grow up (Xia et al., 2025; Filipović et al., 2023). The major raw materials contain more crystalline cellulose and disordered minerals. The fine mineral content and hydrolysis of resistant organic matter improved the soil for plants.

Thermogravimetric analysis (TGA)

TGA present information about thermal stability and decomposition pattern of vermicompost. The three major phases of weight loss were usually observed in the vermicompost (Bhat et al., 2022; Pizzanelli et al., 2023):

1- Evaporation of Moisture between 50-150°C,

2 - Pyrolysis (decomposition of organic matter) at 200-400°C;

3- Progressive degradation of stable humic fractions above 400°C (Xia et al., 2025; Díaz et al., 2021);

The greater percentage of stable weight loss of mature vermicompost indicates that it is more stable and a greater degree of humification than the raw materials.

5. Vermicompost for Sustainable Agriculture

Vermicompost is a simple organic soil amendment that promotes better growth to plants and improves the condition of the soil by adding nutrients and improving soil structure. It is used to minimize the use of chemical fertilizers because it converts old complex organic residues into a stable product with a nutrient content that facilitates plant growth.

5.1. Improvement of soil physical properties

Vermicompost helps to improve soil health and plant growth by improving aggregation, porosity, and water-holding capacity. It contains humic substances which help in the formation of stable soil aggregates and thus allow roots to grow and make it more workable (Giri & Pokhrel, 2022; Yang et al., 2024). These aggregates form bigger pores which provide better aeration allowing enough supply of oxygen to the roots and soil organisms (Sharma et al., 2019; Ramzan et al., 2021). Moreover, the porosity of vermicompost helps in increasing water-holding capacity, minimizes runoff, and prevents soil erosion with an average increment of 25.3% of water-holding porosity when compared to other soil conditions through meta-analysis (Castellini et al., 2024; Zhang et al., 2023; Ma et al., 2022).

5.2. Improvement of the soil chemistry

Vermicompost enhances the quality of the soil and plant development due to a number of reasons. It contains high levels of macronutrients, like nitrogen, phosphorus, and potassium, which are readily available to plants because earthworms decompose organic materials and transform such nutrients into sources that can be absorbed by plants, such as nitrates and soluble phosphates (Karimi et al., 2024; Ratnasari et al., 2023). Besides the macronutrients, vermicompost contains all the essential micronutrients, such as calcium, magnesium, zinc, and iron, which are not always available in aged soils or are insufficiently provided by synthetic fertilizers (Karimi et al., 2024; Thirunavukkarasu et al., 2023).

The reason for this is because it has relative neutral pH which is maintained by the presence of high amounts of humic acids which acts as a buffer to prevent soils from becoming too acidic or alkaline, thus improving the availability of plant nutrients (Thirunavukkarasu et al., 2023; Pathma & Sakthivel, 2019). Lastly, the vermicompost is organic and with high humus content, which increases the nutrient holding capacity of the soil, preventing its leaching and making available the nutrients such as calcium, potassium, and magnesium to the roots of the plants where and when they are needed (Arancon et al., 2019; Castellini et al., 2024).

5.3. The role of vermicompost in increasing the life of soil

Vermicompost creates a microclimate in the soil environment and turns it into a mini-living environment. It is also very rich in many beneficial bacteria, fungi, and other living organisms that continue to break down the organic matter and release nutrients slowly, which make the soil fertile (Sharma et al., 2019; Yatoo et al., 2021). Such microbes appear to control soil-borne diseases, which is based on nutrient competition, the production of antibiotics, and the enhancement of plant resistance (Karimi et al., 2024; Sharma et al., 2019; Katiyar et al., 2023). Also, phytohormones (*auxins*, *gibberellins, cytokinins*) have been generated by earthworms and microbes in vermicompost, enhancing root development, seed germination, and growth (Karimi et al., 2024; Hanc et al., 2019). Vermicomposting is also a solution to fundamental agricultural problems and it helps in circular agriculture. It releases nutrients gradually, which reduces the use of chemical fertilizers, giving rise to up to 134 % more available nitrogen and 257 % more phosphorus and enables the incorporation of rock minerals to enhance phosphorus and potassium, which decreases expenditure and eliminates water pollution (Ma et al., 2022; Jha et al., 2023; Lackner & Besharati, 2025; Karimi et al., 2024).

Additionally, it transforms low-cost organic wastes including food leftovers, farm wastes, and animal wastes into useful soil amendments, decreasing waste and pollution and enhancing crop yields (Mahish et al., 2024; Lackner & Besharati, 2025). The closed-loop recycling process recycles the nutrients back into the soil, keeps the soil healthy, carbon-conserving, and offers a resource-efficient and sustainable approach to farming (Hendrix et al., 1992; Puyuelo et al., 2019).

6. Problems and Possibilities of Vermicompost Application

The introduction of vermicompost as an ecological farming initiative entails the compromising of labor and high advantages of the environment. This application could be viewed as reasonable in case of the robust knowledge of the manner in which it is possible to manage the feedstock, guarantee the quality of the product and maximize the overall beneficial in the soil health and circular economy.

6.1. Constraints and challenges

A major problem of feedstock is regulation of the quality as well as consistency of the final product that rightfully is contingent on the composition and characteristics of the feedstock. The quality of the vermicompost is difficult to manage because the nutrient profiles, microbial activity, and stability of this worm vary with the input organic materials (Yang et al., 2024). One of the most crucial quality issues is salinity.

Some feedstocks derived from food and kitchen wastes contain high concentrations of soluble salts, which cause increase in the electrical conductivity (EC) of the final vermicompost (Ramzan et al., 2021). High EC levels can inhibit plant growth, especially for salt sensitive species, and could increase existing soil salinity problems in arid and semi-arid regions where salinization already threatens productivity (Malal et al., 2024; Omar et al., 2024).

Besides quality of product, there are several operational and agronomic constraints that limit its large-scale adoption. Collecting, transporting and storing organic materials is a very complicated task, which requires continuous management of humidity, aeration and temperature (Matišić et al., 2024).

In many agricultural systems, organic residues suitable for vermicomposting also serve as animal fodder or domestic fuel, which creates competition for biomass resources and reduces availability for vermicomposting (Matišić et al., 2024). agronomically, the benefits of organic supplements such as vermicompost tend to manifest in longer time, improving soil structure, microbial activity and nutrient cycling in the long term compared to mineral fertilizers which have, an immediate nutrient release (Tang et al., 2023; Yang et al., 2024). This delayed response time could render vermicomposting less attractive to producers seeking short-term productivity gains despite its long-term ecological and soil health benefits.

6.2. Opportunities for soil health and circularity

Despite the current operational difficulties, vermicomposting has a great potential to maintain a healthy soil and improve the principles of the circular economy in farming. If properly utilized, vermicompost can help in improving the physical, chemical and biological aspects of soil. Physically and chemically, vermicompost and other organic amendments have been confirmed to decrease the bulk density, enhance the porosity, and rise the water- retention capacity

(Gazi et al., 2024). In fact, studies were indicated that adding of vermicompost improve soil structure and aggregate stability, that help in retaining moisture and reducing compaction (Mulatu & Bayata, 2024; Gazi et al., 2024). In addition, incorporation of organic matter has the potential to increase soil organic carbon (SOC) and total nitrogen, favouring nutrient storage in the soil profile (Yang et al., 2024).

On the biological side, vermicompost enhances microbial communities, promoting microbial biomass, enzymatic activity, and nutrient cycling. Repeated applications can lead to an increase in microbial biomass by up to 100% and enzymatic activity by up to 30% (Tang et al., 2023; Oyege & Bhaskar, 2023). For instance, field trials of experimental of vermicompost demonstrated increases in total carbon, total nitrogen, mineralizable nitrogen, and greater activity of C-N-P cycling enzymes compared to plots receiving inorganic fertilization alone (Iqbal et al., 2024). Vermicompost is a proven way to enhance microbial activity, microbial diversity, and beneficial microorganisms, which results in accelerating nutrient turnover and improving soil fertility (Oyege & Bhaskar, 2023). In salt-affected or saline soils, vermicompost has been shown to ameliorate salt stress by improving soil aggregation and restoring microbial communities, a recent study showed that vermicompost increased maize salt tolerance by promoting macro-aggregation, microbial community dynamics, and more effective N mineralization in the rhizosphere (Zhang et al., 2023).

In saline-alkali soils, vermicompost (often combined with other organic amendments) has the potential to mitigate electrical conductivity, decrease pH, and enhance soil physicochemical and microbial quality. For example, a field experiment the integration of vermicompost with a soil conditioner reduced soil conductivity and improved plant biomass and microbial quality under saline-alkali soil (Yang et al., 2024; Malal et al., 2024; Ai et al., 2024). A pot experiment in soda saline-alkali soils indicated that vermicompost significantly lowered pH, exchangeable percentage of sodium, and improved enzyme activity, organic acids, and microbial taxa, which together facilitated higher plant biomass versus control (Liu et al., 2025).

The process aligns strongly with circular economy principles by transforming organic waste into a high-value biofertilizer, reducing landfill burden, and lowering dependence on synthetic fertilizers (Matišić et al., 2024).

Moreover, vermicompost helps in the mitigation of climate change by promoting the formation of carbon stabilization and soil aggregates in soil carbon sequestration on a long-term basis (Chowdhury et al., 2024; Yuan et al., 2025). Overall, vermicompost post-processing of the soil within the agricultural systems encourages regenerative management of soil and seals their nutrient and carbon cycles.

7. Future Perspectives and Recommendations

7.1. Optimizing the vermicomposting process

Future research should emphasize process optimization for vermicomposting, especially when using industrial and challenging agricultural feedstocks. A prevailing gap in the literature is the lack of systematic substrate formulation studies and the insufficient control over operational variables under real-world (non-lab) conditions (Thirunavukkarasu et al., 2023). Key parameters such as C/N ratio, moisture content, pH, aeration, and temperature strongly influence decomposition rates, earthworm health, and the biochemical quality of vermicompost (Zhou et al., 2022). Multivariate mixture-design methods (e.g. I-optimal or D-optimal designs) combined with predictive modelling (e.g. Artificial Neural Networks) have been successfully applied in substrate mixture optimization to predict quality metrics (e.g. pH, EC, C/N) (Muthuveni et al., 2024). Meanwhile, the integration of AI and machine learning holds strong promise: models can forecast maturation stages, detect suboptimal conditions, and drive real-time control/adjustments (e.g. adjusting moisture or aeration) (Temel et al., 2023). Furthermore, IoT-based sensors and automated control systems (e.g. portable bins with pH, moisture, and temperature sensors) are already being piloted to continuously monitor and manage vermicompost environments (Sahoo et al., 2023).

With the development of the field, it is possible that the multi-factor designs of experiments and AI modelling and sensors-actuator feedback systems will lead to increased throughput, improved consistency in product quality, and simplified scaling to commercial systems.

7.2 Building quality standards and certification

In order to promote the market development and ensure the safe use of vermicompost in agriculture, the need to have clear and region-specific quality standards and certification structures is increasing. This is necessary to set standards that guarantee consumer and farmer trust as well as product safety and environmental standards (Matišić et al., 2024). Although, vermicomposting is gaining popularity since scientific works show a quality of products may be gained will different significantly due to emerging variances on feed stock, feed stock management, and curing time to organized measure on testing and certification is required (Zhang et al., 2024).

Regulatory frameworks -like the one used in some of Europe to produce organic products- establish a maximum allowable level of heavy metals (e.g. cadmium, lead, chromium, nickel), pathogens, and moisture levels, which are advisable models to other regions (Jakubus & Michalak-Oparowska, 2022). On the same note, such regulations as the Fertilizer Control Order (FCO) in

India demand that vermicompost should be compliant with nutrient content standards, pH, C/N ratios, and microbial loading prior to being released to market (Chenna & Chouksey, 2024). Periodic lab tests usually would indicate that nutrient levels are acceptable but other indicators to include especially moisture levels and microbe counts can be out of the acceptable range which points to the necessity of a better standardization of production and curing (Chenna & Chouksey, 2024; Zhou et al., 2022).

Having national and regional certification programs would make the products have the same quality and the raw materials traceable and the rate of application is safe. These programs also might have such requirements as that feedstock, especially manure and food waste, be of non-industrial origin, which will minimize the risks of contamination.

A combined certification program, which is based on the existing Organic Materials Review Institute (OMRI) and European Union (EU) compost certifications, would further enhance cross-border visibility and trading with and enhance the overall adoption of high-quality vermicompost in the sustainable agricultural systems (OMRI, 2023; European Commission, 2022).

7.3 Field trials and long-term studies

While controlled and laboratory experiments provide mechanistic insights, long-term field trials across diverse soils and climatic zones are indispensable for evaluating the sustained effects of vermicompost on soil health, nutrient dynamics, crop growth, and resilience under variable conditions (Oyege & Bhaskar, 2023). For instance, a recent 7-year field study in a salinization-affected region demonstrated that vermicompost application progressively reduced soil salinity (EC) and increased soil nutrient content, thereby improving the long-term fertility of degraded land (Hossain, et al., 2025).

The vermicompost was used by applying field studies and vermi-filtration over two successive season and revealed higher total carbon, total nitrogen, potential mineralizable nitrogen and the activities of the enzymes in C-N-P cycling than the controls using inorganic fertilizers (Malal & Suarez et al., 2024).

In saline-alkali soils, combining vermicompost with soil conditioners in field experiments lowered soil EC, improved pH, increased available phosphorus, organic matter, and microbial diversity, and boosted biomass yields (Ai et al., 2024). Beyond nutrient effects, vermicompost has been shown to enhance soil structure, porosity, aeration, and moisture retention, and deliver biologically active compounds-such as enzymes, humic substances, and phytohormones-that promote plant growth and stress tolerance (Mulatu & Bayata, 2024).

7.4. Policy support and market development

Government support and creation of efficient markets are the key to success in vermicomposting among farmers. This assumption on the presence of barriers among the farmers that would hinder their adoption is supported by the empirical literature sources, and these barriers may be grouped into financial (high equipment start-up cost) and informational (lack of practical knowledge, lack of vision) factors that hinder the adoption process (Rastegari et al., 2023; Zheng et al., 2023).

The involved government and other agencies in the field of agriculture can also play a significant role by focusing on these obstacles by designing conducive policies that will directly fight the obstacles. These measures may include financial incentives that is, subsidies or low-interest loans to finance the expenses in question, practical and practical training organization to help resolve all barriers, as well as a possibility to demonstrate the profitability of the whole process: vermicomposting in the long term (Rastegari et al., 2023; Zheng et al., 2023).

7.5. Inclusion into waste management systems

Waste management systems will also be introduced into the existing framework. One of the alternatives that can be considered to be used in managing the organic fraction of municipal solid waste (MSW) especially in developing countries where the wastes are mainly organic in nature, is vermicomposting. When a systematic integration into the formal waste management systems is done, the environmental liability of the city waste will be transformed into a cyclic resource channel (Das et al., 2022).

Another approach is vermicomposting alternative method which is economically effective and less harmful to the environment since it reduces land degradation, emission of greenhouse gases, and pollution through landfilling (which is a costly technology such as incineration and pyrolysis) (Thirunavukkarasu et al., 2023).

It is applicable to community based and decentralized waste management initiatives so that local populations can generate greater quantities of nutrient-enhancing organic farm manure by lowering transportation expenses, and increasing the concentration of vermicompost producers by natural/sensory bio-contamination (Devi & Khwairakpam, 2023). These systems are however sensitive to correct separation of sources to avoid contamination of organic feedstock with heavy metals or any other contaminant in mixed municipal waste streams ((Das et al., 2022). Better feedback is obtained by setting up source level lockout systems, awareness and local inclusion leading to creation of healthy vermicompost.

In addition, the bridge-waste valorization system that integrates the postproduction of vermicompost with the assistance of additional technology-anaerobic digestion or generation of biochar and others can be developed in order to receive co-production and discharge both the energy and nutrients, which facilitates the philosophy of the circular economy (Ravish et al., 2025). These joint biotechnological plans not only amplify the effectiveness of resources, research, but are also aligned to the climate-wise urban waste treatment plans in accordance with the sustainable development goals (SDGs).

8. Conclusion

In this world restricted to the percentage of organic waste growth and the imperative of sustainable agriculture, vermicomposting should be another strong component of biotechnology bridging the gap to offer a solution to this problem by synthesizing the two problems. It is a biological intensification process in which an interaction between the earthworms and the micro-organism take place, where waste products of heterogeneous and problematic character are further transformed into a stabilized nutrient-rich soil amendment full of microscopic organisms. Vermicompost so achieved is not only a fertilizer but also a soil conditioner of fine porosity containing higher water-carrying capacity, good humus levels with hormones and microbes that regulate plant growth. Its application implies the rebuilding the structure and biological activity of the soil, the resilience of the soil, its capacity to hold water, as well as ensuring a continuous flow of nutrients and elements of growth.

It positively influences the development and the resilience of the plant growth directly and reduces the agricultural sector reliance on the application of synthetic inputs and the resulting environmental impact. Despite the fact that still there are some problems within this sphere regarding raw material management, quality control and market structuring they can be solved by conducting further research, properly established quality standards and positive policy relations. Finally, the vermicomposting is part of a so-called circular bioeconomy that is a circular strategy of addressing an ecologically regulating problem of waste disposal currently disputing a linear problem. Its incorporation into agricultural and municipal waste management systems are concrete and critical steps to achieve the creation of more resilient food systems and the return to soil fertility and the need to establish a sustainable relationship between human activity and the environment.

References

Adhikari, B. K., Trémier, A., Barrington, S., & Martinez, J. (2013). Biodegradability of municipal organic waste: A respirometric test. Waste and Biomass Valorization, 4(2), 331–340.

Ai, F., He, L., Li, Q., Li, B., Zhang, K., Yang, H., & Zhang, C. (2023). Vermicompost combined with soil conditioner improves the ecosystem multifunctionality in saline-alkali land. Water, 15(17), 3075.

Aira, M. & Monroy, Fernando. (2006). Changes in microbial biomass and microbial activity of pig slurry after the transit through the gut of the earthworm Eudrilus eugeniae (Kinberg, 1867). Biology and Fertility of Soils. 42. 371-376. 10.1007/s00374-005-0047-4.

Aira M, Monroy F, Domínguez J. Earthworms strongly modify microbial biomass and activity triggering enzymatic activities during vermicomposting independently of the application rates of pig slurry. Sci Total Environ. 2007 Oct 15;385(1-3):252-61. doi: 10.1016/j.scitotenv.2007.06.031.

Andrade-Sifuentes, A., Peña-Uribe, G. d. J., Sáenz-Mata, J., Quezada-Rivera, J. J., Palacio-Rodríguez, R., & Muro-Pérez, G. (2024). The integration of phosphorus-solubilizing rhizobacteria, *Eisenia fetida*, and phosphorus rock improves the availability of assimilable phosphorus in the vermicompost. Sustainability, 16(17), 7576.

Angst, Š., Mueller, C. W., Cajthaml, T., Angst, G., Lhotáková, Z., Bartuška, M., Špaldoňová, A., & Frouz, J. (2017). Stabilization of soil organic matter by earthworms is connected with physical protection rather than with chemical changes of organic matter. Geoderma, 289, 29–35.

Ansar, A., Du, J., Javed, Q., Adnan, M., & Javaid, I. (2025). Biodegradable waste in compost production: A review of its economic potential. Nitrogen, 6(2), 24.

Arancon, N. Q., Van Cleave, J., Hamasaki, R., Nagata, K., & Felts, J. (2019). The influence of vermicompost water extracts on growth of plants propagated by cuttings. International Journal of Fruit Science.

Barros, M. V., Salvador, R., de Francisco, A. C., & Piekarski, C. M. (2020). Mapping of research lines on circular economy practices in agriculture: From waste to energy. Renewable and Sustainable Energy Reviews, 131, 109958.

Castellini, M., Bondì, C., Giglio, L., & Iovino, M. (2024). Impact of vermicompost addition on water availability of differently textured soils. Heliyon, 10(15), e35699. https://doi.org/10.1016/j.heliyon.2024.e35699

Che Sulaiman, I. S., & Mohamad, A. (2020). The use of vermiwash and vermicompost extract in plant disease and pest control. In C. Egbuna & B. Sawicka (Eds.), Natural Remedies for Pest, Disease and Weed Control (pp. 187–201). Academic Press.

Chen, Y., Chang, S. K. C., Chen, J., Zhang, Q., & Yu, H. (2018). Characterization of microbial community succession during vermicomposting of medicinal herbal residues. Bioresource Technology, 249, 542–549.

Chenna, H. N. P., & Chouksey, S. K. (2024). Quality evaluation and characterization of organic compost suitable for agricultural utilization. International Journal of Recycling of Organic Waste in Agriculture, 13(5).

Chowdhury, R., Paul, S., Goswami, L., Bhattacharya, S.S. (2024). The Role of Waste Vermicompost on Soil Organic C Sequestration in Arable Lands: Some Critical Arguments. In: Bordoloi, N., Bauddh, K., Baruah, K. (eds) Agricultural Greenhouse Gas Emissions: Problems and Solutions. Springer, Singapore.

Cucina, M. (2023). Integrating anaerobic digestion and composting to boost energy and material recovery from organic wastes in the circular economy framework in Europe: A review. Bioresource Technology Reports, 24, 101642.

Das, D., Abbhishek, K., Banik, P., & Swain, D. K. (2022). Effects of vermicomposting with rock-mineral enriched vermicompost (pot experiment). Environmental Technology & Innovation, 28, 102956. https://doi.org/10.1016/j.eti.2022.102956

Deng, H., Li, X., & Wang, Y. (2024). Farmers' adoption of agriculture green production technologies: perceived value or policy-driven? Environmental Science and Pollution Research, 31(10), 15481–15498.

Devi, Chaichi & Khwairakpam, Meena. (2023). Decentralized Composting and Vermicomposting for Agricultural Waste Management: Recycle at Source. 10.1007/978-981-99-4472-9_18.

Domínguez, J., & Edwards, C. A. (2011). Relationships between composting and vermicomposting: Relative values of the products. In C. A. Edwards, N. Q. Arancon, & R. Sherman (Eds.), Vermiculture technology: Earthworms, organic wastes, and environmental management (pp. 11–26). CRC Press.

Domínguez, J., Aira, M., & Gómez-Brandón, M. (2010). Vermicomposting: Earthworms enhance the work of microbes. In J. Domínguez & C. A. Edwards (Eds.), Soil microbiology and sustainable crop production (pp. 93–114). Springer.

Domínguez, J., & Edwards, C. A. (2020). Nutrient transformations during vermicomposting of organic wastes. In C. A. Edwards, N. Q. Arancon, & R. Sherman (Eds.), Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management (2nd ed., pp. 91–112). CRC Press.

Dube, B., Chimdessa, D., & Sori, G. (2024). Nutrient composition and characterization of vermicompost from various organic materials in Bedele District, Ethiopia. Journal of Agriculture and Allied Sciences, 13, 001. DOI: 10.4172/2347- 226X.13.3.001

Dume, B., Hanc, A., Svehla, P., Michal, P., Chane, A. D., & Nigussie, A. (2023). Composting and vermicomposting of sewage sludge at various C/N ratios: Technological feasibility and end-product quality. Ecotoxicology and Environmental Safety, 263, 115255.

Díaz, M. J., Ruiz-Montoya, M., Palma, A., & de-Paz, M.-V. (2021). Thermogravimetry Applicability in Compost and Composting Research: A Review. Applied Sciences, 11(4), 1692. https://doi.org/10.3390/app11041692

Edwards, C.A., Arancon, N.Q. (2022). The Use of Earthworms in Organic Waste Management and Vermiculture. In: Biology and Ecology of Earthworms. Springer, New York, NY. https://doi.org/10.1007/978-0-387-74943-3_14

Edwards, C. A., & Arancon, N. Q. (2022). Interactions between earthworms, microorganisms, and other invertebrates. In C. A. Edwards, N. Q. Arancon, & R. L. Sherman (Eds.), Vermiculture technology: Earthworms, organic wastes, and environmental management (pp. 213–240). Springer. https://doi.org/10.1007/978-0-387-74943-3_9

Edwards, C. A., & Arancon, N. Q. (2022). Vermicomposting for sustainable waste management and soil fertility enhancement: Advances and prospects. Applied Soil Ecology, 176, 104478. https://doi.org/10.1016/j.apsoil.2022.104478

Edwards, C. A., Arancon, N. Q., & Sherman, R. (2011). Vermiculture technology: Earthworms, organic wastes, and environmental management. CRC Press.

European Commission. (2022). EU rules on producing and labelling organic products (from 2022) [Regulation (EU) 2018/848 summary and consolidated framework]. European Union.

Filipović, Adrijana & Mandić, Ana & Hadziabulic, Alisa & Johanis, Hana & Stipanovic, Antonio & Brekalo, Helena. (2023). Characterization and Evaluation of Vermicomposting Materials. Ekológia (Bratislava). 42. 101-107. 10.2478/eko-2023-0012.

Gazi, A., Maity, A., Khatua, N., Sengupta, S., Kundu, S., & Sarkar, T. (2024). Effect of vermicompost on soil quality and crop productivity. International Journal of Agriculture Extension and Social Development, 7(Special Issue 4), 13-23.

Ginni, G., Kavitha, S., Yukesh Kannah, R., Bhatia, S. K., Kumar, S. A., Rajkumar, M., Kumar, A. G., Pugazhendhi, A., Lan Chi, N. T., & Rajesh Banu, J. (2021). Valorization of agricultural residues: Different biorefinery routes. Journal of Environmental Chemical Engineering, 9(4), 105435.

Giri, D., & Pokhrel, P. (2022). Organic farming for sustainable agriculture: A review. Russian Journal of Agricultural and Socio-Economic Sciences, 10(130), 23–33.

Hanc, A., Enev, V., Hrebeckova, T., Klucakova, M., & Pekar, M. (2019). Characterization of humic acids in a continuous-feeding vermicomposting system with horse manure. Waste Management, 99, 1–11.

Hefner, M., Amery, F., Denaeghel, H., Loades, K., & Kristensen, H. L. (2024). Composts of diverse green wastes improve the soil biological quality, but do not alleviate drought impact on lettuce (Lactuca sativa L.) growth. Soil Use and Management, 40(2), e13016.

Hendrix, P. F., Coleman, D. C., & Crossley, D. A. Jr. (1992). Using knowledge of soil nutrient cycling processes to design sustainable agriculture. Journal of Sustainable Agriculture, 2(3), 63–82.

Hossain, M. A., Lokman, M., & Khan, P. A. (2025). Transforming agriculture with vermicompost: Seven years of empirical evidence from drought-prone and salinization-affected regions of Bangladesh. Journal of Cleaner Production, 487, 145595.

Huang, W. Z. (2024). Resource utilization of agricultural waste: From biomass energy to organic fertilizer. Journal of Energy Bioscience, 15(4), 221–232.

Huang, L., Meng, Y., Pan, B., Pan, B., Wei, J., Ding, J., Deng, Y., Su, X., Yuan, Z., & Zhang, M. (2024). Multidimensional effects of green waste vermicomposting on cadmium contaminated soil ecosystems: From physicochemical properties to microbial communities. Journal of Hazardous Materials, 480, 136429.

Iqbal, A., Khan, R., Hussain, Q., Imran, M., Mo, Z., Hua, T., Adnan, M., Abid, I., Rizwana, H., Soliman Elshikh, M., El Sabagh, A., Lal, R., & Tang, X. (2024). Vermicompost application enhances soil health and plant physiological and antioxidant defense to conferring heavy metals tolerance in fragrant rice. Frontiers in Sustainable Food Systems, 8, 1418554.

Jakubus, M., & Michalak-Oparowska, W. (2022). Valorization of quality of vermicomposts and composts using various parameters. Agriculture, 12(2), 293.

Jha, Shankar & Kumar, Rajesh & Kumar, Mukesh & Kumar, Ranjit & Padbhushan, Rajeev. (2023). Enriching vermicompost with rock phosphate applied with inorganic fertilizers improves soil biological quality in calcareous soil. 12. 4870-4874.

Karimi, S., Raza, T., & Mechri, M. (2024). Composting and vermitechnology in organic waste management. In V. Kumar et al. (Eds.), Environmental Engineering and Waste Management (pp. 449–470). Springer Nature Switzerland.

Katiyar, R. B., Sundaramurthy, S., Sharma, A. K., Arisutha, S., Khan, M. A., & Sillanpää, M. (2023). Optimization of Engineering and Process Parameters for Vermicomposting. Sustainability, 15(10), 8090. https://doi.org/10.3390/su15108090

Kumar, A., Jha, A. K., & Kumar, A. (2022). Physico-chemical characterization of vermicompost and enriched vermicompost. Pharma Innovation, 11(4), 1462–1465.

Lackner, M., & Besharati, M. (2025). Agricultural waste: Challenges and solutions—A review. Waste, 3(2), 18.

Li, C., Li, H., Yao, T., Su, M., Li, J., Liu, Z., Xin, Y., Wang, L., Chen, J., & Gun, S. (2020). Effects of microbial inoculation on enzyme activity, available nitrogen content, and bacterial succession during pig manure composting. Bioresource Technology, 306, 123167.

Li, Y., Yang, X., Gao, W., Qiu, J., & Li, Y. (2020). Comparative study of vermicomposting of garden waste and cow dung using *Eisenia fetida*. Environmental Science and Pollution Research, 27(15), 18420–18429.

Lim, S. L., & Wu, T. Y. (2015). Determination of maturity in the vermicompost produced from palm oil mill effluent using spectroscopy, structural characterization and thermogravimetric analysis. Ecological Engineering, 84, 515–519. https://doi.org/10.1016/j.ecoleng.2015.09.050

Liu, Z., Huang, Y., Xu, L., Zhang, W., & Chen, Y. (2025). Remediation of soda saline-alkali soil using vermicompost: The remediation mechanisms and enhanced improvement by maize straw. Journal of Soils and Sediments, 25(1), 41–58.

Lu, M., Hao, Y., Lin, B., Huang, Z., Zhang, Y., Chen, L., Li, K., & Li, J. (2024). The bioaugmentation effect of microbial inoculants on humic acid formation during co-composting of bagasse and cow manure. Environmental Research, 252(Part 1), 118604.

Ma, H., Zhao, S., Hou, J., Feyissa, T., Duan, Z., Pan, Z., Zhang, K., & Zhang, W. (2022). Vermicompost improves physicochemical properties of growing medium and promotes plant growth: A meta-analysis. Journal of Soil Science and Plant Nutrition, 22, 3745–3755. https://doi.org/10.1007/s42729-022-00924-7

Mahala, V., Meshram, N., Dalvi, V., Shigwan, A., Tripathi, V. D., Rane, A., & More, V. (2019). Physicochemical and biological characterization of vermicompost prepared from different residues of agroforestry component. Applied Biological Research, 21, 255. https://doi.org/10.5958/0974-4517.2019.00034.X

Mahish, P. K., Verma, D. K., Ghritlahare, A., Arora, C., & Otero, P. (2024). Microbial bioconversion of food waste to biofertilizers. Sustainable Food Technology, 2(2), 689–708.

Mal, S., & Chattopadhyay, G. N. (2024). Optimizing Microbial Activity during Vermicomposting with Different Earthworm Densities. Asian Journal of Soil Science and Plant Nutrition, 10(4), 54-61.

Malal, H., Ait Hamza, M., & Lakhtar, H. (2024). The ability of vermicompost to mitigate the impacts of salinity stress on soil microbial community: A review. Avicenna Journal of Environmental Health Engineering, 11(1), 55–62.

Malal, H., Suarez Romero, V., Horwath, W. R., Dore, S., Beckett, P., Ait Hamza, M., Lakhtar, H., & Lazcano, C. (2024). Vermifiltration and sustainable agriculture: unveiling the soil health-boosting potential of liquid waste vermicompost. Frontiers in Sustainable Food Systems, 8, Article 1383715.

Mallikarjuna Rao, M., Botsa, S. M., Prabhakara Rao, T., Goddu, S. R., & Vijayasanthi, C. (2024). A comprehensive review on agricultural waste production and onsite management with circular economy opportunities. Discover Sustainability, 5, 288.

Manheim, D. C., Yeşiller, N., & Hanson, J. L. (2021). Gas emissions from municipal solid waste landfills: A comprehensive review and analysis of global data. Journal of the Indian Institute of Science, 101, 423–452. https://doi.org/10.1007/s41745-021-00234-4

Martín-Sanz-Garrido, C., Revuelta-Aramburu, M., Santos-Montes, A. M., & Morales-Polo, C. (2025). A review on anaerobic digestate as a biofertilizer: Characteristics, production, and environmental impacts from a life cycle assessment perspective. Applied Sciences, 15(15), 8635.

Masin, C. E., Fernandez, M. E., Lescano, M. R., & Zalazar, C. S. (2020). Bioconversion of agro-industrial wastes: Combined compost and vermicompost processes using *Eisenia fetida* for stabilization of poultry litter.

Matišić, M., Dugan, I., & Bogunović, I. (2024). Challenges in sustainable agriculture—The role of organic amendments. Agriculture, 14(4), 643.

Maçin, K. E., Arıkan, O. A., Altınbaş, M., & Damgaard, A. (2024). Decarbonizing university campuses: A business model for food waste management at Istanbul Technical University (İTÜ) Ayazağa Campus, Turkey. Environmental Progress & Sustainable Energy, 43(2), e14316.

Mudiyanselage, N. A., & Herat, S. (2021). Organic waste management: A review of practices from selected Asian countries. International Journal of Environment and Waste Management.

Mulatu, G., & Bayata, A. (2024). Vermicompost as organic amendment: Effects on some soil physical, biological properties and crops performance on acidic soil: A review. Frontiers in Environmental Microbiology, 10(4), 66-73.

Muthuveni, M., Deebika, S., Boopathy, T., Nithya, R., & Thirunavukkarasu, A. (2024). I-optimal mixture design and artificial neural network for the sustainable production of vermicompost. Biomass Conversion and Biorefinery, 14, 10147–10160.

Nanda, S., & Berruti, F. (2021). Municipal solid waste management and landfilling technologies: A review. Environmental Chemistry Letters, 19(2), 1433–1456.

Nie, E., Wang, W., Duan, H., Zhang, H., He, P., & Lü, F. (2023). Emission of odor pollutants and variation in microbial community during the initial decomposition stage of municipal biowaste. Science of the Total Environment, 861, 160612.

Omar, M. M., Massawe, B. H. J., Shitindi, M. J., Pedersen, O., Meliyo, J. L., & Fue, K. G. (2024). Assessment of salt-affected soil in selected rice irrigation schemes in Tanzania: Understanding salt types for optimizing management approaches. Frontiers in Soil Science, 4, Article 1372838.

OMRI (Organic Materials Review Institute). (2023). Compost and vermicompost standards under the National Organic Program. Organic Materials Review Institute.

Oyege, I., & Bhaskar, M. S. B. (2023). Effects of vermicompost on soil and plant health and promoting sustainable agriculture. Soil Systems, 7(4), Article 101.

Panagiotis Regkouzas, P., Manolikaki, I., & Diamadopoulos, E. (2025). Assessing biochar and compost from the organic fraction of municipal solid waste on nutrient availability and plant growth of lettuce in a pot experiment. Circular Economy and Sustainability, 5, 525–539.

Pandey, D. K., & Mishra, R. (2024). Towards sustainable agriculture: Harnessing AI for global food security. Artificial Intelligence in Agriculture, 12, 72–84.

Paswan, M. K., & Tiwari, A. C. (2021). Are the residents of Varanasi city practicing enough to manage their kitchen waste? Acta Scientific Nutritional Health, 5(4), 19–29.

Pathma, J., Sakthivel, N. Microbial diversity of vermicompost bacteria that exhibit useful agricultural traits and waste management potential. SpringerPlus 1, 26 (2012). https://doi.org/10.1186/2193-1801-1-26

Paul, T., Field, J. L., Jahn, C. E., DeFoort, M. W., & Leach, J. E. (2013). Biomass for thermochemical conversion: Targets and challenges. Frontiers in Plant Science, 4, 218.

Peng, W., Wang, Y., Cui, G. et al. Compost quality, earthworm activities and microbial communities in biochar-augmented vermicomposting of dewatered activated sludge: the role of biochar particle size. Biochar 6, 73 (2024). https://doi.org/10.1007/s42773-024-00365-8

Pereira, M. M. A., Moraes, L. C., Mogollón, M. C. T., Borja, C. J. F., Duarte, M., Buttrós, V. H. T., Luz, J. M. Q., Pasqual, M., & Dória, J. (2023). Cultivating biodiversity to harvest sustainability: Vermicomposting and inoculation of microorganisms for soil preservation and resilience. Agronomy, 13(1), 103.

Puyuelo, B., Arizmendiarrieta, J. S., Irigoyen, I., & Plana, R. (2019). Quality assessment of composts officially registered as organic fertilisers in Spain. Spanish Journal of Agricultural Research, 17(1), e1101.

Qin, J., Fu, X., Chen, X., et al. (2021). Changes in physicochemical properties and microfauna community during vermicomposting of municipal sludge under different moisture conditions. Environmental Science and Pollution Research, 28, 31539–31548. https://doi.org/10.1007/s11356-021-12846-5

Ragab, O., Al Shibli, B., Al Maghawry, S., Al Balushi, B., El Amir, M., Al Hindasi, H., & Al Shibli, H. (2025). Solid waste management status made in Middle East Arab countries: A review. Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 178(3), 206–220.

Rama Lakshmi, C. S., Rao, P. C., Padmaja, G., Sreelatha, T., Madhavi, M., & Sireesha, A. (2014). Evaluation of different vermicomposts and conventional composts for their maturity indices. Indian Journal of Agricultural Research, 48(3), 205–210. https://doi.org/10.5958/j.0976-058X.48.3.034

Ramzan, S. et al. (2021). Responses of Soil Properties to Organic Amendments. In: Hakeem, K.R., Dar, G.H., Mehmood, M.A., Bhat, R.A. (eds) Microbiota and Biofertilizers. Springer, Cham. https://doi.org/10.1007/978-3-030-48771-3_3

Rastegari, A., Alavi, S., & Hosseini, M. (2023). Drivers and barriers in farmers' adoption of vermicomposting: A behavioral approach. International Journal of Agricultural Sustainability, 21(5), 587–603.

Ratnasari, A., Syafiuddin, A., Mehmood, M. A., & Boopathy, R. (2023). A review of the vermicomposting process of organic and inorganic waste in soils: Additives effects, bioconversion process, and recommendations. Bioresource Technology Reports, 21, 101332.

Ravindran, B., & Mnkeni, P. N. S. (2016). Bio-optimization of the carbon-to-nitrogen ratio for efficient vermicomposting of chicken manure and waste paper using *Eisenia fetida*. Environmental Science and Pollution Research, 23(18), 19068–19077.

Ravish, P., Chaudhry, S., & Sharma, A. (2025). Impact of different crop residue burning activities on seasonal variation in ambient air quality. Discover Atmosphere, 3, 22.

Rehman, S. u., De Castro, F., Aprile, A., Benedetti, M., & Fanizzi, F. P. (2023). Vermicompost: Enhancing plant growth and combating abiotic and biotic stress. Agronomy, 13(4), 1134.

Sahoo, B., Mandal, K., Panda, A., Sahu, B., Swain, S., & Mohanty, G. (2023). Automated vermicomposting using portable bin (IoT based). International Journal for Research in Applied Science & Engineering Technology (IJRASET).

Scheinberg, A., Wilson, D. C., & Rodic, L. (2010). Solid Waste Management in the World's Cities: Water and Sanitation in the World's Cities 2010. Earthscan for UN-Habitat.

Sharma, B., Vaish, B., Monika, Singh, U. K., Singh, P., & Singh, R. P. (2019). Recycling of organic wastes in agriculture: An environmental perspective. International Journal of Environmental Research, 13, 409–429.

Tang, R., Liu, Y., Ma, R., Zhang, L., Li, Y., Li, G., Wang, D., Lin, J., Li, Q., & Yuan, J. (2023). Effect of moisture content, aeration rate, and C/N on maturity and gaseous emissions during kitchen waste rapid composting. Journal of Environmental Management, 326(Part A), 116662.

Temel, F. A., Cagcag Yolcu, O., & Turan, N. G. (2023). Artificial intelligence and machine learning approaches in composting process: A review. Bioresource Technology, 370, 128539.

Terán-Samaniego, K., Robles-Parra, J. M., Vargas-Arispuro, I., Martínez-Téllez, M. Á., Garza-Lagler, M. C., Félix-Gurrlola, D., Maycotte-de la Peña, M. L., Tafolla-Arellano, J. C., García-Figueroa, J. A., & Espinoza-López, P. C. (2025). Agroecology and sustainable agriculture: Conceptual challenges and opportunities—A systematic literature review. Sustainability, 17(5), 1805.

Thakali, A., MacRae, J. D., Isenhour, C., & Blackmer, T. (2022). Composition and contamination of source-separated food waste from different sources and regulatory environments. Journal of Environmental Management, 314, 115043.

Thirunavukkarasu, A., Sivashankar, R., Nithya, R., Sathya, A. B., Priyadharshini, V., Kumar, B. P., Muthuveni, M., & Krishnamoorthy, S. (2023). Sustainable organic waste management using vermicomposting: A critical review on the prevailing research gaps and opportunities. Environmental Monitoring and Assessment, 195(5), 630. https://doi.org/10.1039/d2em00324d

Thirunavukkarasu, A., Sivashankar, R., Nithya, R., Bose, S., Priyadharshini, V., Prem Kumar, B., Muthuveni, M., & Krishnamoorthy, S. (2023). Sustainable organic waste management using vermicomposting: a critical review on the prevailing research gaps and opportunities. Environmental Science: Processes & Impacts.

Torrijos, V., Calvo Dopico, D., & Soto, M. (2021). Integration of food waste composting and vegetable gardens in a university campus. Journal of Cleaner Production, 315, 128175.

Uhlig, E., Sadzik, A., Strenger, M., Schneider, A.-M., & Schmid, M. (2025). Food wastage along the global food supply chain and the impact of food packaging. Journal of Consumer Protection and Food Safety, 20, 5–17.

Usta, A. N., & Guven, H. (2024). Vermicomposting organic waste with *Eisenia fetida* using a continuous flow-through reactor: Investigating five distinct waste mixtures. Journal of Environmental Chemical Engineering, 12(6), 114384.

Velásquez-Chávez, T. E., Sáenz-Mata, J., Quezada-Rivera, J. J., Palacio-Rodríguez, R., Muro-Pérez, G., Servín-Prieto, A. J., Hernández-López, M., Preciado-Rangel, P., Salazar-Ramírez, M. T., Ontiveros-Chacón, J. C., & Peña, C. G.-D. l. (2025). Bacterial and Physicochemical Dynamics During the Vermicomposting of Bovine Manure: A Comparative Analysis of the *Eisenia fetida* Gut and Compost Matrix. Microbiology Research, 16(8), 177. https://doi.org/10.3390/microbiolres16080177

Xia, H., Huang, W., Huang, K., Yang, R., Li, T., & Mao, H. (2025). Effects of salt content on degradation and transformation performance of kitchen waste during vermicomposting. Journal of Environmental Chemical Engineering, 13(5), 117884.

Yang, Z., Luo, Y., Chen, H. et al. Vermicompost Addition Improved Soil Aggregate Stability, Enzyme Activity, and Soil Available Nutrients. J Soil Sci Plant Nutr 24, 6760–6774 (2024). https://doi.org/10.1007/s42729-024-02002-6

Yatoo, A. M., Ali, M. N., Baba, Z. A., Alsohim, A. S., Muthukumaran, M., & Sayyed, R. Z. (2024). Effect of macrophyte biomass-based vermicompost and vermicompost tea on plant growth, productivity, and biocontrol of Fusarium wilt disease in tomato. Biocatalysis and Agricultural Biotechnology, 60, 103320.

Yuan S, Wu Y, Balcazar JL, Wang D, Zhu D, Ye M, Sun M, Hu F. (2025). Expanding the potential soil carbon sink: unraveling carbon sequestration accessory genes in vermicompost phages. Appl Environ Microbiol91: e00296-25.

Zhang, H., Li, J., Zhang, Y., & Huang, K. (2020). Quality of Vermicompost and Microbial Community Diversity Affected by the Contrasting Temperature during Vermicomposting of Dewatered Sludge. International Journal of Environmental Research and Public Health, 17(5), 1748. https://doi.org/10.3390/ijerph17051748

Zhang, Q., Guo, X., Zhang, Q., Li, Z., & Zhao, T. (2024). Fate of heavy metals and importance of influencing factors during vermicomposting. Journal of Cleaner Production.

Zhao, B., Wang, Y., Li, L., Ma, L., Deng, Y., & Xu, Z. (2023). Adjusting pH of the Secondary Composting Materials to Further Enhance the Lignocellulose Degradation and Promote the Humification Process. Sustainability, 15(11), 9032. https://doi.org/10.3390/su15119032

Zhou, Y., Xiao, R., Klammsteiner, T., Kong, X., Yan, B., Mihai, F.-C., Liu, T., Zhang, Z., & Awasthi, M. K. (2022). Recent trends and advances in composting and vermicomposting technologies: A review. Bioresource Technology, 360, 127591

Zhou, Y., Xiao, R., Klammsteiner, T., Kong, X., Yan, B., Mihai, F.-C., Liu, T., Zhang, Z., & Awasthi, M. K. (2022). Recent trends and advances in composting and vermicomposting technologies: A review. Bioresource Technology, 360,127591.https://doi.org/10.1016/j.biortech.2022.127591.

14

HARNESSING MICROBIAL POTENTIAL: BIOFERTILIZER AS SUSTAINABLE STRATEGY FOR CROP PRODUCTION AND SOIL IMPROVEMENT

Irum Yousaf[1], Mehwish Nadeem[2], Muhammad Sajjad[3], Sami ur Rehman[4], Michele Benedetti[5], Korkmaz Bellitürk[6]

1. Introduction

To cope with the growing food requirements driven by population surge, farmers are adopting diverse strategies to enhance productivity and nutritional quality of produce. The global demand for food and agriculture commodities is projected to increase by nearly 60% by the year 2030 (Vasave et al., 2024). One of the major challenges is to boost agricultural productivity while protecting the environment. Fertilizers have been extensively applied to enhance crop yields on arable land. Application of synthetic fertilizers is essential to become self-sufficient in food production, but excessive use of these fertilizers deteriorates land. They disrupt the nutrients balance, lower soil fertility and water holding capacity, and pollute water beyond permissible limits (Marzouk et al., 2025). Alternatively, biofertilizers are easy to use, non-toxic, affordable, and ecologically friendly (Thomas & Singh, 2019).

Biofertilizers (BFs) are comprised of active or dormant microorganisms including bacteria, fungi, algae, and actinomycetes. These microorganisms play critical functions in improving soil fertility by facilitating nitrogen fixation, solubilization and mobilization of plant nutrients. Furthermore, they secrete plant growth regulators that enhance root development and overall plant growth (Kumar et al., 2018). Along with providing essential minerals, biofertilizers confer protective benefits by improving plant resistance against pathogens. Previous studies have demonstrated that their application improves seedling survival rates, facilitates the detoxification of harmful compounds,

1 Department of Botany, Faculty of Basic Sciences, Government College University, Faisalabad 38000, Pakistan. ORCID: 0009-0005-6502-3662. irumyousaf23@gmail.com
2 Department of Botany, Faculty of Life Sciences, Government College University, Faisalabad 38000, Pakistan. ORCID: 0009-0006-9401-093X. mehwishnadeem1234@gmail.com
3 Department of Agronomy, Faculty of Agriculture, University of Agriculture Faisalabad, Pakistan. ORCID: 0000-0002-4064-4076. muhammadsajjaduaf@gmail.com
4 Department of Biological and Environmental Sciences and Technologies (DiSTeBA), University of Salento, Via Monteroni, I-73100 Lecce, Italy. ORCID: 0000-0002-3973-7961. sami.urrehman@unisalento.it
5 Department of Biological and Environmental Sciences and Technologies (DiSTeBA), University of Salento, Via Monteroni, I-73100 Lecce, Italy. ORCID: 0000-0001-9936-9649. michele.benedetti@unisalento.it
6 Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Tekirdag Namık Kemal University, Tekirdag, Türkiye. ORCİD: 0000-0003-4944-3497. kbelliturk@nku.edu.tr

accelerates the onset of flowering, and prolongs root system longevity. A further advantage lies in their sustained efficacy as once parental inoculants are established, they are capable of self-propagation, ensuring constant growth and activity for three to four years with regular application, thereby reducing the necessity for repeated external supplementation of biofertilizers (Bumandalai & Tserennadmid, 2019).

Various microorganisms comprising fungi, nitrogen-fixing bacteria, phosphate-solubilizing bacteria and cyanobacteria significantly contribute to ameliorating soil fertility and sustaining plant nutrition (Umesha et al., 2018). Similarly, microorganisms with the capacity to synthesize phytohormones are widely utilized in BFs development. Besides supplying vitamins, indole-3-acetic acid (IAA), and amino acids, these microorganisms boost soil fertility, thereby ensuring sustainable crop productivity (Nosheen et al., 2021). Previous findings suggest that BFs can replace inorganic fertilizers (25-30%), and when applied together with them, can increase crop yields by 10-40% (Zhao et al., 2024). The global BFs market, valued at USD 1.57 billion in 2018, is projected to grow at a compound annual rate of 12.1% between 2022 and 2027 (Shahwar et al., 2023). This trend underscores the growing interest in sustainable agriculture and highlights the recognition that BFs promote environmentally friendly and ecologically balanced farming practices. In this chapter, the emphasis is placed on microbial inoculants with the potential to enhance crop productivity.

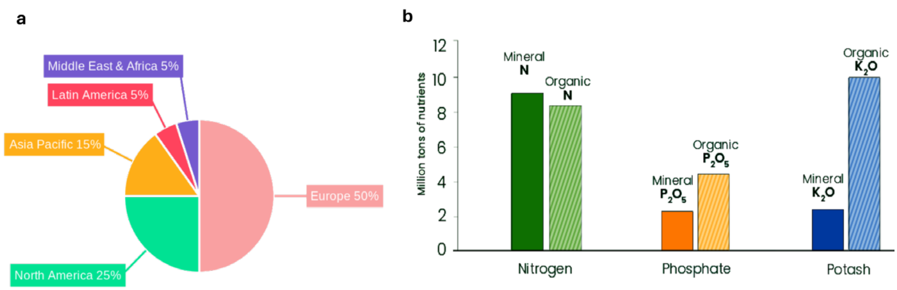


Figure 1. a) Geographical distribution of biofertilizer industry across the globe (Market Report Analytics, 2025). b) Trend of mineral and organic fertilizer consumption in Europe (Fertilizers Europe, 2023).

2. Biofertilizers: Principles and Classifications

Biofertilizers colonize the rhizosphere where they boost plant growth by increasing nutrient availability (Fasusi et al., 2021). They can be applied to seeds, roots, soil, or via foliar sprays. Once established, these microbes multiply and stimulate nutrient mobilization, which improves soil fertility, strengthens plant health, and ultimately increases crop productivity.

Microorganisms help plants through fixing nitrogen (N), making phosphorus (P) and zinc (Zn) more soluble, and supplying nutrients even under stress conditions (Singh et al., 2022). BFs are categorized based on the type of microorganisms they comprise and the specific function they perform through diverse mechanisms, as shown in Figure 2.

2.1 Nitrogen fixers

Nitrogen is a vital macronutrient for plants, playing a key role in shoot growth, reproductive development, and chlorophyll formation, and supports the production of healthier grains (Sandhu et al., 2021). Even though nearly 78% of the atmosphere is composed of N, plants cannot directly utilize atmospheric dinitrogen (N_2) due to its strong triple bond. For plant use, diazotrophic microorganisms must first convert dinitrogen into ammonia via nitrogen fixation, producing a soluble and non-toxic form of nitrogen (Abbey et al., 2019).

Ammonia produced during nitrogen fixation is subsequently converted into nitrite by ammonia-oxidizing bacteria, and further into nitrate by nitrifying bacteria (Roy et al., 2020). In deeper layers of soil, denitrifying microorganisms transform the remaining nitrate into atmospheric nitrogen, which is released as dinitrogen gas. Together, these transformations illustrate the natural flow of the nitrogen cycle (Mahanty et al., 2017).

Species such as *Bacillus* and *Azotobacter* facilitate nitrogen fixation in forest crops and enhance maize growth (Azeem et al., 2022). Nitrogen-fixing microorganisms are generally grouped into associative, free-living, and symbiotic types. These include blue-green algae (cyanobacteria), symbionts such as *Frankia*, *Rhizobium*, and *Azolla*, as well as free-living bacteria like *Azotobacter* and *Azospirillum* (Aasfar et al., 2021).

2.1.1 Symbiotic nitrogen-fixing bacteria

Plants are macro symbionts in symbiosis, while prokaryotic bacteria are microsymbionts. Among the best-studied examples of mutualism is the symbiotic relationship between *Rhizobium* and legumes, where nitrogen-fixing bacteria colonize plant root nodules. This association develops when plants release flavonoids and isoflavonoids into the rhizosphere, which are recognized by *Rhizobium*, leading to the establishment of a mutualistic association (Hawkins & Oresnik, 2022).

The infection process begins when *Rhizobium* induces root hair curling and develops an infection thread that penetrates the root hair cell. Through this thread, the bacteria are released into the cytoplasm, where they undergo terminal differentiation into Bacteroides. As the Bacteroides proliferate, they become enclosed within a symbiosome, the specialized site where nitrogen fixation occurs (Jimenez-Jimenez et al., 2019). Examples of such symbiotic associations include *Azolla* with the *cyanobacteria*, *Anabaena azollae*, *Frankia* (an actinomycete) with non-leguminous plants including *Casuarina* and *Alnus*, *Rhizobium* with legumes, and cyanobacteria forming associations with gymnosperms (Kawaka, 2022).

2.1.2 Free-living nitrogen-fixing bacteria

Some bacteria can live independently in the environment and fix atmospheric nitrogen under aerobic conditions, without the need for a plant host. These free-living nitrogen fixers complete their life cycle autonomously (Aasfar et al., 2021). Among them, *Azotobacter* is of particular interest; it is a free-living, non-symbiotic bacterium, often investigated for its phototrophic characteristics. Notably, *Azotobacter chrooccum* can fix up to 10 mg N/g of carbon source under in vitro conditions, highlighting it as a potential biofertilizer agent (Mukherjee et al., 2022). In addition to fixing nitrogen, *Azotobacter* produces gibberellic acid, naphthalene acetic acid (NAA), IAA, and vitamin B complex. These compounds enhance soil fertility, improve mineral acquisition, stimulate root development, and suppress root infections, thereby improving crop growth (Sumbul et al., 2020). Examples of free-living N-fixing bacteria include *Clostridium*, *Azotobacter*, *Bacillus*, and *Azospirillum*. When *Bacillus* sp. is applied, it protects plants from stress, produces ammonia, IAA, and substantially elevates their growth (Gohil et al., 2022). *Azospirillum brasilense* enhances plant nutrition, decreases nitrogen needs, and boosts plant biomass and wheat grain production (Galindo et al., 2022).

2.1.3 Associative nitrogen-fixing bacteria

Azospirillum is a gram-negative and aerobic bacterium that fixes nitrogen in close association with plant roots. It is particularly common in crops that follow the C_4 pathway of photosynthesis, including sorghum, maize, sugarcane, and pearl millet, but it also enhances the growth of cereal crops (Yasuda et al., 2022). The first species, *Spirillum lipoferum*, was discovered by M.W. Beijernick in 1925, when he found it living around cereal roots and contributing to nitrogen fixation (Soumare et al., 2020). Apart from fixing nitrogen, *Azospirillum* also secretes phytohormones like cytokinins, gibberellins, and IAA. These substances help plants absorb essential mineral elements, including N, P, and K, while encouraging strong root growth. Similar beneficial effects have been observed in related bacteria such as *Gluconobacter*, *Herbaspirillum*, *Azoarcus,* and *Acetobacter* (Kawaka, 2022).

2.2 Phosphorus-solubilizing bacteria

In soils, phosphorus occurs in both organic and inorganic forms, with roughly 30-65% occurring as organic phosphorus and the remaining 35-70% present exists in inorganic forms. Organic phosphorus is typically inactive and often binds into insoluble compounds, thus unavailable for plant absorption. Inorganic phosphorus, on the other hand, readily reacts with ions such as Fe^{3+}, Al^{3+}, and Ca^{2+}, which leads to the formation of insoluble phosphates. Because of this, continuous use of phosphorus fertilizers often results in forms of phosphate that plants cannot easily take up, leaving soil phosphorus deficiencies unresolved (Singh et al., 2023).

The global phosphate supplies are finite, and they will most likely run out in 50-100 years (Santos et al., 2022). Phosphate-solubilizing bacteria (PSB) are essential to the soil phosphorus cycle because they mineralize organic phosphorus by secreting acids and hydrolyze inorganic phosphorus by using enzymatic activities. This process solubilizes P and increases its availability in soil (Liang et al., 2020). PSB can change the insoluble forms of phosphorus into plant-available forms via a variety of mechanisms. Examples include the production of dissolved phosphate through chelation (extracellular polysaccharides, siderophores), organic, and inorganic acids (phosphatase, phytase) (Neal et al., 2018).

Several investigations have found *Bacillus*, *Pseudocystis*, and *Burkholderia* species in various soil types, including tea gardens, saline soil, heavy metal-containing soils, and forest soils, as well as in rhizosphere soils, with high relative abundance in the bacterial community and increased P solubilization capability (Kashyap et al., 2021; Liu et al., 2021). *Enterobacter*, *Flavobacterium*, *Salmonella*, *Micrococcus*, *Thiobacillus*, *Burkholderia*, *Azotobacter*, *Enterobacteriaceae*, *Serratia marcescens*, and *Baeyerlingia* are among the PSB that are currently found in soil (Gómez-Godínez et al., 2023).

2.3 Sulfur oxidizer

Sulfur (S) is an important component for all living organisms. Plants are primary providers of key compounds such as amino acids (methionine and cysteine), glutathione, vitamins like thiamine and biotin, chlorophyll, Phytochelatins, coenzyme A, and S-adenosyl-methionine. Thus, the availability of S is essential for plant nutrition (Chaudhary et al., 2022; Chaudhary et al., 2023). The most insoluble form of sulfur, metal sulfides (containing the S^{2-} ion), is changed into an accessible form, metal sulfates (with the SO_4^{2-} ion), by sulfur solubilizers, also recognized as sulfur-oxidizing bacteria. Sulfate-reducing bacteria perform the reverse process, referred to as assimilatory sulfate reduction (Wang et al., 2019). Sulfur in soil is transformed by microbial activities through mineralization, immobilization, reduction, and oxidation (Malik et al., 2021).

The Sulfolobales family represents the aerobic sulfur-oxidizing archaea. Among the non-phototrophic obligate anaerobes, *Wolinella succinogenes* is a key example. Other notable sulfur-oxidizing microorganisms are *Paracoccus*, *Sulfolobus*, *Thiobacillus*, *Thermithiobacillus*, *Chlorobium*, *Rhodobacter*, and *Rhodopseudomonas* (Kusale et al., 2021). Sulfur biofertilizers, comprising *Thiobacillus thioxidans* and *Bradyhizobium japonicum*, have shown positive impacts on forage, cereal, and medicinal crops (Zhang et al., 2018). In saline soils, *Halothiobacillus* bacteria enhanced crop yields and can resist elevated salt concentrations (Rezvani Boroujeni et al., 2021).

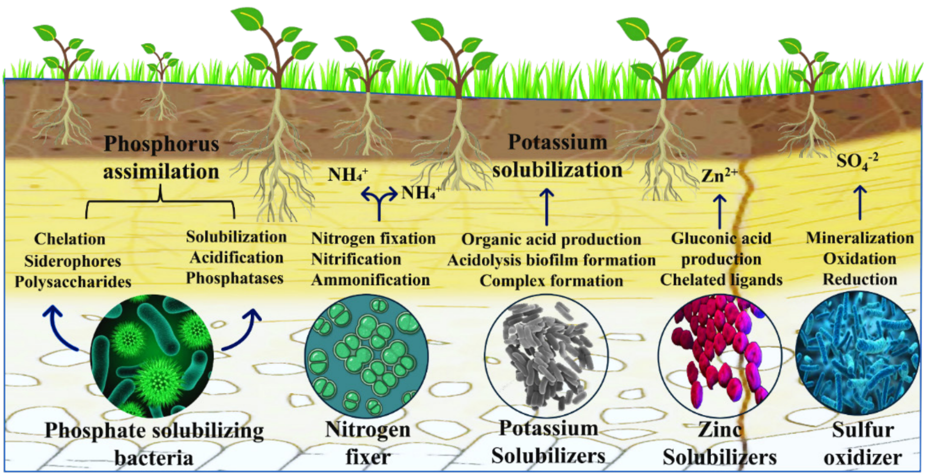


Figure 2. Microbes enhance the nutrient availability in the rhizosphere through diverse mechanisms, including phosphorus solubilization, nitrogen fixation, potassium and zinc mobilization, and sulfur oxidation, thereby improving soil fertility and plant growth.

2.4 Potassium Solubilizers

Potassium is a key macronutrient exhibiting a crucial role in numerous plant metabolic processes (Dahuja et al., 2021). These processes include osmotic regulations induced by abiotic and biotic growth-limiting variables by controlling more than 80% of enzymes, sugar synthesis and translocation, improving nitrogen and phosphorus consumption efficiency, and CO_2 assimilation (Wakeel & Ishfaq, 2021). Although it is abundant, only 2 to 3% of soil K is freely soluble for plants, whereas the remaining 95% of soil K is bonded to other soil minerals (Etesami et al., 2017). K exists in soil in four different forms: exchangeable (ionic), non-exchangeable (fixed), available (soluble), and unavailable (minerals) (Kour, Rana, Kaur, et al., 2020).

By converting fixed forms of K in soil to plant available forms, potassium solubilizing bacteria (KSB) such as *Acidothiobacillus ferroxidans*, *Aspergilus terreus*, *B. edaphicus*, *Bacillus circulans*, *B. Paenibacillus*, and *mucilaginosus* enhance plant development and yield (Meena et al., 2016). In both controlled and field settings, applying KSB facilitates the K solubilization and increases its accumulation in different plant parts (Sood et al., 2023).

2.5 Zinc solubilizes

Zinc-solubilizing bacteria (ZSB) are capable of transforming insoluble forms of zinc (Zn) into plant-available forms. Through several metabolic activities, these bacteria solubilize Zn in soil, which facilitates its absorption by plant roots (Upadhayay et al., 2022). ZSB genera that have been examined the most are *Rhizobium*, *Bacillus*, and *Pseudomonas*. These bacterial species solubilize zinc through distinct processes, and their significance in sustainable agriculture is growing. Other bacterial genera, including *Azotobacter*, *Acinetobacter*, and *Enterobacter* have been shown to effectively solubilize zinc (Nitu et al., 2020; Singh et al., 2024).

The release of organic acid is the key mechanism for Zn solubilization. By releasing organic acids, bacterial strains reduced the pH of the surrounding soil (Upadhayay et al., 2018). Specifically, gluconic acid and its derivatives dissolve insoluble Zn, such as zinc phosphate, carbonate, and oxide, into soluble forms (Kamran et al., 2017). Numerous microbiological strains, such as *Acinetobacter*, *Pseudomonas*, and *Gluconacetobacter* have been shown to generate a large amount of gluconic acid, which is responsible for zinc solubilization. Instead of using gluconic acid, *Burkholderia cepacian* dissolves zinc using oxalic, tartaric, formic, and acetic acids. Further possible mechanisms involve the production of amino acids, siderophores, chelated ligands, vitamins, protons, and oxidoreductive systems on cell membranes (Rani et al., 2025).

2.6 Plant growth-promoting rhizobacteria

Plant growth-promoting rhizobacteria (PGPR) constitute a group of beneficial microorganisms that enhance plant defense mechanisms and increase resistance to subsequent pathogen attacks through diverse physiological and molecular processes. Owing to their non-pathogenic nature, natural occurrence in the rhizosphere, environmental compatibility, and ability to directly promote crop productivity, PGPR are considered more suitable and effective biofertilizer agents compared to synthetic fertilizers (Kumar et al., 2016). Gupta et al. (2002) reported that PGPR can support plant growth both directly and indirectly. They do so by making soil nutrients more available, protecting plants from pathogens, improving soil structure, producing growth-regulating hormones, and even cleaning the soil by removing toxic heavy metals and reducing harmful chemicals like pesticides and fungicides. Numerous symbiotic and non-symbiotic bacteria, including *Klebsiella*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Enterobacter* and *Serratia,* are known to be PGPRs (Saharan & Nehra, 2011).

3.1 Forms and bioformulations of biofertilizers: carriers, liquid consortia, and encapsulation

A physiologically active component of microbial biomass and its metabolite, combined with a carrier material, is called bioformulation. It can be utilized as a nutrient acquisition agent, plant growth booster, and biocontrol agent in ecologically safe methods (Aamir et al., 2020). Proper formulation of biostimulants and fertilizers is crucial, as it directly influences their efficacy and agricultural application. A key element in developing an effective bioformulation is the selection of a suitable carrier, which ensures the successful transfer of live microbial strains from the laboratory to the field. (Richa, 2024). The following lists a few of the bioformulation categories.

3.1 Solid Bioformulation

Solid formulations are typically prepared using either organic or inorganic materials. They can be manufactured in solid, granular, and powder form. The most significant solid formulations are made using a variety of carrier materials, including vermiculite, peat, compost, perlite, coal, polysaccharides, and agro-industrial waste (Mishra & Arora, 2016). Granular, wettable powder, and wettable/water-dispersible solid bioformulations can be applied. Both ectomycorrhizal and arbuscular mycorrhizal fungi can be transported by peat (Zaidi et al., 2017). Another kind of granule with moisture-retentive qualities is vermiculite, which is made of a yellowish-brown substance like mica. It has been employed as a carrier for PGP bacteria such as *Bacillus* and *Pseudomonas* species (Aini et al., 2019).

3.2 Liquid Bioformulations

Aqueous suspensions composed of microbial biomass combined with oils, water, or their combination are known as liquid formulations (Prakash & Arora, 2020). They typically contain 10-40% microorganisms, 1-3% suspended agents, 3-8% surfactants, 1-5% dispersant, and 35-65% carrier liquid. These formulations are generally classified as suspension concentrates. Solid active substances that are stable against hydrolysis but poorly soluble in water are combined to create suspension concentrations. The carrier liquids consisted of water, fruit juices, broth, jaggery syrup, or polyvinylpyrrolidone (Nagachandrabose, 2018). These liquid bioformulations help stabilize bioinoculants during production, distribution, and long-term storage while also extending the shelf life of products and acting as efficient carriers (Jayasudha et al., 2018).

3.3 Encapsulation

In encapsulated bioformulations, polymeric substances are used to coat microbial cells to create beads permeable to gases, nutrients, and metabolites, preserving the vitality of the cells inside the beads. Under adverse or environmental stress circumstances, such as pH, biochemical variables, temperature, mechanical damage, and ionic strength, the encapsulated bioformulation shields the active microbial components (Vassilev et al., 2020). The encapsulation technique involved the use of gelatin, starch, cellulose, and a few other polymers. Microencapsulation and macroencapsulation are the two categories of encapsulation formation techniques. Microencapsulation ranges in size from 1 to 1000 µm, whereas macro-encapsulation uses beads that are mm to cm in size (Wu et al., 2020). However, both solid and liquid bioformulations face challenges, particularly regarding long-term storage and maintaining the viability of microbial spores. To address these limitations, techniques like immobilization and encapsulation have proven effective in enhancing viability and simplifying the field application of bioinoculants (Hussain et al., 2019).

Table 1. Summary of the microbes used in biofertilizers formulations.

Microbe	**Representative Genera/ Species**	**Mechanism of action**	**Crop Applications**	**Bio-formulation**	**References**
N-fixing bacteria	*Azotobacter*, *Rhizobium*, *Azospirillum*	Atmospheric N_2 fixation into ammonia via the nitrogenase enzyme	Vegetables, legumes, cereal crops	Carrier-based (peat), encapsulated, liquid cultures	(Ambechada & Umrania, 2024)
Cyano-bacteria	*Nostoc*, *Anabaena*, *Spirulina*	N-fixation, poly-saccharide production	Cereals, sugarcane, vegetables	Alginate beads, liquid consortia	(Chittora et al., 2020)
PSB	*Pseudomonas*, *Azospirillum*, *Bacillus*	Secrete enzymes, organic acids for P solubilization	Legumes, horticulture crops, cereals	Carrier-based powder, liquid formulation	(Bai et al., 2024)
KSB	*Bacillus circulans*, *Aspergilus Terreus*, *Acidothiobacillus ferrooxidans*	Acidolysis induced release of K^+ from silicate minerals	Tobacco, mulberry, wheat, rice	Liquid, carrier-based formulations	(Pandey & Saharan, 2025)
ZSB	*Pseudomonas*, *Bacillus*, *Acinetobacter*	Solubilization by organic acid production and chelation	Oil seeds, legumes, cereals	Liquid, granular, powder forms	(Sethi et al., 2025)
SOD	*Thiobacillus*, *Sulfolobus*, *Thermithiobacillus*	Oxidize elemental sulfur and H_2S into available sulfate	Oil seeds, horticulture crops, legumes	Carrier-based, liquid	(Ranadev et al., 2023)
PGPR	*Agrobacterium*, *Bacillus*, *Pseudomonas*, *Azospirillum*	Phytohormone production, solubilization of nutrients, siderophores	Pulses, wheat, tomato, potato, radish	Encapsulated, liquid consortia	(Bhattacharyya & Jha, 2012)

PSB: Phosphorus solubilizing bacteria; KSB: Potassium solubilizing bacteria; ZSB: Zinc solubilizing bacteria; SOD: Sulfur oxidizing bacteria; PGPR: Plant growth promoting rhizobacteria.

4. Biofertilizers for Sustainable Crop Production

Biofertilizer application significantly improves soil fertility and agricultural productivity (Yadav & Smritikana, 2019). They improve soil structure and agricultural yield when incorporated into the soil while participating in the nutrient cycle (Sammauria et al., 2020). Microbes' ability to adjust to diverse cultural and environmental situations has made them feasible options for addressing food-related difficulties in the agricultural industry (Galindo et al., 2020). Potential biofertilizers preserve the environment by reducing the adverse impacts of agricultural practices and improving the quality of food, along with enhancing agricultural sustainability (Akhtar et al., 2021). Without having any negative side effects, they increase soil fertility and create phytohormones which enhance plant growth and development (Hasan, 2020).

4.1 Impact on Major Crops

Previous findings have reported that a specific combination of biofertilizers produces superior outcomes when compared to inoculating a single fertilizer. *Azotobacter* and *Azospirillum* inoculation greatly enhanced grain production and total dry weight in field-grown maize, increasing it by up to 115% (Nosheen et al., 2021). Similarly, introducing *Azospirillum* and *Azotobacter* species to rice seedlings has been shown to effectively replace inorganic N fertilizer and boost rice yield from 2-3 t ha^{-1} to 3.9-6.4 t ha^{-1} (Basak et al., 2022). The effect of inoculating rice roots on yield under varying N fertility levels has been examined in another study. Surprisingly, the highest yield was obtained with the least amount of nitrogenous fertilizer (Bechtaoui et al., 2021; Sajjad et al., 2025). Using PSB as biofertilizers could boost sugarcane production by replacing 50% of the costly phosphate fertilizer (Rezvani et al., 2021).

4.2 Impact on Horticultural Crops (Fruits, Vegetables)

The production of horticulture crops faces numerous challenges from the growing global population, climate change, and pest and disease outbreaks. Crop production must be increased immediately while utilizing sustainable practices. Plants are linked to rhizospheric microorganisms that can assist vegetative propagation, boost plant nutrition, and encourage crop development and stress tolerance. It is therefore a feasible strategy to enhance horticulture crop productivity by formulating and supplying biofertilizers that contain these beneficial bacteria (Wong & Teh, 2021).

Soil health, plant nutrient uptake, vegetative growth, and quality of fruit plants have been significantly improved using BFs in fruit crop nutrient management. Consequently, using biofertilizers in fruit crop development has become crucial for maximizing the potential advantages of sustainable, nutrient-dense, and environmentally friendly fruit production (Ali et al., 2023).

Growing vegetables is a potential economic endeavor, and because of their high nutritional value, eating vegetables is beneficial to human health. Vitamins, minerals, dietary fiber, and a variety of phytochemical substances are all abundant in vegetables. However, the yield of vegetable crops grown using biofertilizers is low. By releasing nutrients, producing phytohormones, and protecting vegetable crops from different harmful impacts, PGPR promotes the growth and yield of vegetable crops (Kumar et al., 2022).

4.3 Impact on Legumes

Nitrogen is the most limiting nutrient for plant growth (Bai et al., 2020). The atmospheric N is converted into plant-available forms by nitrogen fixation, which improves crop productivity by 10-50% and supplies 300-400 kg N ha^{-1} $year^{-1}$. It provides plants with up to 25% of their nitrogen. Plant roots release chemicals into the soil that assist bacteria in colonizing and fixing nitrogen. To a varying extent, they can effectively replace chemical fertilizers, lowering the environmental chemical load. They are separated into free-living bacteria like *Azotobacter* and *Azospirillium,* symbionts like *Rhizobium*, *Frankia,* and *Azolla*, and blue-green algae.

6. Biofertilizers in Climate Stress Mitigation under Sustainable Farming System

6.1 Mitigation with a specific focus on plant growth

Biofertilizers host diverse microbial groups, including N-fixing bacteria, PSB, arbuscular mycorrhizal fungi, and plant growth-promoting rhizobacteria, which exhibit remarkable resilience under climate-induced stress (Kumar et al., 2022). Their adaptability enables them to support plant growth and maintain yield stability under drought, salinity, and elevated temperature. This resilience arises from microbial metabolic variability, production of stress-regulating compounds and relationships with host plants (Etesami, 2025). PGPR produces exopolysaccharides and biofilms that create root attachment sites, improve soil aggregation and water retention, which offset drought-related plant stress (Al-Turki et al., 2023). N-fixing bacteria supply plants with biologically fixed nitrogen when stressed, compensating for any reductions in soil fertility. In addition to their nutritional contributions, microbes also provide plants with phytohormones like indole-3-acetic acid, cytokinins, and gibberellins that regulate root development and promote nutrients and water uptake (Mukherjee et al., 2022).

Halotolerant PGPR produces ACC (1-Aminocyclopropane-1-Carboxylic Acid) deaminase, which suppresses ethylene, thus alleviating plant growth reduction due to salinity (Duan et al., 2021). Mycorrhizal fungi maintain hyphal networks that can support soil structure, allow for increased soil exploration for water and nutrients, and stabilize soil organic matter and soil carbon sinks

(Shukla et al., 2025). Collectively, these approaches produce agroecosystem resilience and increase photosynthesis, osmotic balance, and nutrient acquisition, thus supporting stable yields in climate-sensitive agriculture.

6.2 Reducing greenhouse gas emissions and carbon sequestration

Biofertilizers contribute significantly to climate change mitigation by hindering greenhouse gas emissions (GHGEs) and augmenting soil carbon sequestration. Excessive use of N fertilizers is a major source of nitrous oxide, a gas nearly 300 times more potent than CO_2 (Sajjad et al., 2024; Shakeel et al., 2021). Biofertilizers promote N-fixation, reducing the need for inorganic fertilizers and cutting the nitrous oxide emissions from soil nitrification and denitrification (Figiel et al., 2025; Khaliq et al., 2023). In rice-based systems, BFs containing methanotrophic bacteria enhance methane oxidation in the rhizosphere, which limits methane release. PSB improves nutrient use efficiency, reducing dependence on energy-exhaustive synthetic fertilizers and indirectly lowering CO_2 emissions from fertilizer production (Skrzypczak et al., 2025). BFs also enhance carbon sequestration through microbial processes that stabilize soil organic matter. Mycorrhizal fungi produce glomalin-related proteins that strengthen soil aggregates and act as long-term carbon sinks (Son et al., 2024). Microbial inoculants enhance root growth and rhizodeposition, increasing carbon input through exudates and biomass turnover while promoting humification for carbon stabilization (Lei et al., 2023). These mechanisms lower agricultural emissions and build soil carbon storage to support climate-smart agriculture while enhancing crop productivity and resilience for sustainable farming systems (Figure 3).

6.3 Reducing chemical fertilizer use by integrated nutrient management

Integrated nutrient management (INM) promotes the balanced use of synthetic fertilizers in combination with organic fertilizers to elevate soil fertility and maintain crop productivity. Overreliance on inorganic fertilizers in intensive farming resulted in soil acidification, nutrient leaching, water eutrophication, and elevated GHGEs (Mahankale, 2024). The inclusion of biofertilizers in INM increases nutrient use efficiency and reduces the requirement for high chemical inputs. The integration of biofertilizers with reduced synthetic fertilizer rates ensures a continuous nutrient supply, enhances soil structure, water retention, microbial biomass, and supports phosphatase and urease activities (Samantaray et al., 2024). This promotes nutrient cycling, organic matter mineralization, and long-term soil health. From a climate perspective, INM mitigates stress by lowering nitrous oxide emissions and increasing soil carbon sequestration. Research indicates that nitrogen application can be reduced by 30-40% without compromising yields when biofertilizers are applied.

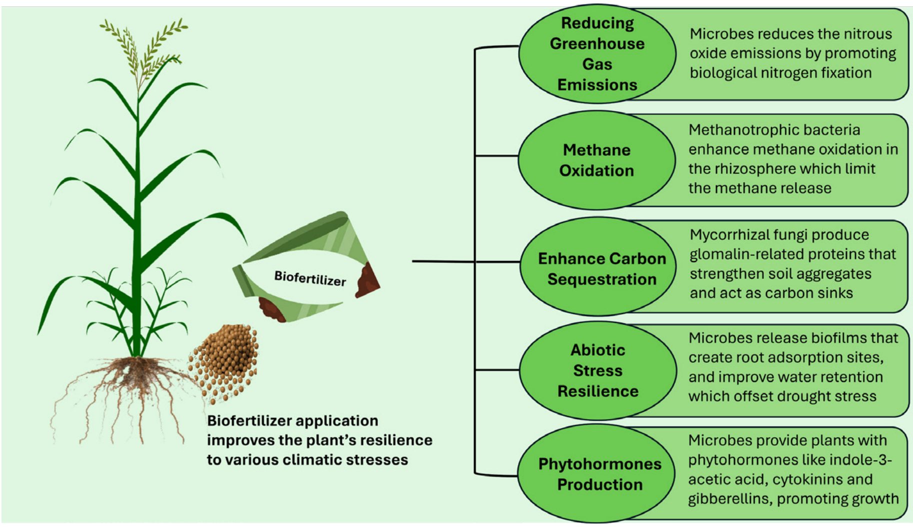


Figure 3. Role of biofertilizers in climate stress mitigation under a sustainable farming system.

7. Agronomic Management Practices to Optimize Biofertilizers Functionality

7.1 Carbon sequestration

Biofertilizer's efficiency in enhancing crop growth, nutrient uptake, and soil health depends heavily on agronomic practices. Microorganisms require suitable environmental conditions and proper management to survive, colonize roots, and continue with their biological functions (Hnini et al., 2024). Sustainable and effective agricultural practices provide the necessary conditions for microbes to survive as well as the later soil carbon sequestration, which bases microbial activity and nutrient cycling (Enebe et al., 2025; Bellitürk et al., 2022). Carbon-rich soils provide energy and nutrients for microbial growth and enzymes to enable biofertilizer effectiveness with varying cropping systems and climate conditions (Kumar et al., 2022). All these practices together build a resilient, productive farming system that maintains soil health and crop yield under challenging environmental conditions.

7.2 Crop rotation and multiple cropping systems

Crop rotation and multiple cropping are fundamental practices in promoting soil fertility and microbial diversity. Crop rotations with legumes and cereals increase soil nitrogen through fixation, subsequently maintaining residual nitrogen for the following crops and reducing reliance on chemical fertilizers, which leads to greater productivity of the system (Liu et al., 2023). In addition, multiple cropping and intercropping maintain continuous exudates and organic residues that support nitrogen, phosphate, and potassium solubilizing microbes (Chamkhi et al., 2022). Diverse cropping systems also diminish pest and disease occurrence, improve soil structure, and develop a balanced micro ecosystem which stabilizes microbial populations under drought and salinity conditions (Fan et al., 2025). Soil tillage is a major factor in controlling rhizosphere activities and microbial activity, where intensive tillage disrupts soil aggregation and thus promotes the collapse of fungal networks, reduces microbial biomass, and restricts nutrient cycling efficiency, which is critical for crop development (Tang et al., 2021). In comparison, reduced tillage or conservation tillage implemented through zero tillage maintains soil structure, increases water-holding capacity, and maintains microbial activities, which sustain nutrient cycling (Sun et al., 2024). Maintaining soil structure, such as porosity and aggregation, will stabilize organic matter, restrict erosion, increase moisture retention, and maintain microbial activity involved in the solubilization of nutrients for plant growth.

7.3 Residue Management and Organic Amendments

Crop residues and organic amendments, including vermicompost, enhance biofertilizer efficacy by improving soil health, nutrient availability and microbial activity, which support sustainable agriculture (Rehman et al., 2023; Aslam et al., 2023; Rehman et al., 2025). The inclusion of plant residues such as stems, leaves, and roots provides constant carbon and nutrients for microbial development (Almagro et al., 2021). The use of green manures, farmyard manure, and vermibiochar enhances organic matter and increases the availability of N, P, and K through enzymatic activities (Rostaei et al., 2024; Ahmed et al., 2023; Rehman et al., 2023). The role of the decomposition of residues in the formation of humus and glomalin-related proteins contributes to improved aggregation, water-holding capacity, and carbon conservation (Hossain, 2021). It creates stable microhabitats that sustain microbial activity and biofertilizer function throughout crop growth. Another benefit of crop residues lies in their ability to stabilize soil temperature and moisture, which provides stable conditions and mitigates stresses to beneficial microbes.

8. Constraints in Biofertilizer Adoption

Biofertilizers offer a sustainable alternative to chemical inputs by boosting soil fertility, crop yields, and ecosystem resilience. However, their large-scale adoption is constrained by interconnected technical, environmental, socio-economic, and regulatory barriers. Technical limitations arise from the living nature of microbial inoculants, whose viability is sensitive to storage conditions, contamination, and formulation challenges. Environmental constraints, including soil heterogeneity, strain specificity, and climate variability, strongly influence microbial survival and field performance, necessitating regionally adapted applications. Knowledge gaps among farmers, exacerbated by weak extension services and inadequate demonstrations, lead to reduced efficacy, highlighting the need for organized training and participatory approaches. Inconsistent product quality and insufficient regulatory oversight undermine confidence, allowing low-grade or counterfeit products to reach markets. Market-related challenges such as high costs, limited supply chains, poor distribution in remote areas, and perceived inferiority to chemical fertilizers further hinder adoption, though these may be mitigated by subsidies, public–private partnerships, and awareness campaigns. Finally, variability in field performance, driven by environmental and agronomic factors, erodes farmer trust. Building reliability through site-specific formulations, rigorous quality control, robust regulatory frameworks, and farmer-focused education is essential for improving adoption and realizing the full agronomic and environmental potential of biofertilizers.

Summary

Chemical fertilizers are crucial for achieving food self-sufficiency; however, their excessive use adversely affects soil fertility, disrupts nutrient balance, reduces water-holding capacity, and contaminates water bodies. Biofertilizers, composed of beneficial microbes, offer a sustainable, ecologically-friendly alternative. They improve nutrient availability through nitrogen fixation, phosphorus solubilization, potassium and zinc mobilization, and sulfur oxidation, while also protecting plants from soil-borne diseases and improving soil health. Key microbial groups in biofertilizers include N-fixers, phosphate solubilizers, arbuscular mycorrhizal fungi, and plant growth-promoting rhizobacteria, which enhance plant growth and maintain stability under various stresses, including salinity, drought, and high temperatures. Additionally, biofertilizer application improves climate change mitigation efforts by reducing GHGEs, enhancing carbon sequestration, and improving nutrient use efficiency. Further research is essential to develop soil-specific strains, optimize biofertilizer formulations, and enhance microbial efficacy through biotechnological approaches.

References

Aamir, M., Rai, K. K., Zehra, A., Dubey, M. K., Kumar, S., Shukla, V., & Upadhyay, R. S. (2020). Microbial bioformulation-based plant biostimulants: A plausible approach toward next generation of sustainable agriculture. In Microbial endophytes (pp. 195-225). Elsevier.

Aasfar, A., Bargaz, A., Yaakoubi, K., Hilali, A., Bennis, I., Zeroual, Y., & Meftah Kadmiri, I. (2021). Nitrogen fixing Azotobacter species as potential soil biological enhancers for crop nutrition and yield stability. Frontiers in Microbiology, 12, 628379.

Abbey, L., Abbey, J., Leke-Aladekoba, A., Iheshiulo, E. M. A., & Ijenyo, M. (2019). Biopesticides and biofertilizers: types, production, benefits, and utilization. Byproducts from agriculture and fisheries: Adding value for food, feed, pharma, and fuels, 479-500.

Ahmed, F., Waris, F., ibni Zamir, S., Sajjad, M., Nazeer, S., Khan, A., & Mustafa, F. (2023). Response of Different Organic and Inorganic Fertilizers on Alfalfa Yield Under Different Types of Irrigation Water. Haya Saudi J Life Sci, 8(1), 1-8.

Aini, N., Yamika, W. S. D., & Ulum, B. (2019). Effect of nutrient concentration, PGPR and AMF on plant growth, yield, and nutrient uptake of hydroponic lettuce.

Akhtar, M., Sarwar, N., Ashraf, A., Ejaz, A., Ali, S., & Rizwan, M. (2021). Beneficial role of Azolla sp. in paddy soils and their use as bioremediators in polluted aqueous environments: implications and future perspectives. Archives of Agronomy and Soil Science, 67(9), 1242-1255.

Ali, S., Ahmad, N., Dar, M. A., Manan, S., Rani, A., Alghanem, S. M. S., ... & Zhu, D. (2023). Nano-agrochemicals as substitutes for pesticides: prospects and risks. Plants, 13(1), 109.

Almagro, M., Ruiz-Navarro, A., Díaz-Pereira, E., Albaladejo, J., & Martínez-Mena, M. (2021). Plant residue chemical quality modulates the soil microbial response related to decomposition and soil organic carbon and nitrogen stabilization in a rainfed Mediterranean agroecosystem. Soil Biology and Biochemistry, 156, 108198.

Aloo, B. N., Makumba, B. A., & Mbega, E. R. (2020). Plant growth promoting rhizobacterial biofertilizers for sustainable crop production: The past, present, and future.

Aloo, B. N., Mbega, E. R., Makumba, B. A., & Tumuhairwe, J. B. (2022a). Effects of carrier materials and storage temperatures on the viability and stability of three biofertilizer inoculants obtained from potato (Solanum tuberosum L.) rhizosphere. Agriculture, 12(2), 140.

Aloo, B. N., Mbega, E. R., Tumuhairwe, J. B., & Makumba, B. A. (2021). Advancement and practical applications of rhizobacterial biofertilizers for sustainable crop production in sub-Saharan Africa. Agriculture & Food Security, 10(1), 57.

Al-Turki, A., Murali, M., Omar, A. F., Rehan, M., & Sayyed, R. Z. (2023). Recent advances in PGPR-mediated resilience toward interactive effects of drought and salt stress in plants. Frontiers in microbiology, 14, 1214845.

Ambechada, J. K., & Umrania, V. V. (2024). Nitrogen-fixing bacteria in biofertilizer production: benefits, limitations and prospects.

Ammar, E. E., Aioub, A. A., Elesawy, A. E., Karkour, A. M., Mouhamed, M. S., Amer, A. A., & El-Shershaby, N. A. (2022). Algae as Bio-fertilizers: Between current situation and future prospective. Saudi Journal of Biological Sciences, 29(5), 3083-3096.

Aslam, Z., Bashir, S., Belliturk, K., Zhang, L., Zaman, Q. U., & Ahmad, A. (2023). Vermicomposting: a sustainable and environment-friendly approach for organic waste management. In Waste Problems and Management in Developing Countries (pp. 365-401). Apple Academic Press.

Atieno, M., Herrmann, L., Nguyen, H. T., Phan, H. T., Nguyen, N. K., Srean, P., & Lesueur, D. (2020). Assessment of biofertilizer use for sustainable agriculture in the Great Mekong Region. Journal of environmental management, 275, 111300.

Azeem, M., Haider, M. Z., Javed, S., Saleem, M. H., & Alatawi, A. (2022). Drought stress amelioration in maize (Zea mays L.) by inoculation of Bacillus spp. strains under sterile soil conditions. Agriculture, 12(1), 50.

Bai, K., Wang, W., Zhang, J., Yao, P., Cai, C., Xie, Z., Luo, L., Li, T., & Wang, Z. (2024). Effects of phosphorus-solubilizing bacteria and biochar application on phosphorus availability and tomato growth under phosphorus stress. BMC biology, 22(1), 211.

Bai, Y. C., Chang, Y. Y., Hussain, M., Lu, B., Zhang, J. P., Song, X. B., ... & Pei, D. (2020). Soil chemical and microbiological properties are changed by long-term chemical fertilizers that limit ecosystem functioning. Microorganisms, 8(5), 694.

Bangash, N., Mahmood, S., Akhtar, S., Hayat, M. T., Gulzar, S., & Khalid, A. (2021). Formulation of biofertilizer for improving growth and yield of wheat in rain dependent farming system. Environmental Technology & Innovation, 24, 101806.

Barin, M., Asadzadeh, F., Hosseini, M., Hammer, E. C., Vetukuri, R. R., & Vahedi, R. (2022). Optimization of biofertilizer formulation for phosphorus solubilizing by Pseudomonas fluorescens Ur21 via response surface methodology. Processes, 10(4), 650.

Basak, B. B., Maity, A., Ray, P., Biswas, D. R., & Roy, S. (2022). Potassium supply in agriculture through biological potassium fertilizer: a promising and sustainable option for developing countries. Archives of Agronomy and Soil Science, 68(1), 101-114.

Bechtaoui, N., Rabiu, M. K., Raklami, A., Oufdou, K., Hafidi, M., & Jemo, M. (2021). Phosphate-dependent regulation of growth and stresses management in plants. Frontiers in Plant Science, 12, 679916.

Bellitürk, K., Rehman, S. A. M. I., Büyükfiliz, F., Rehmat, R., & Benedetti, M. (2022). Bioaugmentation: A Novel Strategy To Cope With Environmental Impacts Of Agrochemicals. In Innovative Agricultural And Environmental Solutions (pp. 7-70). IKSAD Publishing House.

Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World Journal of Microbiology and Biotechnology, 28(4), 1327-1350.

Bumandalai, O., & Tserennadmid, R. (2019). Effect of Chlorella vulgaris as a biofertilizer on germination of tomato and cucumber seeds. International Journal of Aquatic Biology, 7(2), 95-99.

Cakmakcı, R., Akçura, S., & Erat, M. (2021). Effect of co-inoculation of multi-traits bacteria based bio-formulations on the growth, yield and enzyme activities of tea. Türk Tarım ve Doğa Bilimleri Dergisi, 8(3), 594-604.

Chamkhi, I., Cheto, S., Geistlinger, J., Zeroual, Y., Kouisni, L., Bargaz, A., & Ghoulam, C. (2022). Legume-based intercropping systems promote beneficial rhizobacterial community and crop yield under stressing conditions. Industrial Crops and Products, 183, 114958.

Chaudhary, S., Dhanker, R., Kumar, R., & Goyal, S. (2022). Importance of legumes and role of Sulphur oxidizing bacteria for their production: a review. Legume Research-An International Journal, 45(3), 275-284.

Chaudhary, S., Sindhu, S. S., Dhanker, R., & Kumari, A. (2023). Microbes-mediated sulphur cycling in soil: Impact on soil fertility, crop production and environmental sustainability. Microbiological research, 271, 127340.

Chittora, D., Meena, M., Barupal, T., Swapnil, P., & Sharma, K. (2020). Cyanobacteria as a source of biofertilizers for sustainable agriculture. Biochemistry and biophysics reports, 22, 100737.

Dahuja, A., Kumar, R. R., Sakhare, A., Watts, A., Singh, B., Goswami, S., Sachdev, A., & Praveen, S. (2021). Role of ATP-binding cassette transporters in maintaining plant homeostasis under abiotic and biotic stresses. Physiologia plantarum, 171(4), 785-801.

Duan, B., Li, L., Chen, G., Su-Zhou, C., Li, Y., Merkeryan, H., ... & Liu, X. (2021). 1-Aminocyclopropane-1-carboxylate deaminase-producing plant growth-promoting rhizobacteria improve drought stress tolerance in grapevine (Vitis vinifera L.). Frontiers in Plant Science, 12, 706990.

Enebe, M. C., Ray, R. L., & Griffin, R. W. (2025). Carbon sequestration and soil responses to soil amendments–A review. Journal of Hazardous Materials Advances, 100714.

Etesami, H. (2025). The dual nature of plant growth-promoting bacteria: Benefits, risks, and pathways to sustainable deployment. Current Research in Microbial Sciences, 100421.

Etesami, H., Emami, S., & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB):Mechanisms, promotion of plant growth, and future prospects A review. Journal of soil science and plant nutrition, 17(4), 897-911.

Fan, H., Miao, R., Guo, C., Bao, X., He, W., Sun, Y., & Zhao, C. (2025). Research on the effect of diversified cropping on crop quality: A review. Agriculture, 15(5), 456.

Fasusi, O. A., Cruz, C., & Babalola, O. O. (2021). Agricultural sustainability: microbial biofertilizers in rhizosphere management. Agriculture, 11(2), 163.

Fertilizers Europe. (2022). Forecast 2022-2023. Retrieved from https://www.fertilizerseurope.com/forecast-2022-2023/ .

Figiel, S., Rusek, P., Ryszko, U., & Brodowska, M. S. (2025). Microbially Enhanced Biofertilizers: Technologies, Mechanisms of Action, and Agricultural Applications. Agronomy, 15(5), 1191.

Galindo, F. S., Filho, M. C. M. T., Buzetti, S., Rodrigues, W. L., Fernandes, G. C., Boleta, E. H. M., ... & Gaspareto, R. N. (2020). Influence of Azospirillum brasilense associated with silicon and nitrogen fertilization on macronutrient contents in corn. Open Agriculture, 5(1), 126-137.

Galindo, F. S., Pagliari, P. H., Fernandes, G. C., Rodrigues, W. L., Boleta, E. H. M., Jalal, A., Céu, E. G. O., Lima, B. H. d., Lavres, J., & Teixeira Filho, M. C. M. (2022). Improving sustainable field-grown wheat production with Azospirillum brasilense under tropical conditions: a potential tool for improving nitrogen management. Frontiers in Environmental Science, 10, 821628.

Gohil, R. B., Raval, V. H., Panchal, R. R., & Rajput, K. N. (2022). Plant growth-promoting activity of Bacillus sp. PG-8 isolated from fermented panchagavya and its effect on the growth of Arachis hypogea. Frontiers in Agronomy, 4, 805454.

Gómez-Godínez, L. J., Aguirre-Noyola, J. L., Martínez-Romero, E., Arteaga-Garibay, R. I., Ireta-Moreno, J., & Ruvalcaba-Gómez, J. M. (2023). A look at plant-growth-promoting bacteria. Plants, 12(8), 1668.

Gupta, A., Meyer, J. M., & Goel, R. (2002). Development of heavy metal-resistant mutants of phosphate solubilizing Pseudomonas sp. NBRI 4014 and their characterization. Current Microbiology, 45(5), 323-327.

Hasan, M. A. (2020). Cyanobacteria from Rice Field and Comparative Study of Their Performances as Biofertilizer on Rice Plants. J. Glob. Biosci, 9, 8078-8087.

Hawkins, J. P., & Oresnik, I. J. (2022). The rhizobium-legume symbiosis: co-opting successful stress management. Frontiers in plant science, 12, 796045.

Hnini, M., Rabeh, K., & Oubohssaine, M. (2024). Interactions between beneficial soil microorganisms (PGPR and AMF) and host plants for environmental restoration: A systematic review. Plant Stress, 11, 100391.

Hossain, M. B. (2021). Glomalin and contribution of glomalin to carbon sequestration in soil: a review. Turkish Journal of Agriculture-Food Science and Technology, 9(1), 191-196.

Hussain, Z., Khan, M. A., Iqbal, F., Raffi, M., & Hafeez, F. Y. (2019). Electrospun microbial-encapsulated composite-based plasticized seed coat for rhizosphere stabilization and sustainable production of canola (Brassica napus L.). Journal of Agricultural and Food Chemistry, 67(18), 5085-5095.

Jayasudha, S., Kirankumar, K., Mesta, R., & Ippikoppa, R. (2018). Liquid formulation using different oils and shelf life study of effective bacterial bio-agents. International Journal of Current Microbiology and Applied Sciences, 7(4), 317-324.

Jimenez-Jimenez, S., Santana, O., Lara-Rojas, F., Arthikala, M.-K., Armada, E., Hashimoto, K., Kuchitsu, K., Salgado, S., Aguirre, J., & Quinto, C. (2019). Differential tetraspanin genes expression and subcellular localization during mutualistic interactions in Phaseolus vulgaris. PLOS ONE, 14(8), e0219765.

Kamran, S., Shahid, I., Baig, D. N., Rizwan, M., Malik, K. A., & Mehnaz, S. (2017). Contribution of zinc solubilizing bacteria in growth promotion and zinc content of wheat. Frontiers in Microbiology, 8, 2593.

Kashyap, A. S., Manzar, N., Rajawat, M. V. S., Kesharwani, A. K., Singh, R. P., Dubey, S., Pattanayak, D., Dhar, S., Lal, S., & Singh, D. (2021). Screening and biocontrol potential of rhizobacteria native to gangetic plains and hilly regions to induce systemic resistance and promote plant growth in chilli against bacterial wilt disease. Plants, 10(10), 2125.

Kawaka, F. (2022). Characterization of symbiotic and nitrogen fixing bacteria. AMB Express, 12(1), 99.

Khaliq, A., Zafar, M., Sajjad, M., Hassan, M. U., Mudassar, M. A., Shakoor, M. A., ... & Niaz, S. (2023). Nitrogen use efficiency in sunflower (Helianthus annuus l.) influenced by various fertigation and bed planting techniques. Pakistan Journal of Biotechnology, 20(02), 385-392.

Kour, D., Rana, K. L., Kaur, T., Yadav, N., Halder, S. K., Yadav, A. N., Sachan, S. G., & Saxena, A. K. (2020). Potassium solubilizing and mobilizing microbes: biodiversity, mechanisms of solubilization, and biotechnological implication for alleviations of abiotic stress. In New and future developments in microbial biotechnology and bioengineering (pp. 177-202). Elsevier.

Kumar, A., Singh, R., Yadav, A., Giri, D., Singh, P., & Pandey, K. D. (2016). Isolation and characterization of bacterial endophytes of Curcuma longa L. 3 Biotech, 6(1), 60.

Kumar, M. S., Reddy, G. C., Phogat, M., & Korav, S. (2018). Role of bio-fertilizers towards sustainable agricultural development: A review. Journal of Pharmacognosy and Phytochemistry, 7(6), 1915-1921.

Kusale, S. P., Attar, Y. C., Sayyed, R., Malek, R. A., Ilyas, N., Suriani, N. L., Khan, N., & El Enshasy, H. A. (2021). Production of plant beneficial and antioxidants metabolites by Klebsiella variicola under salinity stress. Molecules, 26(7), 1894.

Lei, X., Shen, Y., Zhao, J., Huang, J., Wang, H., Yu, Y., & Xiao, C. (2023). Root exudates mediate the processes of soil organic carbon input and efflux. Plants, 12(3), 630.

Liang, J.-L., Liu, J., Jia, P., Yang, T.-t., Zeng, Q.-w., Zhang, S.-c., Liao, B., Shu, W.-s., & Li, J.-t. (2020). Novel phosphate-solubilizing bacteria enhance soil phosphorus cycling following ecological restoration of land degraded by mining. The ISME journal, 14(6), 1600-1613.

Liu, C., Chen, L., He, Z., Zhang, Z., Xu, Y., Li, Z., Peng, Y., Deng, N., & Chen, Y. (2021). Integration and potential application ability of culturable functional microorganism in oil tea Camellia. Indian journal of microbiology, 61(1), 1-9.

Liu, C., Feng, X., Xu, Y., Kumar, A., Yan, Z., Zhou, J., ... & Zang, H. (2023). Legume-based rotation enhances subsequent wheat yield and maintains soil carbon storage. Agronomy for Sustainable Development, 43(5), 64.

Mahankale, N. R. (2024). RETRACTED ARTICLE: Global influence of synthetic fertilizers on climate change. Applied Geomatics, 16(1), 317-317.

Mahanty, T., Bhattacharjee, S., Goswami, M., Bhattacharyya, P., Das, B., Ghosh, A., & Tribedi, P. (2017). Biofertilizers: a potential approach for sustainable agriculture development. Environmental Science and Pollution Research, 24(4), 3315-3335.

Malik, K. M., Khan, K. S., Billah, M., Akhtar, M. S., Rukh, S., Alam, S., Munir, A., Mahmood Aulakh, A., Rahim, M., & Qaisrani, M. M. (2021). Organic amendments and elemental sulfur stimulate microbial biomass and sulfur oxidation in alkaline subtropical soils. Agronomy, 11(12), 2514.

Market Report Analytics. (2025, August 24). Exploring Biofertilizer Market Evolution 2025-2033 [Report]. Retrieved from https://www.marketreportanalytics.com/reports/biofertilizer-market-399026# .

Marzouk, S. H., Kwaslema, D. R., Omar, M. M., & Mohamed, S. H. (2025). " Harnessing the power of soil microbes: Their dual impact in integrated nutrient management and mediating climate stress for sustainable rice crop production" A systematic review. Heliyon, 11(1).

Meena, V. S., Bahadur, I., Maurya, B. R., Kumar, A., Meena, R. K., Meena, S. K., & Verma, J. P. (2016). Potassium-solubilizing microorganism in evergreen agriculture: an overview. Potassium solubilizing microorganisms for sustainable agriculture, 1-20.

Mishra, J., & Arora, N. K. (2016). Bioformulations for plant growth promotion and combating phytopathogens: a sustainable approach. In Bioformulations: For sustainable agriculture (pp. 3-33). Springer.

Mukherjee, A., Gaurav, A., Singh, S., Yadav, S., Bhowmick, S., Abeysinghe, S., & Verma, J. (2022). The bioactive potential of phytohormones: a review. Biotechnol Rep 35: e00748. In.

Nagachandrabose, S. (2018). Liquid bioformulations for the management of root-knot nematode, Meloidogyne hapla that infects carrot. Crop Protection, 114, 155-161.

Neal, A. L., Blackwell, M., Akkari, E., Guyomar, C., Clark, I., & Hirsch, P. R. (2018). Phylogenetic distribution, biogeography and the effects of land management upon bacterial non-specific Acid phosphatase Gene diversity and abundance. Plant and Soil, 427(1), 175-189.

Nitu, R., Rajinder, K., & Sukhminderjit, K. (2020). Zinc solubilizing bacteria to augment soil fertility—A comprehensive review. Int. J. Agric. Sci. Vet. Med, 8(1), 38-44.

Nosheen, S., Ajmal, I., & Song, Y. (2021). Microbes as biofertilizers, a potential approach for sustainable crop production. Sustainability, 13(4), 1868.

Pandey, K., & Saharan, B. S. (2025). Potassium-solubilizing endophytes: mechanisms and applications in enhancing sustainable agriculture and plant resilience. Symbiosis, 1-15.

Prakash, J., & Arora, N. K. (2020). Development of Bacillus safensis-based liquid bioformulation to augment growth, stevioside content, and nutrient uptake in Stevia rebaudiana. World Journal of Microbiology and Biotechnology, 36(1), 8.

Ranadev, P., Revanna, A., Bagyaraj, D. J., & Shinde, A. H. (2023). Sulfur oxidizing bacteria in agro ecosystem and its role in plant productivity—a review. Journal of Applied Microbiology, 134(8), lxad161.

Rani, N., Chauhan, A., Kaur, S., Solanki, M. K., Tripathi, M., Jain, D., Singh, S., Upadhyay, S. K., & Kaur, G. (2025). Molecular mechanistic of Zn-solubilizing bacteria for agronomic eminence: recent updates and futuristic development. Journal of Plant Growth Regulation, 44(4), 1337-1351.

Rehman, S. U., De Castro, F., Aprile, A., Benedetti, M., & Fanizzi, F. P. (2023). Vermicompost: Enhancing plant growth and combating abiotic and biotic stress. Agronomy, 13(4), 1134.

Rehman, S. U., De Castro, F., Marini, P., Aprile, A., Benedetti, M., & Fanizzi, F. P. (2023). Vermibiochar: A novel approach for reducing the environmental impact of heavy metals contamination in agricultural land. Sustainability, 15(12), 9380.

Rehman, S. U., De Castro, F., Aprile, A., Benedetti, M., & Fanizzi, F. P. (2025). Influence of Vermicompost Tea on Metabolic Profile of *Diplotaxis muralis*: An NMR Spectroscopic Analysis. Environments, 12(10), 366.

Rezvani Boroujeni, S., Kalbasi, M., Asgharzadeh, A., & Baharlouei, J. (2021). Evaluating the potential of Halothiobacillus bacteria for sulfur oxidation and biomass production under saline soil. Geomicrobiology Journal, 38(1), 57-65.

Rezvani Boroujeni, S., Kalbasi, M., Asgharzadeh, A., & Baharlouei, J. (2021). Evaluating the potential of Halothiobacillus bacteria for sulfur oxidation and biomass production under saline soil. Geomicrobiology Journal, 38(1), 57-65.

Richa. (2024). Metabolite-based Bioformulation: Next Generation of Biofertilizers. In Metabolomics, Proteomics and Gene Editing Approaches in Biofertilizer Industry: Volume II (pp. 53-81). Springer.

Rostaei, M., Fallah, S., Carrubba, A., & Lorigooini, Z. (2024). Organic manures enhance biomass and improve content, chemical compounds of essential oil and antioxidant capacity of medicinal plants: A review. Heliyon, 10(17).

Roy, S., Liu, W., Nandety, R. S., Crook, A., Mysore, K. S., Pislariu, C. I., Frugoli, J., Dickstein, R., & Udvardi, M. K. (2020). Celebrating 20 years of genetic discoveries in legume nodulation and symbiotic nitrogen fixation. The Plant Cell, 32(1), 15-41.

Saharan, B. S., & Nehra, V. (2011). Plant growth promoting rhizobacteria: a critical review. Life Sci Med Res, 21(1), 30.

Sajjad, M., Hussain, K., Wajid, S. A., & Saqib, Z. A. (2024). The impact of split nitrogen fertilizer applications on the productivity and nitrogen use efficiency of rice. Nitrogen, 6(1), 1.

Sajjad, M., Hussain, K., Hakki, E. E., Ilyas, A., Gezgin, S., & Shakil, Q. (2025). Impact of Irrigation Techniques on Water-Use Efficiency, Economic Returns, and Productivity of Rice. Sustainability, 17(17), 7712.

Samantaray, A., Chattaraj, S., Mitra, D., Ganguly, A., Kumar, R., Gaur, A., ... & Thatoi, H. (2024). Advances in microbial based bio-inoculum for amelioration of soil health and sustainable crop production. Current Research in Microbial Sciences, 7, 100251.

Sammauria, R., Kumawat, S., Kumawat, P., Singh, J., & Jatwa, T. K. (2020). Microbial inoculants: potential tool for sustainability of agricultural production systems. Archives of microbiology, 202(4), 677-693.

Sandhu, N., Sethi, M., Kumar, A., Dang, D., Singh, J., & Chhuneja, P. (2021). Biochemical and genetic approaches improving nitrogen use efficiency in cereal crops: a review. Frontiers in plant science, 12, 657629.

Santos, H. L., Silva, G. F. d., Carnietto, M. R. A., Oliveira, L. C., Nogueira, C. H. d. C., & Silva, M. d. A. (2022). Bacillus velezensis associated with organomineral fertilizer and reduced phosphate doses improves soil microbial—Chemical properties and biomass of sugarcane. Agronomy, 12(11), 2701.

Sethi, G., Behera, K. K., Sayyed, R., Adarsh, V., Sipra, B., Singh, L., Alamro, A. A., & Behera, M. (2025). Enhancing soil health and crop productivity: the role of zinc-solubilizing bacteria in sustainable agriculture. Plant Growth Regulation, 1-17.

Shahwar, D., Mushtaq, Z., Mushtaq, H., Alqarawi, A. A., Park, Y., Alshahrani, T. S., & Faizan, S. (2023). Role of microbial inoculants as bio fertilizers for improving crop productivity: A review. Heliyon, 9(6).

Shakeel, A., Anjum, L., Ibni Zamir, S., Rizwan, M., Arshad, M., Mehmood, Q., ... & Waqas, A. (2021). Irrigation water quality effects on CO2 emissions along with crop and soil responses. Pakistan Journal of Agricultural Sciences, 58(2), 637-642.

Shukla, S., Didwania, N., & Choudhary, R. (2025). Arbuscular mycorrhizal fungi (AMF): a pathway to sustainable soil health, carbon sequestration, and greenhouse gas mitigation. Journal of the Saudi Society of Agricultural Sciences, 24(4), 22.

Singh, A. K., Singh, J. B., Singh, R., Kantwa, S. R., Jha, P. K., Ahamad, S., Singh, A., Ghosh, A., Prasad, M., & Singh, S. (2023). Understanding soil carbon and phosphorus dynamics under grass-legume intercropping in a semi-arid region. Agronomy, 13(7), 1692.

Singh, P., Arif, Y., Miszczuk, E., Bajguz, A., & Hayat, S. (2022). Specific roles of lipoxygenases in development and responses to stress in plants. Plants, 11(7), 979.

Singh, S., Chhabra, R., Sharma, A., & Bisht, A. (2024). Harnessing the power of zinc-solubilizing bacteria: a catalyst for a sustainable agrosystem. Bacteria, 3(1), 15-29.

Skrzypczak, D., Pstrowska, K., Niciejewska, A., Mazur-Nowacka, A., Wilk, Ł., & Chojnacka, K. (2025). Catalytic innovations in fertilizer production from agricultural waste: Enhancing soil health and sustainability. Applied Catalysis O: Open, 207064.

Son, Y., Martínez, C. E., & Kao-Kniffin, J. (2024). Three important roles and chemical properties of glomalin-related soil protein. Frontiers in Soil Science, 4, 1418072.

Sood, Y., Singhmar, R., Singh, V., & Malik, D. K. (2023). Isolation and characterization of potential potassium solubilizing bacteria with various plant growth promoting traits. Biosciences Biotechnology Research Asia, 20(1), 79-84.

Soumare, A., Diedhiou, A. G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., & Kouisni, L. (2020). Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. Plants, 9(8), 1011.

Sumbul, A., Ansari, R. A., Rizvi, R., & Mahmood, I. (2020). Azotobacter: A potential bio-fertilizer for soil and plant health management. Saudi journal of biological sciences, 27(12), 3634-3640.

Sun, J., Niu, W., Du, Y., Ma, L., Huang, S., Mu, F., ... & Siddique, K. H. (2024). Regionally adapted conservation tillage reduces the risk of crop yield losses: A global meta-analysis. Soil and Tillage Research, 244, 106265.

Tang, H., Xiao, X., Li, C., Shi, L., Cheng, K., Li, W., ... & Wang, K. (2021). Microbial carbon source utilization in rice rhizosphere soil with different tillage practice in a double cropping rice field. Scientific Reports, 11(1), 5048.

Thomas, L., & Singh, I. (2019). Microbial biofertilizers: types and applications. In Biofertilizers for sustainable agriculture and environment (pp. 1-19). Springer.

Umesha, S., Singh, P. K., & Singh, R. P. (2018). Microbial biotechnology and sustainable agriculture. In Biotechnology for sustainable agriculture (pp. 185-205). Elsevier.

Upadhayay, V. K., Singh, A. V., & Khan, A. (2022). Cross talk between zinc-solubilizing bacteria and plants: A short tale of bacterial-assisted zinc biofortification. Frontiers in Soil Science, 1, 788170.

Upadhayay, V. K., Singh, A. V., & Pareek, N. (2018). An insight in decoding the multifarious and splendid role of microorganisms in crop biofortification. Int. J. Curr. Microbiol. Appl. Sci, 7(6), 2407-2418.

Vasave, J., Dudhat, M., Parmar, V., Sisodiya, R., & Deshmukh, S. (2024). Bio-Fertilizers: Harnessing Nature's Power for Sustainable Agriculture. Agronomy, 29.

Vassilev, N., Vassileva, M., Martos, V., Garcia del Moral, L. F., Kowalska, J., Tylkowski, B., & Malusá, E. (2020). Formulation of microbial inoculants by encapsulation in natural polysaccharides: focus on beneficial properties of carrier additives and derivatives. Frontiers in plant science, 11, 270.

Wakeel, A., & Ishfaq, M. (2021). Potassium in plants. In Potash Use and Dynamics in Agriculture (pp. 19-27). Springer.

Wang, R., Lin, J.-Q., Liu, X.-M., Pang, X., Zhang, C.-J., Yang, C.-L., Gao, X.-Y., Lin, C.-M., Li, Y.-Q., & Li, Y. (2019). Sulfur oxidation in the acidophilic autotrophic Acidithiobacillus spp. Frontiers in Microbiology, 9, 3290.

Wong, C. K. F., & Teh, C. Y. (2021). Impact of biofertilizers on horticultural crops. Biofertilizers: Study and Impact, 39-103.

Wu, Z., Li, X., Liu, X., Dong, J., Fan, D., Xu, X., & He, Y. (2020). Membrane shell permeability of Rs-198 microcapsules and their ability for growth promoting bioactivity compound releasing. RSC Advances, 10(2), 1159-1171.

Yadav, K. K., & Smritikana Sarkar, S. S. (2019). Biofertilizers, impact on soil fertility and crop productivity under sustainable agriculture. Environment & Ecology, 89-93.

Yasuda, M., Dastogeer, K. M., Sarkodee-Addo, E., Tokiwa, C., Isawa, T., Shinozaki, S., & Okazaki, S. (2022). Impact of Azospirillum sp. B510 on the rhizosphere microbiome of rice under field conditions. Agronomy, 12(6), 1367.

Zaidi, A., Khan, M. S., Saif, S., Rizvi, A., Ahmed, B., & Shahid, M. (2017). Role of nitrogen-fixing plant growth-promoting rhizobacteria in sustainable production of vegetables: current perspective. In Microbial strategies for vegetable production (pp. 49-79). Springer.

Zhang, X., Liu, Z., Wei, G., Yang, F., & Liu, X. (2018). In silico genome-wide analysis reveals the potential links between core genome of Acidithiobacillus thiooxidans and its autotrophic lifestyle. Frontiers in Microbiology, 9, 1255.

Zhao, G., Zhu, X., Zheng, G., Meng, G., Dong, Z., Baek, J. H., Jeon, C. O., Yao, Y., Xuan, Y. H., & Zhang, J. (2024). Development of biofertilizers for sustainable agriculture over four decades (1980–2022). Geography and Sustainability, 5(1), 19-28.

15

FUNCTIONAL ANALYSIS OF WHEAT PRODUCTION IN TURKEY: THE CASE OF DIYARBAKIR PROVINCE

Mehmet Fırat Baran[1], Mehmet Hüseyin Demirel[2], Mükerrem Atalay Oral[3], Zubair Aslam[4]

1. Introductıon

Productivity is one of the most objective measures used to determine the level of economic growth and development of a country or a sector (Akyüz, 2015). In real terms, economic growth and development can be achieved by incorporating unused resources into production and transferring the currently used resources to more productive areas. This expresses an increase in productivity in general. With the narrow definition, efficiency is stated as an input-output relationship. In broad terms, efficiency expresses the relationship between the production that occurs as a result of the production factors and one or more of these factors. For this reason, it can be defined as the ratio between the amount of goods and services produced and the inputs used in the production of these goods and services.

Countries maintain their economic activities by distributing their limited production factors among different production branches. While carrying out production activities by using limited production factors, it is aimed to maximize the profits of the enterprises on a micro basis and the national income of the country on a macro basis. This is possible with the effective use of production factors reserved for production sectors in the country. In every production activity, the supply of production factors at the most affordable price and their optimum use both provide the sustainable use of natural resources and have a cost-reducing effect (Çelik and Bayramoğlu, 2007).

The physical and mechanical qualities of soils deteriorate due to intensive agricultural practices and increased mechanization, and this deterioration is sped up by the improper use of organic fertilizers and the excessive use of chemical fertilizers. It has become a necessity to investigate the physical and chemical properties of agricultural soils and to take appropriate management

1 Professor. Department of Biyosystems Engineering, Faculty of Agriculture, Siirt University, Siirt , Türkiye, firat.baran@siirt.edu.tr, https://orcid.org/0000-0002-7657-1227
2 Graduate student , Graduate School of Natural and Applied Sciences, Siirt University, Siirt, Türkiye, huseyindem14@gmail.com, https://orcid.org/0000-0001-9483-2489
3 Associated Professor. Elmalı Vocational School of Higher Education, Akdeniz University, Antalya, Türkiye, mukerrem@akdeniz.edu.tr, https://orcid.org/0000-0001-7960-1148
4 Professor, Plant and Microbial Ecology lab., Department of Agronomy, University of Agriculutre, Faisalabad, ORCID: 0000-0002-3094-9175. E-mail: zubair.aslam@uaf.edu.pk

measures for these properties in order to make sustainable production and to use the soil at an optimum level. For successful and sustainable use, it is essential to understand the fundamental properties of the soils, which serve as the foundation for all forms of agricultural output. It is feasible to enhance, develop, and protect the soil's physical, chemical, and biological qualities through sustainable agriculture. Today's agriculture needs to identify the fundamental characteristics of agricultural soils, assess them in light of the intended use in line with these characteristics, and forecast the behavior under any use (Ekberli and Kerimova, 2005; Tümsavaş and Aksoy, 2009; Gülser et al., 2010; Hossain et al., 2015; Gülser, 2016; Gülser et al., 2016; Dengiz and Ekberli, 2017; Lipiec and Usowicz, 2018; Kars and Ekberli, 2019a; Kars and Ekberli, 2019b, Kars and Ekberli, 2020).

Agriculture is the first sector of the economy, and the first professional occupation of mankind. The agricultural sector, like other sectors, performs numerous tasks in the socio-economic structure. Agriculture's contribution to population and employment emerges as production, nutrition, national income and export contribution, raw material supply to industry, transfer of production factors, and shaping the lifestyle of the region's people (Boz, 2004; Cinemre and Kılıç, 2015; Karadaş, 2016, Erbaş, 2020).

Wheat ranks first among the cultivated plants used in human nutrition in terms of cultivation and production in the world. This is because the wheat plant has a wide adaptability. Since it was originally domesticated, wheat has been used as the foundation for human and animal sustenance for 8000 years. In terms of total area cultivated, the wheat plant leads both Turkey and the entire world. Turkey is home to 3.5% of the world's wheat-growing regions (Altuner et al., 2019; Gözükara et al., 2022). Wheat is the main food source of approximately 35% of the world's population and provides 20% of the calories taken from all foods (Kün, 1996; Kars and Ekberli, 2019b). Wheat is used in many food and industrial sectors, especially in bakery products (Anonymous, 2021a). Wheat is strategically important in comparison to other products, particularly because it is the raw material for basic foods and is used in human nutrition. Wheat's nutritional value, as well as its ease of storage and processing, make it even more important. When wheat production falls, the price of bread and bakery products rises, affecting the entire society (Erbaş, 2020). Wheat grain is the main food source of approximately 50 countries due to its suitable nutritional value, easiness of storage and processing. Wheat provides approximately 20% of the total calories provided by plant-based foods to the world population and this rate is 53% in Turkey (Anonymous, 2021a). In addition, Turkey has a large population of farmers that cultivate the wheat plant, which is essential for human nutrition and health (Özçelik and Özer, 2006; Barlas et al., 2018).

World wheat production was around 766 million tons according to International Grain Council (IGC) 2020-2021 season data. Approximately 66% of the total wheat was produced by the top 10 wheat producing countries. China, which has been in the second place in wheat production for many years, is the world's greatest producer with 136 million tons of wheat production in the 2020/21 period, as a result of increasing its production and the decrease in production in the European Union. The European Union ranks second with 135.5 million tons, India ranks third with 107 million tons, and Turkey ranks tenth with 18.5 million tons (Anonymous, 2021b).

According to Turkish Statistical Institute data, Turkey's wheat cultivation area constituted 3.2% of the world wheat cultivation area by 2020-21 production season. This area also constituted 44% of the total cultivated grain area in Turkey. Turkey's wheat cultivation area is 68.5 million decares, and the top 10 provinces that compose 42% of this area are respectively; Konya, Ankara, Diyarbakır, Yozgat, Urfa, Sivas, Çorum, Tekirdağ, Mardin and Eskişehir (Anonymous, 2021a). Local productivity studies are necessary due to regional changes in meteorological, vegetative, and soil characteristics as well as the interplay of soil variables with regional aspects (Kırmızı and Tüfekçi, 1993). Diyarbakir province is one of the few provinces in Turkey in terms of grain. It ranks third in Turkey in terms of wheat production. Diyarbakır province ranks fourth (264 thousand hectares with 3.3% share) in Turkey in terms of wheat cultivation area, and ranks third (845 thousand tons, with 4.2% share) in terms of production (Pala et al., 2018).

The effective use of resources in the enterprises depends on examining the relationship between the input used and the product obtained. There is a requirement for studies on the use of inputs in terms of different production branches in agricultural enterprises. No research was encountered on the econometric analysis of the use of inputs in wheat production in the research region. From this point of view, in this study, a functional analysis of the input usage in wheat production enterprises in Diyarbakır province was done and it was tried to determine whether the production factors were used effectively or not.

2. Material and Methods

The main material of this study was the data obtained by surveys from agricultural enterprises producing wheat in the province of Diyarbakır, which was chosen as the research area. In the collection of the data required for the research, the survey forms prepared in line with the purpose of the subject were filled by the researchers by face-to-face interviews with the producers. In addition, it was utilized from the related researches, reviews, compilations and statistics.

Proportional sampling method formula was used to determine the number of producers surveyed. For a finite population, the sample volume was calculated according to the known or estimated proportion of those with a certain characteristic (Newbold, 1995). The number of enterprises surveyed was found as 175 with 5% margin of error and 95% confidence interval.

$$n = \frac{N.p(1-p)}{(N-1)\sigma^2 p + p(1-p)}$$

N = Population size (1064)

n = Sample size

p = Ratio of the studied feature in the main population

σ^2 p = The variance of the ratio (calculated according to a certain confidence interval and margin of error)

According to 95% confidence interval and 0.05 margin of error;

$Z_{a/2}\,\sigma_p = r$

$1.96\ \sigma_p = 0.05$

$\sigma_p = 0.02551$

In the functional analysis of wheat production, the relationship between the production amount and the inputs was determined. The variables included in the model are given below.

Y = Yield (kg ha^{-1})

X1 = Amount of seeds (kg ha^{-1})

X2 = Nitrogen fertilizer (kg ha^{-1})

X3 = Phosphorus fertilizer (kg ha^{-1})

X4 = Machinery (h ha^{-1})

X5 = Labor (h ha^{-1})

X6 = Pesticides (TL ha^{-1})

X7 = Fuel (l ha^{-1})

X8 = Wheat cultivation area (ha)

The Cobb-Douglas production function was applied in the econometric analysis of the above-mentioned variables. The purpose of applying this production model is to comply with the data obtained regarding the production activity, to provide easiness of calculation, to evaluate the obtained records statistically, and to provide a sufficient degree of freedom even when the data is scarce (Heady and Dillon, 1966).

Cobb-Douglas type function is in exponential form and is converted to linear form with logarithmic transformation (Karkacıer, 2001).

$Y = a.x_i^b$ (Exponential form) or

$Log\,Y = \log a + \beta_i \,.\, logx_i$ (Linear form)

In the function, "Y" expresses the dependent variable and "x_i" expresses the independent variables. The β coefficient shows the production elasticity of the independent variable and its total gives the return to scale. Return to scale indicates how much an increase in production will result in a one-unit increase in production factors in the long run. The results are evaluated as follows.

When e = 1, there is constant returns to scale,

When e < 1, there is decreasing returns to scale,

When e > 1, there is increasing returns to scale.

The data of the variables are converted into logarithmic values and the parameters a and b are calculated according to the Least Squares Method or the Maximum Likelihood Method. The equation is obtained by typing the calculated parameters in exponential form.

The marginal efficiency of the variables (Xi) used in production was calculated using the geometric averages from the Cobb-Douglas production function by using the following equation (Zoral, 1973).

$$Mpi = \beta i.Yi/Xi$$

X_i: the average of the production resource,

Y_i: the average of production output

If there are k variable resources in the production function, the average production is calculated for each resource. Since the logarithmic transformation is used in the Cobb-Douglas type or logarithmic production function, the mean of the X and Y's is the geometric mean. The marginal income is found by multiplying the marginal yield and the product price.

The following formula was used to calculate the efficiency coefficients of the factors (Karkacıer, 2001).

$$Efficiency\ coefficient = \frac{Marginal\ income}{Marginal\ cost}$$

If efficiency coefficient = 1, the factor is used effectively

If efficiency coefficient > 1, the factor is used less, factor usage should be increased.

If efficiency coefficient < 1, the factor is overused, factor usage should be reduced.

From the calculated production equation, the technical substitution rate (marginal technical substitution rate) between the factors, in other words, the amount of factor X2 versus to the amount of the factor X1 in order to obtain a production amount at the Y level is calculated by using the equation below.

$$a_{X1,X2} = \frac{\beta_2 . X1G}{\beta_1 . X2G}$$

In the formula, $\bar{X}_i$ is the geometric mean of the data of the variables.

If one of the two inputs has a negative and the other positive production elasticity, there is no substitution relationship between them. Therefore, substitution can be calculated between the factors which have the same coefficient signs. The marginal technical substitution rate between two factors consists of the marginal product value ratio found according to the geometric mean of these factors (Gündoğmuş, 1998).

Autocorrelation in the econometric model was analyzed with the Durbin-Watson test. The presence of multicollinearity was investigated using the Variance Inflation Factor (VIF) and Tolerance Value (TV) methods. When VIF is calculated equal to or greater than 10 (VIF≥10), there is a multicollinearity problem in the model (Pallant, 2005). Low VIF and high TV values are the main indicators of the absence of multicollinearity.

3. Research Results and Discussion

Descriptive statistics of the variables used in the production function are given in Table 1. In the research area, it was determined that an enterprise produced wheat on an average area of 1074.58 ha and obtained 5482.03 kg ha^{-1} from wheat production and in order to reach this production amount, 294.70 kg of seed, 120.93 kg of N, 127.93 kg of P, 4.47 h machinery, 5.40 h labor force, 47.90 l diesel fuel were used and 471.25 TL for pesticides was spent.

Table 1. Descriptive statistics of the variables used in the production function

Variables	Average	Standard deviation	Minimum	Maximum
Yield (kg ha^{-1})	5482.03	844.94	3500.00	6450.00
Seed (kg ha^{-1})	294.70	10.28	280.00	340.00
N (kg ha^{-1})	120.93	5.62	111.52	131.09
P (kg ha^{-1})	127.93	3.62	115.00	138.00
Machinery (h ha^{-1})	4.47	1.34	3.17	6.57
Labor (h ha^{-1})	5.40	0.57	4.30	7.60
Pesticides (TL ha^{-1})	612.36	158.91	345.00	747.50
Fuel (l ha^{-1})	47.90	3.43	41.20	63.00
Wheat cultivation area (ha)	1074.58	638.89	300.00	4000.00

The results of the regression analysis carried out to determine the effect levels of some inputs on the wheat production are given in Table 2. The equation related to the production function is given below as an exponential form.

$$Y = 4.515 * X_1^{-0.140} * X_2^{-1.048} * X_3^{0.756} * X_4^{0.050} * X_5^{-0.170} * X_6^{-0.342} * X_7^{0.329} * X_8^{-0.031}$$

The determination coefficient (R^2) of the production function was estimated as 0.500, and it can be said that the independent variables had the power to explain the wheat production amount by 50%, in other words, approximately 50% of the change in the wheat production value can be explained by the independent variables in the model. The F-test value showed that the regression model as a whole was significant at the 1% level. TV and VIF values indicated that there was no multicollinearity problem between the independent variables, and the Durbin-Watson d statistical value showed that there was no high-order relationship between the error terms of the dependent variables, in other words, there was no autocorrelation. Thus, it was determined that the model was chosen correctly and no specification error was made.

The sum of the coefficients of the model was found to be -0.596. This value indicated that there was a decreasing return to scale in wheat production enterprises. It was determined that if all production factors were increased by 1%, the amount of production would decrease by approximately 1.596%.

In the studies conducted in cotton production by Semerci and Çelik (2018) and Candemir (2021), it was determined that there was a decreasing return to scale in cotton enterprises, which was similar to the research result.

When the production elasticity of the independent variables were examined, it was seen that the inputs of seed (X1), nitrogen (X2), labor (X5), medicine (X6) and wheat cultivation area (X8) had production elasticity with negative signs, while other factors had production elasticity with positive signs. The negative sign of production elasticity in the production function showed that it was not possible to calculate the economic optimum by using this equation. However, it is possible to draw conclusions about which factor should be reduced or increased (Heady and Dillon, 1966; Zoral, 1973).

Although four of the explanatory variables of the model were found to be statistically significant, the other four variables were not significant. Nitrogen amount (N), phosphorus amount (P) and fuel amount variables were found to be statistically significant at the 1% significance level, and the pesticide price variable was statistically significant at 5% significance level.

It was determined that a 100% increase in the phosphorus (X3) and fuel (X7) variables would increase the yield by 75.6% and 32.9%, respectively, while a 100% increase in the use of nitrogen (X2) and pesticides (X6) would decrease the yield by 104.8% and 34.2%, respectively. Although this situation seems like a negative result, it can be explained by the law of diminishing returns, which is widely seen in agriculture. While other variables are constant, the increase in nitrogen and pesticides use will decrease the yield proportionally and absolutely after a certain extent. According to water and soil studies, one of the most significant issues limiting wheat production in producer settings is the lack of fertilization (Boling et al., 2010; Küçükçongar et al., 2014)

In the study conducted by Akar (2007) on wheat and sunflower production in the Thrace Region, a positive significant relationship was found between wheat and sunflower income and fertilizer costs, seed costs, labor costs and pesticides costs. In the study conducted by Çelik and Bayramoğlu (2007) on cotton production in Şanlıurfa province, a significant negative relationship was found between yield and pesticides use.

According to Erbaş's (2020) research, farmers produced an average of 216.73 kg of the main crop (wheat) and 221 kg of the by-product (straw) from 1 decare of land. Additionally, it was discovered that the producers spend 204.60 TL in total to produce 1 decare of wheat. It is recognized that 15.67% of production expenses are fixed costs and 84.33 % of them are made up of variable costs. The cost of producing 1 kg of wheat was 0.75 TL, while its selling price was 0.84 TL. The price to sell 1 kg of straw was calculated to be 0.19 TL. As a result, the production of decare wheat brought in a gross profit of 51.50 TL and a net profit of 19.44 TL for the producers. The proportional profit was found to be 1.10 TL. The producers do have positive gross and net profit from growing wheat, but this is insufficient.

In the study carried out by Ali and Khan (2014), results further showed that one percent increase in value of land under wheat crop, labor, chemical fertilizer and tractor plough would raise the wheat yield by 0.052, 0.566, 0.130 and 0.438 percent, respectively and were found statistically significant.

The costs of seed, fertilizer, irrigation, soil preparation, and labor were included in the study "The Effect of Various Factors on Wheat Production" by Iqbal et al. (2015) in Peshawar, Pakistan. As a consequence, it has been discovered that 35.2% of the total costs associated with producing wheat in the research area are spent on fertilizer, 30.30% on field rent, and 15.1% on soil preparation. Mehrjerdi and Mark (2018) determined that fertilizer-related variables had positive signs on wheat yield and were also statistically significant. This implied as the fertilizer usage increased wheat productivity also increased. In the study conducted by Candemir (2021) on cotton production in Kahramanmaraş, while the variables of fertilizer costs and fuel costs, which were explanatory variables in the model, were found to be statistically significant, the variables of labor, pesticide, seed and equipment rental costs were found to be insignificant. The cost of fertilizer, irrigation, and machinery use was found to have a substantial impact on the price of wheat production in the study carried out by Zhang et al. (2016) in China. Additionally, it was claimed that modeling and optimization applications based on Cooperate Environmental Sustainability (CES) decreased the costs of fertilizer and pesticides by 42.83 % and 21.41 %, respectively. The analysis of the physical and chemical characteristics of the soils is typically related to the determination and use of various agricultural methods in raising the productivity level of wheat crops (Cantero-Martinez et al., 2007; Gursoy et al., 2010; Machado et al., 2007; Ozdemir et al., 2014).

Table 2. Regression analysis results

Variables	Coefficient	Standard error	T value	P value	TV	VIF
Constant	4.515	0.953	4.737	0.000***		
Seed (kg ha^{-1})	-0.140	0.276	-0.507	0.613	0.777	1.286
N (kg ha^{-1})	-1.048	0.214	-4.911	0.000***	0.813	1.230
P (kg ha^{-1})	0.756	0.285	2.658	0.009***	0.843	1.186
Machinery (h ha^{-1})	0.050	0.114	0.440	0.661	0.524	1.908
Labor (h ha^{-1})	-0.170	0.123	-1.381	0.169	0.481	2.081
Pesticides (TL ha^{-1})	-0.342	0.134	-2.551	0.012**	0.845	1.184
Fuel (l ha^{-1})	0.329	0.034	9.689	0.000***	0.814	1.228
Wheat cultivation area (ha)	-0.031	0.021	-1.481	0.140	0.672	1.021
R^2	0.500					
F test	20.584***					
Durbin-Watson d	1.917***					

*** p<0.01, ** p<0.05, * p<0.10

The marginal yields of the factors whose effects on wheat production were investigated are given in Table 3. As can be seen from the table, the amount of phosphorus (X3) variable had the highest marginal yield followed by the amount of fuel (X7). The negative signs of the seeds, nitrogen, labor, pesticides and cultivation area indicated that these inputs were overused.

The marginal income used in the calculation of the efficiency coefficients was found by multiplying the marginal yield of the factors by the product price. When the marginal incomes of the production factors were examined, as in the marginal yield values, the highest marginal income was in the phosphorus amount input, followed by the fuel amount input. Considering the efficiency coefficients, -0.14 for seed amount (X1), -2.88 for nitrogen amount (X2), 1.94 for phosphorus amount (X3), 0.08 for machinery (X4), -2.12 for labor (X5), -0.30 for pesticides (X6). 0.50 for fuel (X7) and -0.01 for area (X8). The use of factors less than 1 according to the efficiency coefficient should be reduced and the use of factors greater than 1 should be increased. In this case, it was determined that seed, nitrogen, labor, pesticides and cultivation area variables were used excessively due to the negative signs. The efficiency coefficient of the phosphorus amount variable was greater than 1. This indicated that the use of phosphorus for wheat production was insufficient in the region. In other words, it should be regarded to the use of fertilizer according to the type and amount of fertilizer in the period the plant needed.

Table 3. Marginal values and efficiency coefficients of the model coefficients

Y = 660.21	Seed (X1)	Nitrogen (X2)	Phosphorus (X3)	Machinery (X4)	Labor (X5)	Pesticides (X6)	Fuel (X7)	Area (X8)
Geometric mean	2.47	2.08	2.11	0.64	0.73	2.77	1.68	2.96
Marginal yield	-37.43	-332.33	236.91	51.18	-154.54	-81.58	129.40	-6.91
Marginal income	-82.35	-731.12	521.20	112.60	-339.98	-179.48	284.67	-15.19
Marginal cost (factor prices)	589.14	253.68	268.57	1500.00	160.20	589.42	572.89	2000.00
Marginal efficiency coefficient	-0.14	-2.88	1.94	0.08	-2.12	-0.30	0.50	-0.01

Marginal technical substitution rates are given in Table 4. According to the estimated results, while other explanatory factors of the production function were used at the same level, in order to achieve the same production level, a decrease of 8.88 units in nitrogen amount, 4.13 units in labor, 2.18 units in pesticide prices and 0.18 units in planting area should be made in return for one unit increase in seed amount. Again, a one-unit increase in nitrogen required a 0.47 reduction in labor, 0.25 in pesticide price, and 0.02 in planting area. If the amount of phosphorus was increased by one unit, a restriction of 0.22 units from the machinery and 0.55 units from the amount of fuel would be required in order to achieve the same production level. Besides, a decrease of 2.53 units in fuel amount for one unit increase in machinery; a decrease of 0.53 units in pesticide prices and 0.04 units in cultivation area for a one-unit increase in the labor and a decrease of 0.08 units in the cultivation area for one-unit increase in the pesticide's prices were required.

Table 4. Marginal technical substitution rates between the factors

	Seed (X1)	Nitrogen (X2)	Phosphorus (X3)	Machinery (X4)	Labor (X5)	Pesticides (X6)	Fuel (X7)	Area (X8)
Seed (X1)		8.88			4.13	2.18		0.18
Nitrogen (X2)					0.47	0.25		0.02
Phosphorus (X3)				0.22			0.55	
Machinery (X4)							2.53	
Labor (X5)						0.53		0.04
Pesticides (X6)								0.08

4. Conclusion

In this study, the Cobb-Douglas production function was used to analyze the functional relationship between the inputs used in wheat production and the production obtained. Among the variables in the model, nitrogen, phosphorus and fuel variables were found to be significant at the level of 1%, and the pesticide variable at the level of 5%. According to the efficiency analysis results, it was seen that the use of seeds, nitrogen, labor, pesticides was high, and the use of phosphorus was insufficient.

According to the analysis results, it was observed that the use of fertilizers and pesticides were effective on the wheat yield, and this can be interpreted as the producers' use of fertilizers and pesticides according to their own experiences. In fertilizer and pesticide applications, not only the amount of input used, but also factors such as application time and type are important. Receiving different amounts of products with the same inputs suggests that some problems have been encountered in the application of the inputs and the timing of the applications. Publishers can be effective in reducing such wastes in the use of the inputs.

Since chemical fertilizers are the agricultural inputs that concern almost all segments, it is a subject that needs to be examined and planned very well. Chemical fertilizers consumed in Turkey are often used without any analysis or expert opinion. In addition, the less known or unknown fertilizer application times and methods lead to incorrect fertilizer use. Balanced fertilization based on soil plant analysis will positively affect the production amount and the negative effects of fertilizers on the environment will be minimal. All producers should be obliged to have soil analysis, the supports should be conditional on soil analysis, and the necessary opportunities should be created for free soil analysis. As a result, the first steps required for sustainable agriculture will be taken with the help of these practices and procedures.

References

Akar, G. 2007. Economic analysis of fertilizer usage in Thrace Region Master's thesis. Trakya University Graduate School of Natural and Applied Sciences, Department of Agricultural Economics – Tekirdağ.

Akyüz, L. 2015. Public institutional structure of France and the Netherlands in the field of agriculture and their comparison to Turkey (Fransa ve Hollanda'nın tarımsal kamu teşkilat yapıları ve Türkiye ile karşılaştırılması). EU Expertise thesis. Ministry of Food, Agriculture and Livestock–Ankara.

Ali, S. and M. Khan. 2014. Technical efficiency of wheat production in District Peshawar, Khyber Pakhtunkhwa, Pakistan. Sarhad Journal of Agriculture 30(4): 433-441.

Altuner, F., Oral, E., & Ülker, M. (2019). The place of wheat farming in Van province in Turkey and the region, its problems, and proposed solutions. Yüzüncü Yıl University Journal of Agricultural Sciences, 29(2), 339-351. https://doi.org/10.29133/yyutbd.495652.

Anonymous. 2021a. Wheat farming (Buğday tarımı). Available at https://arastirma.tarimorman.gov.tr/ktae/Belgeler/brosurler/Bu%C4%9Fday%20 Tar%C4%B1m%C4%B1.pdf

Anonymous. 2021b. Wheat production amounts (Buğday üretim miktarları). Available at https://fdc.nal.usda.gov/

Barlas, N.T., Cönkeroğlu, B., Unal, G. and Bellitürk, K., 2018. The Effect of Different Vermicompost Doses on Wheat (*Triticum vulgaris* L.) Nutrition. Journal of Tekirdag Agricultural Faculty (JOTAF), 15 (2): 1-4.

Boling, A. A., Tuong, T.P., Van Keulen, H., Bouman, B. A. M., Suganda, H., & Spiertz, J. H. J. (2010). Yield gap of rainfed rice in farmers' fields in Central Java. Indonesia. Agricultural Systems, 103(5), 307-315. https://doi.org/10.1016/j.agsy.2010.02.003.

Boz, İ. 2004. The Role of the Agricultural Sector in Economic Development. In: Development Economics: Selected Topics, Ed: Sami Taban-Muhsin Kar, Ekin Kitabevi Yayınları, Bursa, ss (137-158).

Candemir, S. 2021. Efficiency and functional analysis of cotton production in Turkey: Case of Kahramanmaraş Province. Custos e @gronegócio on line 17(2): 100-122.

Cantero-Martinez C, Angas P, Lampurlanes J (2007). Long-term yield and water use efficiency under various tillage systems in Mediterranean rainfed conditions. Annals of Applied Biology 150: 293–305.

Cinemre H.A. and Kılıç, O., 2015. Tarım Ekonomisi. Ondokuz Mayıs Üniversitesi Ziraat Fakültesi, Ders Kitabı No:11 (5.baskı), Samsun, s:179.

Çelik, Y., and Z. Bayramoğlu. 2007. Functional analysis of cotton in the Harran Plain of Şanlıurfa province. Journal of Agriculture Faculty of Selçuk University. 21(41): 42-50.

Dengiz O, Ekberli İ, 2017. Investigation of the physicochemical and thermal properties of some vertisol sub-group soils. Academic Journal of Agriculture, 6(1): 45-52.

Ekberli İ, Kerimova E, 2005. Changes in certain physical-chemical parameters of irrigated clay soil in the Shirvan region of Azerbaijan. Journal of the Faculty of Agriculture, Ondokuz Mayıs University, 20(3): 54-59.

Erbaş, N. 2020. Cost Analysis of Winter Wheat (Triticum aestivum L.) Production in Agricultural Enterprises in Yozgat Province, Journal of the Institute of Science and Technology, 10 (2):1318-1328.

Heady, E.O., and J. L. Dillon. 1966. Agricultural Production Functions. Iowa State University Press, Ames, Iowa, USA.

Hossain MF, Chen W, Zhang Yu, 2015. Bulk density of mineral and organic soils in the Canada's arctic and sub-arctic. Information Processing in Agriculture, 2: 183-190.

Gülser C, Demir Z, İç S, 2010. Changes in some soil properties at different incubation periods after tobacco waste application. Journal of Envıronmental Biology, 31(5): 671-674.

Gülser C, 2016. Changes in soil physical properties with hazelnut husk and tobacco waste applications. VII International Scientific Agriculture Symposium, Agrosym 2016", 6-9 October, Jahorina, Bosnia and Herzegovina. Proceedings, pp. 2032-2036.

Gülser C, Ekberli İ, Candemir F, Demir Z, 2016. Spatial variability of soil physical properties in a cultivated field. Eurasian Journal of Soil Science, 5(3): 192-200.

Gündoğmuş, E. 1998. Functional analysis and calculating the production cost of winter wheat (*Triticum aestivum* L.) on the farms of Akyurt District of Ankara Province. Tr. J.of Agriculture and Foresty. 22(3): 251-260.

Gürsoy S, Sessiz A, Malhi SS (2010). Short-term effects of tillage and residue management following cotton on grain yield and quality of wheat. Field Crops Research, 119: 260- 268.

Gözükara, G., Kutlu, İ. & Gülmezoğlu, N. (2022). Determination of the Productivity Status of Wheat-Growing Soils in the Brown and Brown Forest Major Soil Groups of Eskişehir Province. International Journal of Agricultural and Wildlife Sciences, 8 (1), 119-132. DOI: 10.24180/ijaws.982684.

Iqbal M, Fahim M, Zaman Q, Usman M, 2015. Effect of various factors on wheat production. National Agricultural Research Centre, Islamabad, Pakistan. https://agris.fao.org/agris-search/index.do, (date of Access 17.08.2022).

Karadaş K, 2016. Calculation of Wheat Production Costs in Agricultural Enterprises in Ağrı Province. Alınteri Journal of Agricultural Sciences, 31 (B)-2016, 33-31, Kastamonu

Karkacıer, O. 2001. Functional Analyses Related to the Field of Agricultural Economics and Some Quantitative Findings That Can Be Derived from These Analyses. Gaziosmanpaşa University Faculty of Agriculture Publications. Number: 49. Tokat

Kars N, Ekberli İ, 2019a. Examination of certain physical and chemical soil properties of cultivated agricultural areas in Çarşamba Plain. Journal of Agricultural Sciences of Anatolia, 34: 210-219.

Kars, N., Ekberli, İ. 2019b. Investigation of Some Physical and Chemical Properties of Soils Under Wheat Crops in the Çarşamba Plain. Soil Water Journal, 2019, 8 (1), 18-28.

Kars, N., Ekberli, İ. (2020). Determining the productivity status of agricultural areas where soybeans are grown in Çarşamba Plain. Journal of Soil Science and Plant Nutrition, 8 (1), 14-25. DOI: 10.33409/tbbbd.756822.

Kün, E. 1996. Grains-I Cool Climate Grains. Ankara University Faculty of Agriculture Publications, publication number:1451, Ankara.

Küçükçongar, M., Kan, M., & Özdemir, F. (2014). The use of direct seeding in wheat farming and determining farmer opinions: The case of Konya Province. Bahri Dağdaş Journal of Plant Research, 1(1-2), 26-35.

Lipiec J, Usowicz B, 2018. Spatial relationships among cereal yields and selected soil physical and chemical properties. Science of the Total Environment, 633: 1579-1590.

Machado S, Petrie S, Rhinhart K, Qu A (2007). Long-term continuous cropping in the Pacific Northwest: tillage and fertilizer effects on winter wheat, spring wheat, and spring barley production. Soil and Tillage Research 94, 473–481.

Mehrjerdi, M.H., and T. Mark. 2018. Estimating the productivity of wheat production: an implication of stochastic frontier production function model. Invited presentation at the 2018 Southern Agricultural Economics Association Annual Meeting, February 2-6, 2018, Jacksonville, Florida.

Newbold, P. 1995. Statistics for Business and Economics. Prentice-Hall International, New Jersey.

Özçelik, A, Özer, O.O, 2006. Analysis of the Relationship Between Wheat Production and Price in Turkey Using the Koyck Model. Ankara University Faculty of Agriculture Journal of Agricultural Sciences,12(4), 333-339, Ankara.

Özdemir Ö, Gülser C, Ekberli İ, Kop ÖT (2014). Effects of acid soil conditioning practices on certain soil properties and yields. / Journal of Soil Science and Plant Nutrition, 2(1): 27- 32.

Pala, F., Mennan, H., Çığ, F. and H. Dilmen. 2018. Determination of weed seeds mixed with wheat product in Diyarbakır. Turk J. Agric Res. 5(3): 183-190. DOI: 10.19159/tutad.342885

Pallant, J. 2005. SPSS Survival Manual: A Step-by-Step Guide to Data Analysis Using SPSS for Windows. 3rd Edition, Open University Press, New York.

Semerci, A. and A. D. Çelik. 2018. Functional analysis of cotton production in Hatay province. Journal of Tekirdağ Agricultural Faculty. 15(2): 78-86.

Tümsavaş Z, Aksoy E, 2009. Determination of the fertility status of brown forest soils belonging to the large soil group. Journal of the Faculty of Agriculture, Uludağ University, 23(1): 93-104.

Zhang F, Zhan J, Zhang Q, Yan H, Sun Z, 2016. Allocating agricultural production factors: A scenario-based modeling of wheat production in Shandong Province, China. Physics and Chemistry of the Earth, Parts A/B/C. Volume 96, December 2016, 55-63p.

Zoral, K.Y. 1973. Cobb-Douglas Application of the Production Function to Potato Production in the Yukarı Pasinler Plain. Atatürk University Faculty of Agriculture Publications No: 303, Ankara.

16

COVER CROPS FOR LIVESTOCK: LINKING SOIL HEALTH AND FORAGE NUTRITION

Muhammad Mahboob Ali Hamid[1], Kayahan Yılmaz[2]

1. Introduction

The current situation is that the combination of cover crops and livestock systems is the driving force for the new age of agriculture. This allows it to become not only a more environmentally-friendly alternative but also a more resilient. Cover crops are mostly plants other than those for direct harvesting, grown primarily to protect and enrich the soil, and thus they contribute significantly to propagating these benefits (Snapp et al., 2019). Given that the global livestock sector is increasingly challenged by climate change, soil erosion, and feed shortages, the ability of cover crops to serve as both soil regenerators and feed resources has been a topic of extensive discussion in research and practice (Finney et al., 2017; Blanco-Canqui et al., 2020).

The Food and Agriculture Organization (FAO, 2022) states that cover crops are currently used on less than 5% of total cropland in South Asia. However, the area is said to have the most significant potential to enhance soil fertility through the use of leguminous species such as Vicia sativa (common vetch) and Trifolium alexandrinum (berseem clover).

On a holistic scale, the adoption of cover cropping practices is highly varied, with more conversions in developed regions like North America and Europe, where manufacturers are incentivized and the state has conservation policies supporting their use (USDA-NRCS, 2023). On the contrary, the application of such combination cropping systems in poor countries has yet to be widely expanded, but it is advancing rapidly.

So, these plants not only bolster soil nitrogen levels but also provide high-protein forage for ruminants, which, in turn, minimizes reliance on expensive concentrate feeds (Raza et al., 2021).

The incorporation of cover crops into crop-livestock systems in Pakistan is also increasing, especially in the Punjab and Sindh regions. Ahmad et al. (2020) conducted a study that revealed the benefits of sowing berseem clover and oats (Avena sativa) in the rotation. In addition, it has been proven that these cover

1 Animal Nutrition Study Program, Institute of Animal and Dairy Sciences, Faculty of Animal Husbandry, University of Agriculture, Faisalabad 38040, Punjab, Pakistan, dr.mmahboob@uaf.edu.pk, ORCID: https://orcid.org/0000-0002-1109-5469

2 Tekirdağ Namık Kemal University, Faculty of Agriculture, Department of Animal Science, Tekirdağ, Türkiye. ORCID ID: 0000-0001-6899-5663, E-mail: kyilmaz@nku.edu.tr

crops would increase soil organic carbon by about 18% and, as a result, dairy cows' milk yield would increase by about 12% compared to conventional fallow systems. Nevertheless, the implementation of these practices is still hindered to some extent by knowledge deficiencies, the absence of policy incentives, and competing land priorities (Hassan et al., 2023).

2. Theoretical Foundation and Principles

As an auxiliary component of the agricultural ecosystem, cover crops provide biophysical, chemical, and biological processes that enhance soil productivity and forage quality. The idea of the project relies on the ecological rule of permanent soil cover, which is to decrease soil erosion, preserve soil organic matter, and to recover microbe biodiversity (Blanco-Canqui et al., 2015). Due to the extreme differences with annual multiple-use plants, which are harvested for commercial purposes, cover crops are basically only sown as a green manure for the soil fertility improvement during the fallow time or between cropping seasons after the plants have been harvested and are left alone for the period of time.

Soil Health Restoration Mechanisms

Cover crops play a crucial role in promoting soil structure and nutrient cycling. For instance, the leguminous plants, Trifolium alexandrinum (berseem clover) and Vicia sativa (vetch), are able to form a cooperative relationship with Rhizobium bacteria, which in turn, will fix nitrogen gas and increase the amount of nitrogen in the soil and decrease the use of synthetic fertilizers (Drinkwater & Snapp, 2021). This is particularly important in semi-arid and low-input systems, such as the mixed crop-livestock regions of Pakistan, where nitrogen-depleted soils are the main reasons for reduced crop and forage yields (Raza et al., 2021).

Root exudates of monocotyledons and legumes are not only the precursors of some types of readily decomposable organic substances but also the most effective microbial colonization stimulators. The soil microbial formation of these fungi causes the soil aggregates to be more stable due to the higher percentage of organic matter and are thus more effective in changing the soil's physical properties like porosity, infiltration, and water-holding capacity (Wang et al., 2022) employing root biomass decayed directly through roots in soil organic carbon accumulation, which is a crucial soil fertility and climate resilience marker (Blanco-Canqui & Wortmann, 2020). On the contrary, in livestock-integrated systems, organic matter returns through manure, directly supporting nutrient cycling and closing the loop between livestock feeding and soil regeneration (Poeplau & Don, 2015).

Forage Productivity and Nutritional Dynamics

In addition to their properties for increasing soil fertility, cover crops are also used as forages, becoming part of the livestock diet. The apparent quality of cover crops depends on mixing, maturity, and handling methods. A mixture of legumes as cover crops typically provides animals with 16-22% crude protein and low fiber content.

The supplementation of forage cover crops into the livestock diet not only improves milk quality and daily weight gain but also increases the efficiency of rumen microbial fermentation (Ketterings et al., 2021). To illustrate, the joint research that was carried out in India and Pakistan showed that berseemoats' rotations were the reason for the dairy cows grazing on 10-15% more milk than those under the standard winter fallow system, and simultaneously, the rise of soil nitrogen (Ahmad et al., 2020; Singh et al., 2021). The result demonstrates that both animal productivity and ecosystem function can be improved simultaneously, a key advantage of these systems.

Ecological and Agroecosystem Stability

From an environmental perspective, cover crops are indeed among the best methods for conserving energy and materials and strengthening systems, making them more resilient. Not only do the cover crop roots remain constantly active, reducing nutrient loss from leaching, but they also take up nitrogen left over from previous crops. Therefore, they play a role in mitigating environmental pollution (Basche et al., 2016). Also, the area under soil and the plant biomass, which contribute to soil erosion and dust emissions, are significant problems in semi-arid Southern Punjab and Sindh (Hassan et al., 2023).

3. Integrating Cover Crops in Livestock Systems

The livestock production systems have been transformed by cover crops which is the introduction of a new sustainable agricultural technique that integrates soil conservation, forage supply, and animal nutrition. Furthermore, new studies found out that cover crops are multifunctional as they are not just nutrient sources, they are also feed resources, and nutrient recyclers, and environmental buffers (Franzluebbers & Stuedemann, 2015; Finney et al., 2017). This collaboration has been especially favorable in crop-livestock systems that are run together since it makes it possible for the plant and animal components to function together in a very efficient manner thus increasing the resilience of the ecosystem.

Concept and System Design

Cover crop-livestock integration (CCLI) is a technique where cover crops like legumes or grass are used to get the grazing capacity, harvest, or incorporate the crop into the soil. This method assists in maintaining ground cover in winter time crops and also supplies feed to animals (Basche et al., 2016). The system's arrangement is determined by the different agricultural climatic conditions, cropping calendars, and animal species involved. For example, winter rye (Secale cereale) and hairy vetch (Vicia villosa), as used in temperate systems, are winter covers that cattle or sheep graze before planting in spring (Blanco-Canqui & Wortmann, 2020).

Conversely, these species are the leading winter annuals for plants in subtropical and semi-arid belts, such as berseem (Trifolium alexandrinum) or oat (Avena sativa), which are the ones that provide adequate fodder and consequently high biomass during the feed deficit period (Ahmad et al., 2020; Raza et al., 2021).

Such systems can only be effective if the timing is done right. Cover crops must integrate with the current rotation plan and should not pose any threat to the primary cash crops. Generally, winter legumes are seeded after kharif (summer) crops like maize or rice have been harvested, ensuring cover crops are seeded before the next crop cycle starts. They are then grazed or harvested for hay or silage before the next cropping cycle begins (Hassan et al., 2023). Paddock cropping with livestock improves nutrient recycling through manure deposition, thereby enhancing N balance and soil fertility for the subsequent crop (Sainju et al., 2019).

Forage Yield and Nutritional Value

The forage productivity of cover crops depends on the species, growth period, and management intensity. Table 1 illustrates the yield and nutritional characteristics of the most common cover crops utilized for livestock feed in different agroecological zones.

Table 1. Major Cover Crop Species for Livestock Feeding under Different Agroclimates

Agroclimate/ Region	Dominant Species	Crude Protein (%)	Dry Matter Yield (t ha^{-1})	Notable Benefits
Temperate (USA, EU)	Secale cereale (Rye), Vicia villosa (Hairy vetch)	13–18	4–7	Winter ground cover, soil nitrogen fixation
Mediterranean	Trifolium subterraneum, Lolium multiflorum	16–20	3–5	High-quality grazing, early spring growth
Semi-arid (Pakistan, India)	Trifolium alexandrinum, Avena sativa, Vicia sativa	14–22	6–10	Forage during the winter feed gap improves soil fertility
Tropical (Brazil, Sub-Saharan Africa)	Crotalaria juncea, Brachiaria ruziziensis	12–16	8–12	Nitrogen fixation, weed suppression
Highland (Ethiopia, Nepal)	Lablab purpureus, Pisum sativum	15–19	4–8	Drought resilience, smallholder livestock feed

Data compiled from Finney et al., 2017; Franzluebbers and Stuedemann, 2015; Ahmad et al., 2020; Raza et al., 2021; Silva et al., 2020; Souza et al., 2023; Mekonnen et al., 2022; Ketterings et al., 2021

The data powerfully demonstrate that leguminous cover crops, such as Trifolium and Vicia species, have higher protein content. In contrast, the grass species Avena sativa and Lolium multiflorum can produce more dry matter, which is a primary source of energy for them. These results are consistent with those obtained in the Punjab province of Pakistan, where the mixed oat–berseem system achieved a dry matter yield of 8.5–9.2 t ha^{-1} with crude protein levels exceeding 18% (Ahmad et al., 2020). These combinations not only help fill the feeding gap but also improve milk yield and animal performance, thereby positively affecting smallholder farmers.

Grazing Management and Soil Impacts

Animals grazing on cover crops are involved to create a dynamic feedback loop in the cycling of soil nutrients. Controlled grazing practices promote deposition of manure and urine on the soil surface; hence, there is an enhancement in the quantity of available nitrogen and biomass of the microbes (Wang et al., 2022). Nevertheless, there are issues when the rates of stocking is excessive or when grazing is performed on wet soils. Consequently, the soil is compacted, which destroys the soil structure and reduces the rate of infiltration. A study in the Midwest of the U.S. revealed that rotational grazing system had the soil bulk density in the optimal range (less than 1.45 g cm 3 -1), far greater than that in unrestricted grazing (Basche and the team, 2016).

In the canal-irrigated systems in Pakistan, the same has been observed. The stability of the soil that had an aggregation was enhanced by 12% when the livestock grazed on rotationally managed mixtures of berseem and oats. Meanwhile, comparison with continuous grazing has shown that the rates of infiltration have risen by 22 percent (Hassan et al., 2023). This is an obvious implication: in the case of livestock being handled, it can enhance the soil characteristics and not diminish them.

Nutrient Recycling and Ecosystem Benefits

Recycling of nutrients is the greatest advantage of integrated systems. Cover crops restore the soil the nutrients the earlier crops have left in the soil moving them into the roots and stems. Such nutrients are further devoured by animals or broken down in plants. Animals released manure in the course of grazing, which recycles these nutrients once more and completes the nutrient cycle (Drinkwater and Snapp, 2021). As per the estimates, through the combination of legumes and grasses, it is possible to recycle 80-100 kg N ha-1 annually with the help of grazing and incorporation of residues (Poeplau and Don, 2015).

Alongside, it is the role of the systems to reduce green house gas emissions by augmenting soil carbon capturing and cutting emissions of nitrous oxide linked to synthetic manure (Blanco-Canqui et al., 2020). The combined crop-livestock systems primarily serve as a sustainability tool, enhancing efficiency and productivity, reducing environmental footprints, and promoting farm resilience.

Regional Applications and Farmer Adoption

Although the advantages are evident, adoption rates vary considerably across different geographic areas. In Pakistan, research farms and some dairy units spearhead the adoption of this technology, while little knowledge of it exists among smallholders (Hassan et al., 2023). Particular issues, such as land fragmentation, insufficient extension support, and seed scarcity, are significant constraints on the large-scale use of this technology. However, the Pakistan Agricultural Research Council (PARC) and Punjab Livestock Department, through their on-farm trial projects that present yield and financial benefits, make their contribution to the promotion of the technology.

Also, such transitions are noticeable in different parts of the world. Similarly, in the US and Brazil, productive capacity cost-share programs and carbon credit initiators have been the cause of fast adoption (USDA-NRCS, 2023; Souza et al., 2023). Likewise, India is where the National Dairy Development Board incorporated cover cropping into fodder security programs; on the other hand, Pakistan is the country where, through university research centers UVAS and UAF, they are piloting berseem-oat-vetch systems to ameliorate feed availability during winter.

Practical Integration Framework

For the successful incorporation of cover crops into livestock systems, it is vital to have a systematically organized management plan. Important actions are:

1. Plant Growth Selection: Select species that are compatible with climate, soil, and livestock needs.

2. Sowing and Rotation Timing: Adjust with the harvesting of main crops to obtain maximum soil cover and forage yield.

3. Grazing Management: Apply the method of grazing cycle rotation to achieve equilibrium in the use of biomass and the protection of the soil.

4. Residue Management: Add the biomass that is not grazed to the soil to raise the amount of organic matter.

5. Monitoring: Constantly examine the profitability of the crops as well as the soil to determine the state of the system.

These principles are the building blocks of climate-smart livestock systems, which not only increase production but also maintain ecological balance. Through their use, Pakistan and other developing countries can shift the traditional crop-livestock systems into regenerative, self-standing systems.

4. Soil Health Benefits and System Resilience

Productive and sustainable livestock systems are built on healthy soils. Soil degradation, characterized by organic matter loss, erosion, salinity, and compaction, has been a serious obstacle to agricultural production globally over the last 2 decades (FAO, 2022). Cover crops have been identified as one of the most effective biological control measures to regain the previous state of these environmental problems, in addition to providing various benefits to soil health and the environment.

Improving Soil Organic Matter and Carbon Sequestration

Cover cropping offers several advantages, including the buildup of soil organic matter (SOM), which is essential for soil fertility and ecosystem stability. The increment of soil organic carbon (SOC) storage in the long term process is largely due to the incorporation of the root biomass as well as the crop residues maturing on the cover crops (Wang et al., 2022). According to global meta-analyses, ongoing enhancement of the SOC (0.3-0.5 Mg C ha-1 yr-1) in response to the addition of cover crops can occur depending primarily on the type of soil and its management (Poeplau & Don, 2015; Blanco-Canqui & Wortmann, 2020).

In irrigation-based agroecosystems in Pakistan, berseem clover (Trifolium alexandrinum) and oats (Avena sativa) have exerted the most significant influence. According to Ahmad et al. (2020), practicing cover crop–livestock integration for four consecutive years resulted in a 17-20% increase in soil organic carbon levels compared to continuous cereal cropping. This upgrade is accompanied by increased nutrient-holding capacity and improved soil structure and water retention, which are vital productive factors in arid and semi-arid areas.

Nutrient Dynamics and Biological Activity

Some of the most valuable inputs to nutrient recycling in cover crops are the uptake of residual nitrogen and the reduction of nitrogen deficiency through microbial mineralization. The primary mechanism by which legume mixed systems function is atmospheric nitrogen fixation, facilitated by the nitrogenase reaction and the symbiotic relationship between Rhizobium bacteria and the legume root system. In total, they can fix between 60 and 120 kg N ha^{-1} in a season (Drinkwater & Snapp, 2021). Oats and rye are non-leguminous green cover plants that act as "nutrient scavengers," taking up excess nitrate deeper in the soil and thus reducing losses through leaching and water contamination (Finney et al., 2017).

The presence of more diverse microorganisms characterizes cover-cropped soils. These days, soil respiration rates, enzyme activity (especially dehydrogenase and phosphatase), and microbial biomass carbon have increased by 25-45% under continuous cover cropping compared with bare fallow (Wang et al., 2022). In Punjab dairy livestock systems, Raza et al. (2021) found that berseem-oat rotations had higher microbial activity and faster nutrient turnover, which correlated with a 15% increase in soil available nitrogen.

Soil Structure, Erosion Control, and Water Regulation

The root systems of cover crops play an important role in enhancing soil structure. For example, the deep-rooted species rye (Secale cereale) and radish (Raphanus sativus) produce biopores for aeration and decrease bulk density (Basche et al., 2016). Legume roots, being slimmer, do not hinder aggregation through root exudates and microrelationships. Generally, the overall effects of this process are improved porous and permeable soil structure, resulting in improved infiltration and reduced surface runoff. Recently, studies worldwide have shown that erosion rates in areas under cover cropping systems are 50-70% lower than those under conventional-fallow systems (Silva et al., 2020).

Berseem and vetch were used as cover crops in the irrigated regions of Faisalabad and Okara, Pakistan. Their application, in turn, led to a 35% reduction in topsoil loss from cash cover crops and grazing, and farmers reported a 20-25% increase in infiltration (Hassan et al., 2023). These advantages are especially crucial in areas with irregular rainfall, as soil cover can significantly reduce the frequency of flash floods and droughts.

Climate Resilience and Environmental Regulation

Cover crops are those that positively affect the ecological equilibrium. They are pretty good for the environmental value because they can store soil organic carbon and reduce nitrate leaching. Therefore, with this ability, they can reduce the release of certain greenhouse gases, namely dimethyl ether (N2O) and carbon dioxide (CO2) (Blanco-Canqui et al., 2020). Further, they benefit from efficient water use, which helps the cropping-livestock system withstand climate stress better.

According to Raza et al. (2021), the soil moisture holding capacity in covered-crop rotations was approximately 15-18 percent greater than the soil moisture holding capacity in bare fallow in the Pakistan semi-arid systems. This enhances the ability of crops and forages to survive and be productively viable in the occurrence of dry weather which is escalating as a result of changing weather patterns. Cover crops have been noted to cause a significant limit in the use of fertilizer and emissions; hence, these can be implemented to facilitate the use of a climate-resilient approach toward agriculture (USDA-NRCS, 2023).

Table 2. Soil and environmental indicators improved by cover crops (Global vs. Pakistan)

Indicator	Global Average Improvement	Pakistan (Representative Studies)
Soil Organic Carbon (SOC)	+0.4 Mg C ha^{-1} yr^{-1}	+0.35 Mg C ha^{-1} yr^{-1}
Soil Nitrogen (Total N)	+12–20%	+15–18%
Microbial Biomass Carbon	+25–45%	+30–40%
Aggregate Stability	+20–35%	+12–22%
Water Infiltration Rate	+15–30%	+20–25%
Erosion Reduction	–50 to –70%	–35%
Nitrate Leaching	–25 to –40%	–20 to –30%

Data synthesized from Poeplau and Don, 2015; Finney et al., 2017; Basche et al., 2016; Blanco-Canqui and Wortmann, 2020; Drinkwater and Snapp, 2021; Silva et al., 2020; Ahmad et al., 2020; Raza et al., 2021; Wang et al., 2022; Hassan et al., 2023

Synergies Between Soil Health and Forage Nutrition

The correlation of soil and forage quality is direct. Soil fertility through cover cropping increases, and then forages benefit from a more complete nutritive profile, like higher crude protein, better digestibility, and more balanced mineral content. The benefits of improved soil structure and moisture retention include uniform plant growth, resulting in uniform forage yields (Ketterings et al., 2021). In a study conducted at the mixed systems in Pakistan, berseem-oat rotation system was found to be better adapted to soil and plant conditions as compared to traditional one, thus under this system, they had forages with 14-18% higher protein and 12% lower fiber than traditional systems (Ahmad et al., 2020).

This interaction is a manifestation of a closed-loop model: fertile soil produces high biomass, which, in its turn, helps the livestock to grow healthier, thus providing manure and organic matter to the soil, which enhances the ecological balance. These systems indicate that livestock facility alongside cover crops can maintain a regeneration cycle as opposed to a linear removal.

5. Regional Perspectives and Case Studies

The performance of cover crop–livestock systems shows significant fluctuations across regions, driven by differences in agroecological factors, livestock types, and management intensity. The last ten years have seen considerable evidence from both temperate and tropical zones highlighting the potential of these systems to be adaptable and productive across various environments (Poffenbarger et al., 2017; Franzluebbers, 2022). A case in point is developing countries such as South Asia, which include Pakistan, where cover crops are not just conservation tools, but along with their counterparts, are the major players in the management of feed and soil fertility all year round (Ahmad et al., 2020; Raza et al., 2021).

The following sub-sections will discuss the regions where cover crops integrated with livestock production have been successful, the achievements from implementation, and lessons learned. They will then focus on the different experiences of Pakistan.

North America: Sustainable Intensification and Carbon Economy

In the overall objective of achieving sustainable intensification, livestock systems have incorporated the use of cover crops much faster in North America. Over 6 million hectares have been reported in the US under USDA-NRCS and Sustainable Agriculture Research and Education (SARE) programs implementing cover crop strategies, representing a 400% increase since 2010 (USDA-NRCS, 2023).

Typical structures include winter rye or hairy vetch with maize-soybean rotations, followed by cattle grazing in spring. Fields in Georgia and Iowa proved the concept of cover crop-grazed pastures, saving costs for feed by 15-20% and increasing net farm returns by USD 85-125 per hectare annually (Franzluebbers & Stuedemann, 2015). Additionally, organic carbon in the soil increased by 0.45 Mg C ha^{-1} annually; meanwhile, nitrate leaching decreased by 30% (Poffenbarger et al., 2017).

In the United States, a significant policy-fueled action is the carbon credit market, which compensates producers who apply cover crops and rotational grazing to soil carbon sequestration (USDA, 2023). The monetary rewards for grain-growing farmers demonstrate that environmental advantages can be achieved simultaneously with farm profitability, enabling the mechanism to spread and become sustained.

Europe: Environmental Stewardship and Policy Support

In Europe, cover cropping is one of the mechanisms of the Common Agricultural Policy (CAP) and is part of the "green direct payments" initiative. The catch crops mustard (Sinapis alba) and phacelia (Phacelia tanacetifolia) were successfully tested in France, Germany, and the Netherlands to stop nutrient leaching in the winter (Basche et al., 2016).

Temporarily, intercropping these crops with sheep and dairy cattle has contributed to the improvement of soil health and the decrease of feed deficits in mixed farming areas (Lüscher et al., 2019). For instance, in the Po Valley in Italy, pastures of Italian ryegrass-clover mixtures grazed by dairy cattle not only increased soil microbial biomass but also reduced the application of synthetic N fertilizer by 25% (Borrelli et al., 2020). Likewise, these systems demonstrated that the Mediterranean climate in Spain enhances water retention in the soil and shows a greater ability to endure droughts in the summer (Blanco-Canqui et al., 2020).

South America: Livestock Crop Synergies in the Tropics

In the tropical areas of South America, the integration of the cover crop and livestock has become the mainline of the ICLF system. EMBRAPA, which is a program led by Brazil, covers more than 17 million hectares with such integration with dominant Brachiaria species, sorghum, and legume mixtures (Balbino et al., 2019).

These systems involve planting soybeans, maize, and forage cover crops in rotation, with animals grazing the cover crops during the off-season. Investigations carried out in the state of Mato Grosso showed an 18% increase in soil carbon and a 22% increase in nitrogen retention. Livestock raised in this model case were even reported to gain an additional 0.8–1.2 kg per day (Carvalho et al., 2021).

The co-benefits of integration, such as restored soil structure, increased biodiversity, and reduced GHG emissions, are best learned from Brazilian experiences. The method aligns with the country's ABC+ low-carbon agriculture plan, which aims to reduce total CO_2-equivalent emissions of 1.1 billion tonnes by 2030 through the adoption of regenerative practices.

Asia and Australia: Adapting Cover Crops to Climate Variability

Australia and China exhibit different yet complementary patterns of cover crop-livestock adjustment. In Australia, a country with persistent rainfall fluctuations, legumes such as vetch, lupin, and serradella are added to cereal-livestock systems (Bell et al., 2020). Farmers shared that the soil nitrogen levels are enhanced by the (+18%) increase, and the erosion is lowered in the questionable dryland areas.

In China, the expansion of permanent cover crop-livestock systems is growing rapidly, driven by funding from the "Green Agricultural Development" program. The study conducted in Henan and Inner Mongolia discovered that the rye-alfalfa rotation system, when sheep-grazed, increased soil water retention and mitigated desertification risks (Liu et al., 2021). The average forage biomass of cover crops was 8.4-ton ha^{-1}, which is more than the 5.9-ton ha^{-1} only for traditional fallow systems.

Both localities pivot on adapting to and mitigating the effects of weather, fully manifesting the transformation of degraded and semi-arid ecosystems through the use of cover crops.

Pakistan: Forage Productivity, Soil Fertility, and Livestock Efficiency

Pakistan is a unique example, as cover crops not only provide forage but also help restore soil fertility. As logged crops and livestock systems and small-scale farming are the mainstay, cover crops such as berseem clover (Trifolium alexandrinum), oat (Avena sativa), sorghum (Sorghum bicolor), and vetch (Vicia sativa) have been the most critical component of the sustainable feed production (Ahmad et al., 2020; Raza et al., 2021).

Mature oat mixtures cultivated on 4.3 million hectares in Punjab not only make a significant contribution but also provide over 60% of the total green fodder supply during winter (Pakistan Economic Survey, 2023). As evidenced by the long-term field studies conducted at the University of Agriculture Faisalabad and the Fodder Research Institute Sargodha, berseem-oat rotations enhance the soil organic carbon, total N, and available phosphorus by an average of 15–18%, 12%, and 10–15%, respectively, in comparison to cereal-only systems (Hassan et al., 2023).

Livestock productivity also contributes positively to the situation. According to Nadeem et al. (2022), the buffaloes that consume berseem-oat silage are capable of producing milk 8-10% higher than the average and have better feed conversion ratios. Small ruminants that are allowed to graze on legume cover crops demonstrate a notable gain in weight and fertility as a result of the much higher protein (14–18%) and digestibility (72–76%) in the forage (Khan et al., 2021).

In addition to agronomic benefits, cover cropping enhances resource efficiency. The intercropping of short-duration legumes between cotton and wheat crops reduced fertilizer costs by 18-22% and increased soil biological activity by 30% (Raza et al., 2021). This demonstrates that cover crops can not only mitigate feed supply issues through effective soil management practices but also enhance soil fertility levels and buffer forage, provided the proper management is followed.

Table 3. Forage and Soil Responses in Integrated Cover Crop–Livestock Systems in Pakistan (2018–2024)

Cover Crop Species	Location / Province	Forage Yield (t ha^{-1})	Soil Organic Carbon Change (%)	Nitrogen Uptake (kg ha^{-1})	Livestock Response
Berseem (T. alexandrinum) + Oat (A. sativa)	Punjab (Faisalabad)	12.6	+18	112	+9% milk yield in buffaloes
Vetch (V. sativa) + Sorghum (S. bicolor)	Sindh (Tandojam)	9.4	+15	105	+14% liveweight gain in goats

Berseem–Oat Rotation	Punjab (Sargodha)	10.8	+16	119	+8% feed efficiency
Cowpea (V. unguiculata) after Wheat	KPK (Peshawar)	8.2	+12	98	
Lablab (L. purpureus) + Maize Residues	Balochistan (Quetta)	7.6	+10	94	

Compiled from Ahmad et al., 2020; Khan et al., 2021; Raza et al., 2021; Nadeem et al., 2022; Hassan et al., 2023.

Lessons and Opportunities for Scaling

Cover crop-livestock systems offer significant agronomic, ecological, and economic benefits when integrated into the environment. In advanced countries, governments encourage people to plant various tree species by offering carbon credits. Meanwhile, their primary motivation is to restore the soil and ensure food security for their livestock in associated countries.

Pakistan has three directions to go:

1. Establishing participatory trials in the provincial livestock departments to promote the research-extension linkages.
2. Fostering legume-based rotations in national fodder policies through incentives to decrease dependence on chemical nitrogen.
3. Incorporating cover crop management into climate adaptation frameworks, among others, the National Climate Change Policy (2021).

Such efforts may achieve a 25-30% increase in the national fodder availability and a 15-20% improvement in the soil fertility indices within a decade.

6. Environmental and Economic Implications

The introduction of the cover crop in the livestock production systems does not only offer economic and environmental related benefits, including the need to conserve soils, but also benefits the producers. Nutrient recycling, reduction of greenhouse gas emissions, promotion of biodiversity, and stabilization of farm profits depend on this type of production system as the most suitable technology (Blanco-Canqui et al., 2020; Franzluebbers, 2022). Cover crop-livestock systems combine two aspects: ecological sustainability and financial gain that is important particularly in regions such as Pakistan where water resources are limited.

Environmental Implications

Soil Quality and Carbon Sequestration

The elevation of soil organic carbon (SOC) and the activity of biological life in cover crop-livestock systems are among the dominant outcomes in research conducted in various regions of the world. The introduction of manure and plant residues, along with the decomposition of dead organic matter, leads to faster humus formation, and the physical soil condition is better when soil textural difference (Poffenbarger et al., 2017) is taken into account.

Franzluebbers and Stuedemann (2015) stated that SOC accumulation rates were 0.4-0.6 Mg C ha^{-1} yr^{-1} in rye and in the crimson clover's case, the grazed systems in the southeastern USA. Likewise, a meta-analysis by Poeplau and Don (2015) of 139 long-term studies found that adding cover crops increased SOC by 15-25% compared with bare fallow, particularly when legumes were used.

In Pakistan, the rotations of legumes have also been seen with similar results. At the Fodder Research Institute, Sargodha, soils under a berseem-oat rotation sequestered an additional 18% Soil Organic Carbon over 5 years, along with higher microbial biomass and enzyme activity (Hassan et al., 2023). The rhizobial symbiosis associated with berseem results in nitrogen fixation rates of 120-180 kg N ha-1, which directly improves soil fertility and reduces dependence on synthetic fertilizers (Raza et al., 2021).

Greenhouse Gas Mitigation

Greenhouse gas (GHG) dynamics are affected both directly and indirectly by cover crops. They, first of all, lower nitrous oxide (N_2O) emissions by reducing nitrogen fertilizer needs, and they, on the other hand, increase carbon sequestration by the improved soil structure and the carbon storage (Basche et al., 2016). Studies conducted in the integrated systems in Brazil and Argentina showed that they had a net GHG reduction of 1.1-1.6 Mg CO_2-eq ha^{-1} yr^{-1}, mainly due to the legume fixation and manure-soil interactions (Carvalho et al., 2021). On the other hand, in mixed systems with rotational grazing, methane emissions per unit of milk or meat production decreased by 10-18% due to improved feed digestibility (Franzluebbers, 2022).

Indeed, the smallholder systems of Pakistan have the same potential for mitigation. For example, Nadeem et al. (2022) showcased that by incorporating berseem-oat silage in their diet, the buffalo can directly decrease their enteric emissions of methane (g CH_4/kg milk) by 12% against the wheat straw-based diets.

Water Conservation and Erosion Control

Cover crops also help reduce soil erosion and surface runoff, which are key factors in the irrigated and semi-arid areas of Pakistan. In on-farm trials in Multan, the combination of oats and vetch in the cotton–wheat rotation system reduced runoff losses by 27% and sediment loss by 35% compared to conventional fallow (Ahmad et al., 2020).

Internationally, other research conducted in Australia and Europe reported reductions of 40-60% in erosion and a considerable increase in water infiltration rates (Bell et al., 2020; Borrelli et al., 2020). These gains in the hydrological context make cover cropping a critical factor in climate adaptation, particularly amid erratic monsoon rainfall.

Economic Implications

Reduced Input Costs and Enhanced Feed Security

Integrating cover crops and livestock creates an on-farm feed resource that can partially replace commercial feeds. On the other hand, high-protein green fodder is an alternative to the expense of buying concentrates, which make up a significant portion of livestock production costs in Pakistan (Pakistan Economic Survey, 2023).

Comparative Global Regional Summary

The representative findings on input savings, emission reductions, and profitability gains from cover crop-livestock systems, explored in global and Pakistan studies, are summarized in Table 4.

Table 4. Comparative Environmental and Economic Impacts of Cover Crop–Livestock Systems (2015–2024)

Region / Country	**Cover Crop System**	**Input Savings (%)**	**GHG Reduction (CO_2-eq/ha/yr)**	**SOC Change (%)**	**Profitability Change**
USA (Georgia)	Rye + Clover (Beef grazing)	18	1.4	+22	+USD 125/ha/yr
Brazil	Brachiaria–Soybean (ICLF)	20	1.6	+18	+USD 95/ha/yr
France	Mustard + Phacelia (Dairy)	15	1.1	+20	+EUR 85/ha/yr
Australia	Vetch–Lupin (Sheep grazing)	12	1.0	+16	+AUD 110 /ha/yr
Pakistan (Punjab)	Berseem–Oat (Buffalo)	22	0.8	+18	+9% milk yield
Pakistan (Sindh)	Vetch–Sorghum (Goats)	18	0.7	+15	+14% weight gain
Pakistan (Sargodha)	Legume–Cereal Rotation	20	0.9	+16	+8% feed efficiency

Compiled from Franzluebbers & Stuedemann, 2015; Lüscher et al., 2019; Carvalho et al., 2021; Bell et al., 2020; Ahmad et al., 2020; Khan et al., 2021; Hassan et al., 2023

Broader Sustainability Context

The economic and environmental aspects of the cover crop-livestock systems offer their contributions directly to the achievement of several United Nations Sustainable Development Goals (SDGs), such as:

- SDG 2 (Zero Hunger): As a result of the enhancement of forage supply and livestock productivity.
- SDG 13 (Climate Action): GHG emissions mitigation and soil carbon depletion are the ways.
- SDG 15 (Life on Land): The processes of soil degradation reversal and biodiversity improvement.

In the context of Pakistan, the addition of cover crops to the existing fodder-based systems would not only increase total green fodder by 25-30% but would also decrease fertilizer imports annually by USD 70-90 million, and it would also help achieve the national GHG mitigation target (Pakistan Climate Change Authority, 2024).

7. Conclusions and Future Outlook

Livestock systems can adopt environmentally friendly practices, such as introducing cover crops, to improve soil health, forage quality, and overall livestock productivity. During the last ten years, the results of various studies worldwide have been almost the same: well-managed cover cropping systems improve soil structure, organic matter content, and nutrient cycling, while simultaneously providing high-quality forage that can reduce feed costs and improve animal performance (Blanco-Canqui et al., 2020; Finney et al., 2017). Through this process, humans in temperate regions can move to the tropical areas. Instead of extracting resources, they can use a regenerative farming approach that integrates the soil, plant, and animal microbiomes through a circular agroecosystem.

Global Synthesis of Benefits

In North America, Europe, and parts of Asia, the adoption of cover crops has expanded noticeably, and it is expected that around 35-40 million hectares of cover cropping will be in operation in 2024 (FAO, 2024). With the backing of conservation incentive programs and integrated livestock-forage rotations, the United States and Brazil demonstrated the strongest and most consistent adoption of cover cropping (Blaser et al., 2022). In these practices, multi-species cover crops, especially the cereal-legume combinations, can increase the soil organic carbon by 0.2-0.5 Mg ha-1 yr-1, lower the soil erosion by 70%, and provide more biologically active soils that are a habitat for more species (Basche et al., 2016; Kramberger et al., 2020).

Likewise, the forage value of cover crops is now considered a significant co-benefit. Vetch and rye, triticale and lablab, and oat and berseem clover mixtures are the ones that almost always produce between 5 and 8 tons of dry matter per hectare, often with crude protein levels above 18 and 20% respectively (Kim et al., 2020; Iqbal et al., 2021). Nutritional attributes like these are pretty essential for ruminant health, especially when feed is limited or costs are fluctuating. Adding livestock to the cover crop system not only provides nutrient recycling through manure but also reduces reliance on synthetic fertilizers (SARE, 2023).

The Way Forward

Cover crops are a combination of both biological innovation and social adaptation as they enable a shift to regenerative livestock systems. The sustainable structure should focus on:

1. There should be an increase of the biodiversity such as local legumes and grasses.
2. Changing grazing and harvesting practices to contribute to acting on the dual goals of soil health and forage yield.
3. System monitoring using the application of the digital tools (remote sensing and nutrient mapping).
4. Sector partnership is via the chain of agricultural universities, research institutes and government bodies to adoption of the ideal practices.

Finally, livestock cover crops are an exceptionally productive but potentially under-utilized method to attain agricultural sustainability in both the world and Pakistani setting. In their turn, they are the connection between the improvement of soil health and the improvement of forage quality on which stable agroecosystems capable of adjusting to climate change to ensure food security depend. The current test is not showing off these achievements, which have been long acknowledged, but changing the scientific knowledge to practice and policy. With the help of cooperation between research and farmers in the country and appropriate policies creating circular climate-smart production systems is the possibility within the livestock industry in Pakistan and other developing nations.

References

Ahmad, N., Raza, S., & Imran, M. (2020). Effect of berseem clover and oat cover crops on soil organic carbon and dairy productivity under mixed farming systems in Punjab, Pakistan. Pakistan Journal of Agricultural Sciences, 57(4), 1123–1132.

Ahi, Y., Bellitürk, K., & Gültaş, H. T. (2019). Fuzzy logic analysis of soil fertility parameters in irrigated areas. Fresenius Environmental Bulletin, 28(10), 7176–7182.

Basche, A. D., Kaspar, T. C., Archontoulis, S. V., Jaynes, D. B., Sauer, T. J., Parkin, T. B., & Miguez, F. E. (2016). Soil water improvements with the long-term use of a winter rye cover crop. Agricultural Water Management, 172, 40–50.

Bellitürk, K., Açıkgöz, F. E., & Çelik, H. (2021). Organic matter dynamics in soils under different cover cropping systems. International Journal of Agriculture and Biology, 25(3), 635–644.

Blanco-Canqui, H., Ruis, S. J., & Wortmann, C. S. (2020). Does cover crop residue and root biomass increase soil organic carbon? Soil Science Society of America Journal, 84(6), 1867–1878.

Blaser, S. R., Reinsch, T., Loges, R., & Taube, F. (2022). Grass-clover cover crops and their potential in carbon sequestration and nutrient recycling in temperate regions. European Journal of Agronomy, 132, 126416.

FAO (Food and Agriculture Organization of the United Nations). (2022). Status and Trends of Soil Organic Carbon in South Asia. FAO, Rome, Italy. Retrieved from http://www.fao.org/soil-organic-carbon

FAO (Food and Agriculture Organization of the United Nations). (2024). The State of Food and Agriculture 2024: Climate-Smart Livestock Systems. FAO, Rome, Italy.

Finney, D. M., White, C. M., & Kaye, J. P. (2017). Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agronomy Journal, 109(1), 39–52.

Hassan, A., Soomro, S. A., & Jamali, M. A. (2023). Barriers to the adoption of sustainable cover cropping in mixed farming systems of Sindh, Pakistan. Sarhad Journal of Agriculture, 39(2), 145–152.

Iqbal, M. A., Ahmad, M., & Rafiq, M. (2021). Forage productivity and quality of legume–grass mixtures under different irrigation regimes in semi-arid Punjab. Pakistan Journal of Botany, 53(5), 1789–1798.

Kim, S. H., Lee, J. H., Kim, W. H., & Park, T. I. (2020). Evaluation of multi-species cover crops for forage yield and quality in integrated crop–livestock systems. Agronomy, 10(7), 1028.

Kramberger, B., Gselman, A., Janzekovic, M., Kaligaric, M., & Bracko, B. (2020). Effects of cover crops on soil mineral nitrogen and on the yield and nitrogen content of subsequent maize. European Journal of Agronomy, 115, 126044.

Mutua, J., Kihanda, F., & Mureithi, J. (2019). Forage legume cover crops for improving soil nitrogen and drought resilience in Ethiopian mixed farming systems. Experimental Agriculture, 55(3), 475–487.

Patel, J. R., Sharma, R., & Meena, R. S. (2021). Integrated cover cropping and livestock systems for improving milk yield and soil fertility in semi-arid India. Tropical Animal Health and Production, 53(2), 207.

Raza, S. H., Imran, M., & Hussain, A. (2021). Leguminous cover crops as dual-purpose species for soil fertility enhancement and ruminant nutrition. Journal of Animal and Plant Sciences, 31(1), 77–85.

SARE (Sustainable Agriculture Research and Education). (2023). Integrating Cover Crops in Grazing Systems: Economic and Ecological Benefits. University of Vermont Extension, USA. Retrieved from https://www.sare.org/resources/integrating-cover-crops

Shahzad, M. S., Anwar, Z., & Nadeem, A. (2022). Role of forage legumes as cover crops in sustainable soil management under Pakistani conditions. Journal of Environmental Management, 321, 115903.

Snapp, S. S., Gentry, L. E., & Harwood, R. R. (2019). Management intensity, not biodiversity, is the driver of ecosystem services in a long-term row crop experiment. Agriculture, Ecosystems & Environment, 286, 106659.

Soomro, S. A., Jamali, M. A., & Hassan, A. (2021). Evaluation of vetch and berseem cover crops for forage and soil improvement under Sindh climatic conditions. Pakistan Journal of Agricultural Research, 34(3), 452–459.

USDA-NRCS (United States Department of Agriculture – Natural Resources Conservation Service). (2023). Cover Crop Trends, Innovations, and Economics. Washington, D.C., USA. Retrieved from https://www.nrcs.usda.gov

17

PHYTOCHEMICAL-BASED BIOPESTICIDES AS TOOLS FOR ENHANCING SOIL HEALTH AND SUSTAINABLE NUTRIENT DYNAMICS IN AGROECOSYSTEMS

Joseph Ugochukwu Ekenwosu[1]

1. Introduction

The global demand for sustainable agricultural practices is increasingly urgent, driven by concerns over environmental degradation, pesticide resistance, and the need for long-term food security. While traditional chemical pesticides are effective in pest suppression, they also pose significant risks, such as disrupting soil microbiota, reducing enzymatic activity, and altering nutrient cycling within ecosystems (Navshree, 2025). In response, biopesticides, derived from natural organisms or phytochemicals, have emerged as promising alternatives. These agents, ranging from microbial agents such as *Bacillus thuringiensis* to botanicals like neem oil and plant-incorporated protectants, offer targeted pest control with reduced environmental impact (Tadesse et al., 2024). Among these phytochemicals, plant-derived compounds with pesticidal properties are especially notable for being biodegradable and eco-friendly.

Integrating biopesticides into Integrated Pest Management (IPM) helps maintain sustainable agroecosystems. Specifically, this approach reduces chemical inputs, supports beneficial microbes, and improves soil health (Tadesse et al., 2024). There are several types of biopesticides: microbial, biochemical, and plant-based formulations, all of which have proven useful in holistic pest control strategies. Furthermore, combining biopesticides with biofertilizers offers additional benefits. For example, microbial inoculants like Plant Growth-Promoting Rhizobacteria (PGPR) not only suppress pests but also improve nutrient dynamics, soil structure, and crop productivity (Marcinkevičienė et al., 2022). Agroecosystems are managed environments where plants, microbes, and humans interact; these complex systems depend on healthy soil for productivity and ecological balance. In this context, regenerative practices that improve microbial diversity, soil structure, and nutrient cycling align well with phytochemical-based pest management approaches (Marcinkevičienė et al., 2022).

1 Dr. Department of Animal and Environmental Biology, Faculty of Biological Sciences, Imo State University, Owerri, Imo State, Nigeria. ORCID: 0000-0001-7744-2462

Emerging research underscores both the benefits and complexities of using phytochemical-based biopesticides. For example, field studies have shown that combining biopesticides with cover cropping improves soil aggregate stability and reduces compaction, which enhances root biomass, a critical indicator of soil health (Marcinkevičienė et al., 2022). However, the behavior of biopesticides in soil varies depending on their chemical properties and environmental conditions.

Factors such as organic matter, microbial activity, temperature, and soil texture influence their degradation and ecological interactions. While neem-derived azadirachtin and essential oils are effective, they may temporarily inhibit target and non-target microbial activity, affecting soil enzyme processes such as dehydrogenase, phosphatase, and urease activities.

Recent advances in molecular tools have deepened our understanding of these interactions. High-throughput sequencing techniques, such as Illumina MiSeq, now allow detailed profiling of soil microbial community shifts in response to biopesticide applications (Li et al., 2024). When combined with metabolomics, these techniques provide comprehensive insights into how phytochemicals affect microbial diversity, metabolic activity, pest suppression, and soil functioning (Xue, 2022). Furthermore, multi-omics approaches that integrate metagenomics, metabolomics, and functional gene prediction offer holistic perspectives on how biopesticides influence soil microbial community structure, nutrient cycling, and ecosystem resilience. Such insights can inform the design of optimized biopesticide formulations that balance pest suppression with the preservation of beneficial microbiota. The adoption of precision agriculture technologies further strengthens the role of phytochemicals in sustainable farming. Smart soil sensors, geographic information systems (GIS), global positioning systems (GPS), remote sensing, and variable-rate technologies enable the spatially targeted application of biopesticides (Mansoor et al., 2025). By ensuring precise dosages, these tools minimize environmental contamination while improving field-level efficiency.

2. Phytochemical Composition and Modes of Action

Phytochemicals are naturally occurring, bioactive compounds in plants that play a critical role in defense against pests and pathogens. They include a wide range of secondary metabolites such as alkaloids, flavonoids, phenolics, terpenoids, essential oils, tannins, and saponins, many of which possess pesticidal, antifungal, and antibacterial properties (Isman, 2022). Among the most studied phytochemicals are azadirachtin from neem (*Azadirachta indica*), pyrethrins from chrysanthemum (*Chrysanthemum cinerariifolium*), rotenone from *Derris* roots, and essential oils such as eugenol and citronellal from aromatic plants like clove (*Syzygium aromaticum*) and lemongrass (*Cymbopogon citratus*)

(Tadesse et al., 2024). These compounds exert their effects through multiple biochemical pathways. For instance, azadirachtin disrupts insect molting and feeding behavior by interfering with ecdysteroid synthesis, while pyrethrins affect sodium channel function in the nervous system of insects, leading to paralysis and death (Isman, 2022).

In the context of soil health, these phytochemicals exhibit dual functions: direct pest suppression and indirect enhancement of soil biological activity. By reducing pest populations without significantly harming beneficial soil organisms, they help preserve microbial diversity and maintain balanced nutrient cycling (Acheuk, et al., 2022). Certain compounds also possess bio-stimulatory properties that encourage the proliferation of beneficial microbes, including nitrogen-fixing bacteria and phosphate-solubilizing fungi, thereby supporting nutrient availability and soil fertility (Singh et al., 2023). The degradation of phytochemical residues in soil is another critical factor underpinning their safety and ecological compatibility. Most plant-derived compounds are biodegradable and undergo microbial or enzymatic breakdown, often yielding non-toxic byproducts that integrate into natural biogeochemical cycles (Mishra, et. al., 2022). This rapid degradation minimizes the risk of long-term soil contamination and allows repeated application without cumulative toxicity, an advantage over many synthetic pesticides.

The mode of action of phytochemical-based biopesticides often involves multiple mechanisms simultaneously, which reduces the likelihood of pest resistance development. For example, essential oils act through fumigant toxicity, contact toxicity, and repellency, while also inhibiting critical enzymes in pest physiology (Koul et al., 2022). This multi-target functionality not only enhances efficacy but also prolongs the utility of these compounds in integrated pest management programs.

3. Examples of Specific Phytochemicals and Their Effects on Soil Nutrient Dynamics

Phytochemical-based biopesticides not only suppress pests but also influence soil biological processes that regulate nutrient cycling and fertility. Different plant-derived compounds have been observed to stimulate microbial communities, enhance enzymatic activities, and improve nutrient availability, making them valuable tools for supporting soil health and sustainable crop productivity.

Neem-based formulations, particularly those containing azadirachtin and related limonoids, have been widely studied for their dual role in pest suppression and soil enrichment. Applications of neem cake or aqueous extracts have been shown to increase populations of beneficial microbes such as phosphate-solubilizing bacteria and nitrogen-fixing organisms, thereby enhancing soil nitrogen and phosphorus availability (Kumar et al., 2023). The organic matter content in neem products also serves as a substrate for microbial metabolism, improving soil structure and promoting nutrient mineralization (Sharma & Singh, 2022).

Pyrethrin-based products derived from chrysanthemum flowers have exhibited positive impacts on soil enzymatic activity when applied at recommended concentrations. Soil studies have shown that pyrethrin residues degrade rapidly, allowing microbial communities to recover and, in some cases, proliferate, leading to improved activity of enzymes such as urease, phosphatase, and dehydrogenase (Li et al., 2024). These enzymes are critical for nitrogen and phosphorus cycling, which supports nutrient availability and uptake in crops.

Essential oils, such as eugenol from clove and citronellal from lemongrass, are increasingly being explored for their soil-enhancing properties. Beyond their pesticidal effects, these oils have been reported to stimulate certain beneficial microbial groups involved in organic matter decomposition and nutrient transformation. When applied judiciously, they enhance soil respiration and microbial diversity, contributing to a balanced nutrient cycle without leaving harmful residues (Mishra, et. al., 2022).

Rotenone-based biopesticides, extracted from Derris and Lonchocarpus species, have shown mixed effects on soil nutrient dynamics. While their rapid biodegradability prevents long-term soil toxicity, their application at higher concentrations can temporarily suppress microbial activity, leading to reduced enzymatic functions. However, at optimized doses, they have been found to support a gradual rebound of microbial communities, contributing to soil nutrient stabilization over time (Koul et al., 2022).

Additionally, integrated use of phytochemical-based biopesticides with biofertilizers or organic amendments enhances their positive influence on nutrient dynamics. For instance, combining neem cake with rhizobium inoculants in legume-based systems has resulted in increased nitrogen fixation and improved soil organic matter quality, demonstrating the synergistic benefits of such integrated approaches (Singh et al., 2023).

Phytochemical-based biopesticides often have multifaceted effects that go beyond pest control, influencing nutrient availability, soil microbial balance, and ecosystem functions. One notable effect is the enhancement of organic matter decomposition. For instance, compounds like saponins and alkaloids can stimulate beneficial microbial consortia that accelerate the breakdown of crop residues, thereby releasing essential nutrients such as nitrogen, phosphorus, and potassium in more bioavailable forms (Zhou et al., 2020). This decomposition process not only improves nutrient cycling but also enhances soil structure and water retention, which are crucial for sustainable crop production.

Phytochemicals can also modulate the soil microbiome, promoting beneficial organisms while suppressing harmful pathogens. For example, flavonoids and terpenoids have been shown to selectively enhance populations of nitrogen-fixing bacteria and phosphorus-solubilizing microbes (Khan et al., 2021). This selective stimulation fosters a balanced microbial environment that supports efficient nutrient transformation and uptake by plants.

Additionally, the gradual degradation of phytochemical compounds in the soil often leads to the release of bioactive residues that act as natural soil amendments. These residues can chelate micronutrients such as zinc, copper, and iron, making them more accessible to plants. In degraded or nutrient-depleted soils, such effects contribute significantly to soil fertility restoration without relying on synthetic inputs.

Field studies also demonstrate that phytochemical-based treatments can improve nutrient use efficiency. For instance, the application of neem-based formulations has been associated with increased nitrogen uptake in cereals and legumes due to reduced volatilization losses and enhanced nitrification (Singh & Devi, 2019). This not only improves yield but also minimizes the environmental footprint associated with excessive fertilizer use.

Moreover, these natural biopesticides support sustainable nutrient dynamics in diverse agroecosystems, from intensive monocultures to smallholder mixed-cropping systems. By integrating phytochemical biopesticides with organic amendments or reduced synthetic inputs, farmers can achieve a synergistic effect, improving soil health while maintaining pest control efficacy (Mishra et al., 2022).

Overall, these examples demonstrate that phytochemicals do more than provide pest management solutions. They actively contribute to the restoration and maintenance of soil nutrient dynamics, supporting agroecosystems that are productive, resilient, and environmentally sustainable. This dual role makes them key tools in the transition toward ecologically balanced farming systems, reducing dependence on synthetic inputs while improving soil quality over time.

4. Role of Phytochemicals in Soil Nutrient Dynamics

Phytochemical-based biopesticides influence soil nutrient dynamics through multiple mechanisms that enhance soil fertility, improve nutrient availability, and sustain soil productivity. Unlike synthetic pesticides that often degrade soil quality, phytochemical compounds interact synergistically with soil microbes and organic matter to support nutrient cycling and balance. One key mechanism is the stimulation of soil microbial communities that drive nutrient mineralization and organic matter decomposition. For instance, flavonoids and alkaloids present in plant extracts create a favorable microenvironment for beneficial microbes such as nitrogen fixers and phosphate solubilizers, which in turn enhance the bioavailability of critical nutrients like nitrogen, phosphorus, and potassium (Sharma & Singh, 2021). Similarly, saponins and terpenoids released into the soil act as organic substrates for microbial metabolism, promoting enzymatic activities that accelerate nutrient turnover.

Phytochemicals also contribute to chelation and stabilization of soil nutrients. Phenolic acids and tannins form complexes with micronutrients such as iron, zinc, and copper, reducing leaching losses while maintaining their availability to plants. This process supports micronutrient balance in the soil and ensures steady nutrient supply to crops, which is critical for sustainable production systems. Another important effect of phytochemical biopesticides is the improvement of soil organic carbon and humus formation. Plant-based compounds, particularly lignin-derived phenolics, enhance the stability of soil aggregates and organic matter, thereby improving soil structure and nutrient retention (García et al., 2018). This directly supports nutrient use efficiency and long-term soil health in agroecosystems.

In addition, phytochemical interactions with soil biota help suppress pathogenic microbes while favoring beneficial ones, thereby reducing competition for nutrients and improving nutrient uptake efficiency by plants. For example, neem-derived azadirachtin has been reported to suppress soil borne pathogens while allowing beneficial fungi and bacteria to thrive, indirectly supporting nutrient cycling and plant growth (Isman, 2020). These synergistic roles of phytochemicals highlight their potential in maintaining a balanced soil nutrient ecosystem. Their ability to improve nutrient availability, support microbial-driven nutrient transformations, and enhance soil organic matter makes them valuable tools for integrated soil fertility management in sustainable agriculture.

5. Influence of Phytochemical-Based Biopesticides on Soil Enzyme Activities and Microbial Communities

Phytochemical-based biopesticides exert profound effects on soil enzymatic activities and microbial community dynamics, which are central to nutrient cycling and overall soil health. Soil enzymes such as dehydrogenase, urease, phosphatase, and cellulase serve as sensitive indicators of biological activity and soil quality. Unlike synthetic pesticides, which often suppress enzymatic functions and reduce microbial diversity, phytochemical compounds tend to enhance enzymatic efficiency by stimulating beneficial microbial populations that produce these enzymes. For instance, neem-derived azadirachtin has been shown to enhance dehydrogenase and phosphatase activities, fostering improved nitrogen and phosphorus mineralization in soil systems (Meena et al., 2020). Similarly, compounds extracted from papaya leaves and orange peels contain flavonoids and phenolics that create favorable conditions for beneficial microbes like Bacillus and Pseudomonas, which, in turn, accelerate organic matter breakdown and nutrient release (Ekenwosu et al., 2023).

Microbial community structure is also positively influenced by phytochemical applications. Studies using metagenomic analyses have reported increased diversity and abundance of functional groups involved in nutrient transformation, such as nitrifiers, denitrifiers, and phosphate-solubilizing bacteria, following repeated use of botanical pesticides (Gupta et al., 2019). This enriched microbial diversity enhances ecosystem resilience and promotes sustainable nutrient cycling, even under intensive agricultural practices. The balance achieved through these biopesticides ensures that beneficial microorganisms thrive while pathogenic strains are suppressed, contributing to disease control and soil health simultaneously. This dual benefit underscores the ecological compatibility of phytochemical-based pest control strategies compared to conventional chemical inputs, which often disrupt soil ecological balance and reduce long-term fertility.

6. Mechanisms of Phytochemical–Soil Interactions

The influence of phytochemical-based biopesticides on soil nutrient dynamics is underpinned by a series of chemical, biological, and ecological interactions within the soil environment. Understanding these mechanisms provides insight into how these compounds enhance soil health and support sustainable nutrient cycling in agroecosystems.

Chemical interactions in the soil matrix

Phytochemicals interact with soil colloids and organic matter through adsorption, desorption, and complexation processes. For instance, phenolic compounds can bind to clay minerals and humic substances, influencing their mobility and bioavailability (Singh & Kuhad, 2018). Soil pH, texture, and organic carbon content significantly affect the stability and persistence of these compounds. Acidic soils tend to enhance the solubility of certain phytochemicals, increasing their immediate bioactivity, while neutral to alkaline soils may promote their retention in the soil matrix (Li et al., 2020).

Microbial mediation

Microorganisms play a critical role in metabolizing phytochemicals into bioactive or simpler compounds that influence soil nutrient transformations. Soil bacteria and fungi often degrade flavonoids, terpenoids, and alkaloids, releasing secondary metabolites that act as nutrient sources for microbial communities. Such microbial processes can enhance soil enzymatic activities, including dehydrogenase and urease, which are essential for nutrient mineralization and cycling. Additionally, phytochemicals can selectively stimulate beneficial microbes, such as plant growth-promoting rhizobacteria, while suppressing pathogenic species (Mandal et al., 2022).

Nutrient availability and cycling

Certain phytochemicals directly enhance nutrient availability. Phenolic acids can chelate micronutrients like iron and zinc, making them more accessible for plant uptake (Kumar et al., 2019). Moreover, flavonoids have been reported to stimulate nitrogen-fixing bacteria, thereby improving nitrogen availability in the soil (Lal et al., 2021). Similarly, terpenoid-rich extracts can increase phosphorus solubilization by stimulating phosphate-solubilizing microorganisms, thereby reducing the reliance on synthetic fertilizers.

Allelopathic and synergistic effects

Phytochemicals can exhibit allelopathic effects that suppress soil-borne pathogens while creating niches for beneficial microbial communities. For example, alkaloid-rich extracts from neem and papaya leaves suppress Fusarium species while promoting populations of Trichoderma and Bacillus species known for enhancing nutrient turnover. The synergistic action of multiple phytochemicals in complex plant extracts often leads to improved soil structure, organic matter stabilization, and nutrient cycling efficiency (Ekenwosu, et al., 2023).

Implications for agroecosystem sustainability

By modulating chemical and biological processes, phytochemical-based biopesticides contribute to long-term soil fertility and resilience. Their use reduces the ecological footprint associated with synthetic agrochemicals while promoting sustainable nutrient management strategies (Mandal et al., 2022). In addition, the gradual buildup of bioactive residues in soils supports ecosystem services such as carbon sequestration, soil aggregation, and improved water retention (Singh & Kuhad, 2018).

7. Case Studies: Pawpaw Leaf Extract in Smallholder Farms, Nigeria

In southeastern Nigeria, smallholder farmers have increasingly adopted pawpaw (*Carica papaya*) leaf extract as an eco-friendly and cost-effective alternative to synthetic pesticides. Laboratory analyses revealed that pawpaw leaves contain high levels of alkaloids, flavonoids, saponins, and tannins compounds known for their insecticidal and antimicrobial activities (Ekenwosu et al., 2023).

Quantitative data

A field trial conducted across 10 smallholder farms in Owerri southeastern Nigeria demonstrated remarkable improvements in both crop health and soil quality over two planting seasons:

- **Pest reduction:** Average pest population decreased by 62% compared to untreated plots.
- **Yield increase:** Maize yield improved by 28%, while vegetable yields increased by 34%.
- **Soil health improvement:** Soil microbial activity increased by 40%, and soil organic matter content improved by 0.7%, indicating enhanced nutrient cycling.
- **Cost savings:** Farmers reduced chemical pesticide expenses by an average $22 per planting season.

These findings show that pawpaw leaf extract is not only effective in pest suppression but also supports soil biodiversity and nutrient dynamics. Its affordability and ease of preparation make it particularly suitable for smallholder farmers, aligning with sustainable agriculture and food security goals.

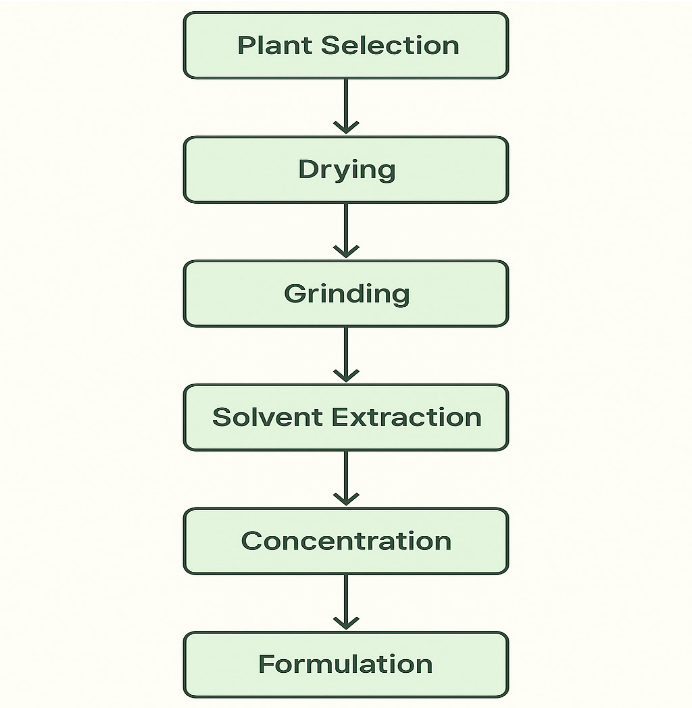


Figure 1 Flow chart showing plant material collection and extract preparation

8. Phytochemicals Versus Chemical Pesticides

Concerns over environmental harm from traditional chemical pesticides drive the growing demand for sustainable biopesticides. Globally, chemical pesticide consumption increased from 2.8 million tonnes in 2010 to 3.5 million tonnes in 2022, representing a 25% rise over the 12-year period. The European Union's (EU) pesticide use in Europe has also increased, from 402,229 tonnes in 2010 to

449,038 tonnes in 2022, representing a 12% rise. It was reported that Germany recorded the highest presence of pesticide residues in Europe both in terms of quantity (average concentration of 0.46 mg/kg) and diversity (Rodríguez-Seijo, et al., 2025). While effective, chemical pesticides pose risks, including soil contamination and toxicity to non-target organisms (Borowik et al., 2023; Navshree et al., 2025). According to Siegfried (1993), pesticides can inhibit ATPase enzymes involved in the movement of ions against a concentration gradient, which are regulated by active transport. Their continuous use has improved food production, but at the cost of soil degradation. Pesticides like cypermethrin are immobile in soil (Jones, 1995), declines soil health by binding to soil organic matter (SOM), harming beneficial microbial communities, and disrupting nutrient cycling and SOM stability (Borowik et al., 2023; Steiner et al., 2024). Although the use of chemical pesticides in agriculture is well-established, their long-term effects on SOM, microbial activity, and soil enzymes in agroecosystems are not well understood (Zhang et al., 2019). Studies have shown that chemical pesticides are highly effective against insects (Jones, 1995**)** and can suppress microbial biomass, alter community composition, and impair enzyme activity, which are all central to nutrient cycling (Rehman, et al., 2024; Aktar et al., 2009). Long-term exposure to pesticide residues can also shift the abundance of key microbial groups, thereby destabilizing SOM (Gunina, et al., 2017).

9. Challenges and Knowledge Gaps

Despite the growing recognition of phytochemical-based biopesticides as environmentally friendly alternatives, their adoption and consistent performance face several challenges. These include:

Limited Standardization and Quality Control

Many biopesticide formulations are prepared locally without standardized protocols, resulting in inconsistent efficacy and difficulties in meeting regulatory requirements (Kumar, et al., 2019)

Inadequate Research Funding and Support

Compared to synthetic pesticides, research on biopesticides receives limited funding, restricting studies on synergistic effects, optimal dosages, and long-term interactions with soil ecosystems (Singh & Choudhary, 2021).

Short Shelf Life and Storage Issues

Most plant-based extracts degrade quickly under heat or light exposure, which limits commercial scalability and practical use by farmers in remote or resource-limited areas (Mishra, et. al., 2022).

Lack of Farmer Awareness and Technical Knowledge

Smallholder farmers often lack access to training or extension services for proper preparation and application, leading to suboptimal pest control and soil benefits.

Regulatory and Policy Barriers

In many developing countries, policies for biopesticide registration are underdeveloped or complex, discouraging entrepreneurs and innovators from producing or marketing these eco-friendly solutions (Food and Agriculture Organization [FAO], 2020).

Limited Field Trials and Long-Term Studies

Most research is conducted under laboratory or greenhouse conditions. Multi-location, long-term field trials are required to validate the performance of phytochemical-based biopesticides under diverse soil and climatic conditions (Sharma, et al., 2022).

Table 1 Future Prospects and Research Needs for Phytochemical-Based Biopesticides

Focus Area	Description	Key Benefits
Molecular Characterization	Use advanced tools (HPLC, MS) to identify bioactive compounds and understand their mechanisms.	Enables accurate formulations and targeted applications.
Formulation and Delivery Technologies	Develop nano-formulations and controlled-release systems for stability and field efficiency.	Enhances bioavailability and reduces rapid degradation.
Integration with Soil Health Monitoring	Combine applications with digital tools and sensors for real-time soil assessment.	Optimizes dosage and timing; improves nutrient dynamics.
Policy and Extension Support	Establish quality standards, training programs, and adoption incentives.	Empowers smallholder farmers and promotes safe usage.
Field-Based, Long-Term Studies	Conduct multi-location trials under real farming conditions.	Validates ecological, economic, and social impacts.
Synergistic Use with Sustainable Practices	Integrate with biofertilizers, organic amendments, and precision agriculture.	Promotes soil regeneration and sustainable productivity.

10. Conclusion

Phytochemical-based biopesticides represent a sustainable alternative to conventional pesticides, offering dual benefits of effective pest suppression and enhanced soil health. Their multifunctional modes of action, ranging from growth regulation and enzyme inhibition to microbial community modulation, make them especially valuable in complex agroecosystems. Unlike synthetic pesticides, which often degrade soil quality and disrupt ecological balance, phytochemicals are biodegradable, eco-friendly, and compatible with integrated farming practices. Evidence from case studies demonstrates that phytochemicals can reduce pest infestations while promoting microbial diversity, improving soil enzyme activity, and enhancing nutrient cycling. However, their effectiveness is influenced by factors such as soil type, dosage, formulation, and crop system. This underscores the need for context-specific application strategies and continued research.

11. Recommendations

Strengthen Research on Soil–Biopesticide Interactions

More field-based studies are needed to explore long-term effects of phytochemicals on soil microbiota, enzyme activity, and ecosystem resilience. Multi-omics approaches should be expanded to capture holistic insights.

Promote Farmer-Centered Adoption

Policies and extension programs should prioritize training farmers on the safe preparation, handling, and application of phytochemical biopesticides. Demonstration farms can enhance awareness and trust in these eco-friendly alternatives.

Encourage Integration with Sustainable Farming Practices

Phytochemicals should be deployed as part of IPM frameworks, combined with crop diversification, cover cropping, and biofertilizer use to maximize benefits for both pest control and soil fertility.

Leverage Precision Agriculture

Adoption of precision tools (soil sensors, GIS, remote sensing) can optimize application, reduce wastage, and tailor phytochemical use to specific field conditions.

Support Policy and Market Incentives

Governments and stakeholders should provide subsidies, certification schemes, and market incentives that encourage the production and use of phytochemical-based formulations, especially among smallholder farmers.

In conclusion, phytochemical biopesticides are not merely substitutes for synthetic chemicals; they are catalysts for sustainable transformation in agriculture. By aligning pest management with soil restoration and ecological resilience, they provide a pathway toward safer food systems, healthier soils, and long-term environmental sustainability.

References

Acheuk, F., Basiouni, S., Shehata, A. A., Dick, K., Hajri, H., Lasram, S., Yilmaz, M., Emekci, M., Tsiamis, G., Spona-Friedl, M., May-Simera, H., Eisenreich, W., & Ntougias, S. (2022). Status and prospects of botanical biopesticides in Europe and Mediterranean countries. Biomolecules, 12(2), 311. https://doi.org/10.3390/biom12020311

Aktar, M. W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticide use in agriculture: Their benefits and hazards. *Interdisciplinary Toxicology, 2*(1), 1–12.

Borowik, A., Wyszkowska, J., Zaborowska, M., & Kucharski, J. (2023). The impact of permethrin and cypermethrin on plants, soil enzyme activity, and microbial communities. *International Journal of Molecular Sciences, 24*(3), 2892.

Ekenwosu, J., Okorie, P., & Amaechi, A. (2023). Field Investigation on Control of Spodoptera frugiperda (FAW) Using Aqueous Plant Extracts in Owerri, Southeast Nigeria. International Journal of Scientific Research in Biological Sciences, 10(4), 32–36. https://ijsrbs.isroset.org/index.php/j/article/view/599

Food and Agriculture Organization of the United Nations (FAO). (2020). *Biopesticides: A review of their use in crop production*. FAO. https://www.fao.org/publications/card/en/c/cb4244en/

García-Jaramillo, M., Arango, L. E., & Correa, A. E. (2018). Response of soil microbial communities to a combined application of glyphosate and nitrogen fertilizers. *Applied Soil Ecology, 123*, 1–8. https://doi.org/10.1016/j.apsoil.2017.09.006

Gunina, A., Dippold, M., Glaser, B., & Kuzyakov, Y. (2017). Turnover of microbial groups and cell components in soil: 13C analysis of cellular biomarkers. *Biogeosciences, 14*(2), 271–283.

Gupta, V., Bhushan, B., & Singh, R. (2019). A review on the impact of pesticides on soil health and microbial communities. *International Journal of Environmental Analytical Chemistry, 99*(13), 1404–1419. https://doi.org/10.1080/03067319.2019.1673856

Isman, M. B. (2020). Botanical insecticides in a new millennium: From a global perspective. *Pest Management Science, 76*(2), 809–813. https://doi.org/10.1002/ps.5528

Jones, A. (1995). *Environmental fate of cypermethrin*. Pesticide Information and Action Team (PIAT).

Khan, M. A., Ali, S., Hussain, M., Nawaz, A., & Raza, S. (2021). Bioremediation of pesticide-contaminated soil: A review. *Environmental Science and Pollution Research, 28*(20), 25307–25321. https://doi.org/10.1007/s11356-021-14065-2

Koul, O., Walia, S., & Singh, R. (2022). Botanical insecticides as an alternative to synthetic pesticides: A review. *Journal of Cleaner Production, 374*, 133887. https://doi.org/10.1016/j.jclepro.2022.133887

Kumar, A., Singh, N., & Sharma, P. (2019). Pesticide residues in agricultural soil and their effects on soil health: A review. *Environmental Science and Pollution Research, 26*(20), 20202–20215. https://doi.org/10.1007/s11356-019-05244-5

Kumar, P., Kumar, S., & Pal, S. (2023). Pesticide toxicity and remediation strategies in agricultural ecosystems: A review. *Journal of Environmental Management, 326*, 116742. https://doi.org/10.1016/j.jenvman.2022.116742

Lal, H., Singh, A., Kumar, R., & Varma, A. (2021). Bioremediation of pesticide-contaminated soil: A review of recent advances. *Environmental Science and Pollution Research, 28*(22), 29845–29858. https://doi.org/10.1007/s11356-021-12501-8

Li, X., Wang, Y., Zhang, W., Chen, J., Li, Y., & Gao, Y. (2024). Cypermethrin exposure alters soil bacterial communities and function: Insights from a long-term field study. *Journal of Hazardous Materials, 461*, 132485. https://doi.org/10.1016/j.jhazmat.2023.132485

Mandal, P., Dey, S., & Chatterjee, K. (2022). A review on the impacts of agrochemicals on soil health. *Journal of Environmental Management, 310*, 114672. https://doi.org/10.1016/j.jenvman.2022.114672

Mansoor, M. M., Khan, M. A., Tariq, A., Aslam, M., Hussain, M., Nawaz, A., & Raza, S. (2025). Impact of cypermethrin on soil microbial community and enzyme activities in agricultural lands. *Environmental Science and Pollution Research, 32*(4), 11467-11481. https://doi.org/10.1007/s11356-024-37599-4

Marcinkevičienė, A., Čmukas, A., Velička, R., Kosteckas, R., & Skinulienė, L. (2022). Effects of biopesticides and undersown cover crops on soil properties in the organic farming system. *Agronomy, 12*(9), 2153. https://doi.org/10.3390/agronomy12092153

Meena, H. R., Khan, M. A., & Singh, R. (2020). Impact of pesticides on soil microbial community and enzyme activities. *International Journal of Current Microbiology and Applied Sciences, 9*(1), 24–35. https://doi.org/10.20546/ijcmas.2020.901.004

Mishra, A., Mohanty, S., Barik, P., Kumar, S., & Mohapatra, P. (2022). Bioremediation of pesticide-contaminated soil: Recent advances and future perspectives. *Environmental Science and Pollution Research, 29*(1), 25–45. https://doi.org/10.1007/s11356-021-16982-1

Navshree, J. (2025). Impact of pesticides on soil health of agroecosystems. In *Sustainable soil health*. CABI. https://doi.org/10.1079/9781800624597.0003

Poslinski, H., Hatley, M., Tramell, J., & Song, B. (2025). Harnessing phytochemicals in sustainable and green agriculture. *Journal of Agriculture and Food Research, 19*, 101633. https://doi.org/10.1016/j.jafr.2025.101633

Rehman, H., Rehman, Z., Das, T. K., Rehman, M., Khan, B. A., Nandi, S., Ahmad, K., Mohanty, S. K., Ur Rehman, W., Naeem, R., Bajaj, M., & Tuka, M. B. (2024). Toxicity evaluation and degradation of cypermethrin-contaminated soil using biochar and *Bacillus cereus* amendments. *Scientific Reports, 14*(1), 29892

Rodríguez-Seijo, A., Pérez-Rodríguez, P., Arias-Estévez, M., Gómez-Armesto, A., Conde-Cid, M., Santás-Miguel, V., Campillo-Cora, C., Ollio, I., Lloret, E., Martínez-Martínez, S., Zornoza, R., Waeyenberge, L., Schrader, S., Brandt, K. K., Loit, K., Põldmets, M., Shanskiy, M., Peltoniemi, K., Hagner, M., & Fernández-Calviño, D. (2025). Occurrence, persistence and risk assessment of pesticide residues in European wheat fields: A continental scale approach. *Journal of Hazardous Materials, 475*, 133177

Sharma, S., & Singh, R. K. (2021). Impact of pesticides on soil microbial community and its functions: A review. *Environmental Science and Pollution Research, 28*(20), 25307–25321. https://doi.org/10.1007/s11356-021-14065-2

Sharma, P., & Singh, N. (2022). Impact of synthetic pesticides on soil microorganisms and their ecological functions: A review. *Current Research in Environmental & Applied Mycology, 12*(1), 101–114. https://doi.org/10.5943/cream/12/1/10

Sharma, P., Patel, V., & Singh, N. (2022). Bioremediation of pesticide-contaminated soil: A review of recent advances. *Journal of Environmental Management, 310*, 114756. https://doi.org/10.1016/j.jenvman.2022.114756

Siegfried, B. D. (1993). Comparative toxicity of pyrethroid insecticides to terrestrial and aquatic insects. *Environmental Toxicology and Chemistry, 12*(9), 1683–1689.

Singh, K., Bhardwaj, A. K., Kumari, S., & Singh, R. K. (2023). Impact of pesticides on soil microbial community and its functions: A review. *Environmental Science and Pollution Research, 30*(20), 57070–57085. https://doi.org/10.1007/s11356-023-26154-1

Singh, R., & Devi, P. (2019). Impact of pesticides on soil enzyme activities: A review. *Journal of Soil Science and Plant Nutrition, 20*(4), 1056–1070. https://doi.org/10.1007/s42729-019-00109-7

Singh, V., & Choudhary, S. (2021). Bioremediation of pesticide-contaminated soil: A review. *Journal of Environmental Management, 290*, 112520. https://doi.org/10.1016/j.jenvman.2021.112520

Singh, V., & Kuhad, R. C. (2018). Bioremediation of pesticide-contaminated soil: A review. *Journal of Environmental Management, 226*, 321–332. https://doi.org/10.1016/j.jenvman.2018.08.026

Soto-Barajas, M. C., Archundia, D., Martínez, O. G. R., López, E., Almazan, J., & Prado, B. (2025). Current and future perspectives on biopesticides analysis in soil. *Journal of Natural Pesticide Research, 12*, 100120. https://doi.org/10.1016/j.napere.2025.100120

Steiner, M., Falquet, L., Fragnière, A. L., Brown, A., & Bacher, S. (2024). Effects of pesticides on soil bacterial, fungal and protist communities, soil functions and grape quality in vineyards. *Ecology and Evolution, 14*(5), e12327.

Tadesse, K. T., Kinyanjui, G. K., Simiyu, S. W., Babalola, O. O., & Obonyo Ndolo, D. (2024). Biopesticides for sustainable agriculture: A review of their role in integrated pest management. *Sustainable Agriculture Reviews, 29*(4), 215–230. https://doi.org/10.5772/intechopen.1006277

Xue, W., Wang, Y., Wu, M., Xu, T., Liu, C., Gu, C., & Zhang, Y. (2022). Effects of pyrethroid and neonicotinoid pesticides on soil enzyme activities and microbial communities: A review. *Journal of Hazardous Materials, 426*, 128032. https://doi.org/10.1016/j.jhazmat.2021.128032

Yasir, M., Hossain, A., & Pratap-Singh, A. (2025). Pesticide degradation: Impacts on soil fertility and nutrient cycling. *Environments, 12*(8), 272. https://doi.org/10.3390/environments12080272

Zhang, R., Bai, Y., Zhang, T., Henkin, Z., Degen, A., Jia, T., Guo, C., Long, R., & Shang, Z. (2019). Driving factors that reduce soil carbon, sugar, and microbial biomass in degraded alpine grasslands. *Rangeland Ecology and Management, 72*(2), 396–404.

Zhou, X., Zhang, Y., & Wei, G. (2020). Impact of cypermethrin on soil microbial communities and enzyme activities. *Ecotoxicology and Environmental Safety, 189*, 110031. https://doi.org/10.1016/j.ecoenv.2019.110031

TITLE: BIOCHAR-AMENDED WASTEWATER IRRIGATION: A SUSTAINABLE APPROACH TO ENHANCE SOIL QUALITY AND PLANT NUTRIENT DYNAMICS UNDER HEAVY METAL STRESS

Asia Arooj[1], Fahd Rasul[2], Sobia Shahzad[3], Umair Gull[4]

1. Introduction

1.1. Global trends in water scarcity and wastewater reuse in agriculture

Freshwater is important abiotic resource for human survival and ecosystem health as it is important for agriculture, manufacturing processes and human life (Layani et al., 2021). Humans withdraw over four trillion cubic meters of freshwater annually from ground and surface sources, driven by population growth, rising individual consumption, and expanded irrigation for agriculture (Hoekstra et al., 2012).

Freshwater consumption for agricultural, industrial and domestic purposes is 70%, 22% and 8%, thus agriculture is major contributor to water scarcity (Pellegrin et al., 2016). Water scarcity is one of the worst ecological stresses that reduces agricultural productivity (Naz et al., 2020). The global human population is expected to increase gradually from 7.6 billion in 2017 to 9.8 billion in 2050 (United Nations, 2017). Rapid population increases water scarcity globally, particularly in the MENA area, where it is predicted that per capita water availability will fall half by 2050, placing a pressure on hydrological and underground resources (World Bank, 2007). Over the past few decades, urbanization has increased rapidly due to rise in the human population that has considerably increase municipal wastewater production (Maryam and Buyukgungor, 2019; Ye et al., 2019).

The management of municipal wastewater is a global challenge, particularly in coastal regions that constitute 60% of total population, as untreated discharge contaminates water bodies and spread diseases (Satyanarayana et al., 2010).

1 Department of Botany, University of Agriculture, Faisalabad, Pakistan (asiauroj9712@gmail.com), ORCID: https://orcid.org/0009-0005-4393-5361
2 Associate Professor, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan (drfahdrasul@gmail.com), ORCID: https://orcid.org/0000-0002-7813-2981
3 Assistant Professor, Department of Botany, The Islamia University of Bahawalpur, Bahawalnagar, Pakistan (sobia.shahzad@iub.edu.pk), ORCID: https://orcid.org/0000-0002-9056-2730
4 Assistant Professor, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan (umairgull@uaf.edu.pk), ORCID: https://orcid.org/0000-0002-2261-8202

Wastewater is used for irrigation purposes in urban and peri-urban farming communities due to water scarcity and poor wastewater infrastructure as it is contaminating the clean water sources. In arid regions, wastewater is used particularly for its reliability and nutrient content (Naz et al., 2020). The utilization of wastewater for irrigation purpose is a global practice (Singh, 2021).

1.2. Emerging concerns of heavy metal accumulation in agroecosystems

Wastewater presents a dual challenge, serving both as a valuable resource and a potential environmental concern (Rutkowski et al., 2007). Wastewater is a drought-resistant strategy that prevents resource depletion and waterway pollution by water scarcity mitigation, nutrient recycling, reduce fertilizer cost, lower carbon emissions, reduce energy cost and recover phosphorus from wastewater to preserve essential nutrient in a resource limited world (Dawson and Hilton, 2011). However, wastewater irrigation poses potential environmental and health risks that need to be addressed, such as heavy metals and saline salts (Li et al., 2009), excess nutrients (Kalavrouziotis et al., 2008) and pathogens (Kazmia et al., 2008) that causes negative effect on human health (Toze,2006), biosafety (Feldlite et al., 2008), biosafety (Feldlite et al., 2008), natural and artificial environment (Rong-guang et al., 2008), groundwater and soil resources (Khan et al., 2008).

Heavy metals are trace elements with an atomic density more than 4 ± 1 g/cm3, are found in wastewater by natural as well as anthropogenic activities. Heavy metal pollutants originate from natural processes such as volcanic eruption, soil erosion, aerosol particulate and urban runoffs as well as from anthropogenic activities such as landfills, fuel burning, electroplating, extraction operations, metal polishing and street runoffs (Akpor, 2014).

Heavy metal contamination in agricultural soils is a global concern. Besides geogenic and climatic factors, rapid urbanization and increased municipal, industrial, domestic, agricultural, technological and medical activities are primary contributors to heavy metal pollution in the environment. This issue is particularly severe in many developing countries, due to insufficient awareness of the toxic effects of heavy metals on both human and crop health (Kumar et al.,2016; Hasnine et al., 2017; Ahmed et al., 2019).

Toxic HMs limit the plant's nutrient acquisition capability and impede metabolic processes, resulting in lower biomass and growth. Metals and metalloids concentration increases due to inhibition of photosynthesis (PS1 and PSII) and increase in methylglyoxal content (Zaid et al., 2020). Heavy metals such as Cd, Zn, Pb, Fe, Cu, Hg, Ni, Mn, Co often exist in minute quantities are regarded as toxic and widespread component in wastewater effluent (Zhou et al., 2020).

HMs have adverse effects on plant growth, metabolism and yield that cause damage to chlorophyll pigments, chloroplast ultrastructure and important physiological processes like photosynthesis and water relations (Mourato et al., 2015). Excess of HMs produces reactive oxygen species in plants, which causes oxidative damage to cellular components (Malkowski et al., 2019).

1.3. Biochar as a multifunctional soil amendment

Biochar is carbon rich material that is manufactured through pyrolysis process by heating the biomass in the absence of oxygen. This process not only converts organic waste into stable form of carbon but also enhances its potential as a soil amendment and a tool for environmental remediation. This unique property of biochar, including its high surface area, enhancing water retention and sequestering carbon, thus contributing to sustainable agricultural practices (Ahmad e al., 2014). Its graphene like carbon matrix and high porosity increases the cation and anion exchange capacity and surface area which block the flow of pollutants and contaminants from water or soil to microorganisms. Biochar used widely in anaerobic digestion to remove microorganisms, trace metals and suspended particles in wastewater treatment process (Tan et al., 2020). Biochar has micropores which expand its surface area and adsorption capacity that determined the type of contaminant. Major biochar adsorption pathways are physical passage, pore filling and precipitation route that adsorb contaminants directly, through pores or from adsorbent layers (Enaime et al*.,* 2020).

Biochar produce by heating various organic materials such as wood, biosolids, crop residues and animal dung in oxygen limited environment which has been studied extensively as it has potential applications in energy production, waste management, climate change mitigation and soil improvement (Qian and Chen 2013). Biochar improve plant growth but its efficacy depend on pyrolysis temperature, soil type and parent material (Sarfraz et al., 2017). Biochar which is produced at 600–700 °C has potential capability to adsorb organic contaminants as they have high aromatic structure, porosity and surface area (Srinivasan and Sarmah, 2015). Therefore, biochar is used widely as potential sorbents in soil remediation and wastewater treatment (Jin et al., 2016).

Biochar is potential soil amendment as it produces stable aromatic carbon structure that has high water retention properties (Sanchez-Garcia et al., 2019). Acacia wood contain various components such as lignin, cellulose and hemicellulose that has diverse pore ranges and recalcitrant carbon structure which enhances adsorption properties (Pituya et al., 2017). Acacia wood biochar produced at gradual pyrolysis is more effective than fast pyrolysis as it does not demolish the wood structure that maintain soil moisture level and enhances crop productivity in water deficit environment (Foster et al., 2016).

Biochar has gained dual attention due to its role in agriculture and environmental management as it improves nutrient retention, soil structure and pollutant leaching. Potential use of biochar in wastewater irrigation systems is to immobilize contaminant in soils, such as heavy metals as it reduces the uptake of contaminants, particularly in areas where wastewater is utilized for irrigation (Olunusi et al., 2024).

1.4. Objectives

The objectives of this chapter is to explore the sustainable use of biochar in wastewater irrigated agricultural systems facing heavy metal stress. It aims to highlight the growing reliance on wastewater due to freshwater scarcity and the associated risks of heavy metal accumulation in soil and crops. The chapter discusses how biochar produced from various lignocellulosic feedstocks, can improve soil properties and reduce the mobility and bioavailability of toxic metals such as Cd, Pb, Cr and Co. It also evaluates the mechanism through which biochar enhances soil quality including ion exchange, surface adsorption and pH regulation. Furthermore, the chapter examines biochar role in stabilizing organic matter, improving nutrient retention and supporting plant nutrient uptake under contaminated conditions. Overall, the chapter provides insight into the potential of biochar amended wastewater irrigation as a strategy to improve soil fertility, support phytoremediation and promote climate resilient, sustainable agriculture.

2. Wastewater Irrigation: Risks and Opportunities

2.1. Historical and current use of wastewater in agriculture

The humans population is expected to increase steadily from 7.6 billion in 2017 to 9.8 billion in 2050 (United Nations, 2017). During last few decades, urbanization has rapidly increased due to human population (Maryam and Buyukgungor, 2019) The shortage of freshwater for irrigation in arid and semi-arid regions is a significant challenge to agricultural production and food security. The increasing scarcity of freshwater resources has led to the widespread use of wastewater for irrigation in agriculture (Qadir et al., 2010). In urban water, only 15–25% of the diverted or withdrawn water is consumed while remaining discharged as wastewater into the urban hydrologic system (Hamilton et al., 2007). In many cities across Asia and Africa, population growth has exceeded sanitation and wastewater infrastructure capacity, creating major challenges for urban wastewater management, 24% of domestic and industrial wastewater is treated in India, and only 2% in Pakistan (IWMI, 2003).

The utilization of wastewater for agricultural irrigation is a practice deeply rooted in human history, emerging as a pragmatic solution to water scarcity and nutrient recycling. Archaeological and historical evidence indicates that ancient civilizations, such as those in Mesopotamia, China, and the Indus

Valley, likely used diluted sewage or drainage water to nourish crops thousands of years ago (Angelakis and Snyder, 2015). More structured systems appeared in Hellenistic and Roman times, exemplified by the connection of sewage conduits to agricultural fields near cities. During the European Middle Ages and into the 19th century, the practice continued, notably in "sewage farms" established near expanding urban centers like Berlin, Paris, and Melbourne. These farms primarily aimed at wastewater disposal to protect public health but simultaneously provided water and nutrients for fodder and non-food crops, forming the foundation of intentional wastewater reuse (Jimenez and Asano, 2008).

The modern era of planned wastewater reuse in agriculture began in earnest in the early to mid-20th century, driven by increasing water scarcity, population growth, urbanization, and the recognition of wastewater's fertilizer value. The advent of more sophisticated treatment technologies, starting with primary and secondary treatment, allowed for safer and more reliable application. Significant projects emerged, particularly in arid and semi-arid regions like Israel (establishing national reuse policies in the 1950s), California (e.g., Monterey Wastewater Reclamation Study for Agriculture in the 1960s-70s), and Mexico (e.g., the Mezquital Valley, one of the world's largest continuous irrigation systems using untreated wastewater for over a century, later transitioning to treated use) (Scott et al., 2004). This period saw a shift from viewing wastewater solely as a disposal problem towards recognizing it as a valuable resource, though often still driven by necessity.

Currently, wastewater agriculture is a globally significant practice, estimated to involve at least 10% of the world's irrigated cropland and tens of millions of farmers (UN-Water, 2021). Its application varies dramatically. In high-income countries and regions with stringent regulations (e.g., USA, EU, Australia, Israel, Singapore), treated wastewater undergoes advanced purification processes (often tertiary treatment including filtration and disinfection, sometimes membrane technologies) to meet strict quality standards (e.g., WHO guidelines, US EPA regulations) before being used for irrigation, including food crops consumed raw (Asano et al., 2007; WHO, 2006). Israel leads globally, reusing nearly 90% of its treated wastewater, primarily for agriculture. Conversely, in many low- and middle-income countries, particularly in rapidly urbanizing areas of Asia, Africa, and Latin America, the predominant practice remains the direct use of untreated or inadequately treated wastewater. This is often driven by severe water scarcity, unreliable freshwater access, proximity to pollution sources, and the vital need for water and nutrients to support livelihoods and urban food supply, despite significant health and environmental risks (Drechsel et al., 2010; Qadir et al., 2010). Farmers frequently rely on diluted or partially settled wastewater from rivers receiving urban discharges.

The scale and nature of current wastewater use highlight a critical duality: while advanced systems demonstrate its potential as a safe, sustainable resource contributing to water and food security, the widespread unregulated use of untreated wastewater poses major challenges. These include risks to farmer and consumer health (exposure to pathogens, heavy metals, pharmaceuticals), environmental contamination (soil salinization, groundwater pollution), and potential market rejection of produce (Drechsel et al., 2010; WHO, 2006). Global efforts, therefore, focus on bridging this gap through promoting safer practices, implementing appropriate risk-based treatment levels (e.g., WHO's Multiple Barrier Approach), improving governance, and supporting affordable treatment technologies suitable for resource-constrained settings, aiming to maximize the benefits while minimizing the risks of this ancient yet increasingly vital practice.

2.2. Nutritional benefits vs. environmental and health risks

Wastewater presents a dual challenge, serving both as a valuable resource and a potential environmental concern (Rutkowski et al., 2007). Wastewater is a drought-resistant strategy that prevents resource depletion and waterway pollution by water scarcity mitigation, nutrient recycling, reduce fertilizer cost, lower carbon emissions, reduce energy cost and recover phosphorus from wastewater to preserve essential nutrient in a resource limited world (Dawson and Hilton, 2011). However, wastewater irrigation poses potential environmental and health risks that need to be addressed, such as saline salts and heavy metals (Li et al., 2009), pathogens (Kazmia et al., 2008), excess nutrients (Kalavrouziotis et al., 2008) that causes negative effect on biosafety (Feldlite et al., 2008), human health (Toze, 2006), biosafety (Feldlite et al., 2008), natural and artificial environment (Rong-guang et al., 2008), soil and groundwater resources (Khan et al., 2008).

Wastewater is a cost-effective fertilizer rich in NPK (48.3, 7.6, and 72.4 mg L^{-1} of potassium, nitrogen and phosphorus) and micronutrients like zinc, iron, copper and manganese (Chaw and Reves, 2001). It is source of macro and micronutrients making them a cost-effective alternative to fertilizers and plant growth regulators, despite it contains many heavy metals (HMs) (like iron, zinc, mercury, cadmium and cobalt etc.) and pollutants that are absorbed and translocated to the edible portion of vegetables and causing detrimental effect on human health, ecosystem and environment. Sewage, industrial and domestic wastewater is used to irrigate vegetables due to short supply of fresh water (Singh, 2021). Treated and untreated wastewater is used to irrigate more than twenty million hectares of land (Singh, 2021).

Elements such as Ca, Mo, Cu, B, Zn, Fe, Ni, Mg, and Mn are classified as essential mineral nutrients for plant productivity and growth by enhancing specific cellular functions such as photosynthesis, respiration, pigment biosynthesis, ion homeostasis, enzyme activity, gene regulation, gene regulation, nitrogen fixation and sugar metabolism (Tiwari and Lata, 2018). However, when accumulated above optimal concentrations, these essential elements adversely affect plant development, growth, and reproduction by disrupting physiological and metabolic processes (Shahid et al., 2015). If the concentration of essential elements falls below certain threshold levels, plants exhibit mineral deficiency symptoms such as stunted growth, chlorosis (yellowing of leaves), necrosis, premature leaf drop, and reduced metabolic functions, ultimately impairing overall plant health and productivity (Shahzad et al., 2023).

HMs or trace metals, are persistent wastewater pollutants that discharge into water bodies causes environmental and health risks. Human exposure occurs through inhalation of dust, fumes, vapors, and ingestion of contaminated food and water. In aquatic ecosystems, heavy metals cause organism mortality, algal blooms, habitat disruption from sedimentation and debris, altered water flow, and both acute and chronic toxicity. Excessive heavy metals in soils reduce crop quality and yield by inhibiting plant growth, nutrient uptake, and metabolic processes (Akpor et al., 2014).

2.3. Heavy metals in wastewater: sources, behavior, and plant-soil interactions

Metals are inorganic substances with atomic densities several times greater than water (1 gcm^{-3}) and classified as heavy metals and metalloids. Based on their physical, chemical, and physiological properties, metals are categorized into subgroups: transition metals like Fe, Cr, Co, Mn, Co, Cu, Ni, Mo; post-transition metals, Zn, Al, Hg, Cd, Pb; alkali metals such as Na, Li, Cs, K; alkaline earth metals such as Ba, Ca, Mg, Be and metalloids or semi-metals, exhibiting both metallic and non-metallic properties such as Sb, Si, B, As (Pourret and Hursthouse, 2019).

HMs are frequently discharged in wastewater from various industrial processes such as electroplating and surface treatment. Additionally, wastewater from tannery, leather, pigment and dye, textile, paint, petroleum refining, wood processing, and photographic film industries contains significant HMs concentrations. These metal ions are toxic to animals and humans and animals, causing physical discomfort, potentially life-threatening illnesses, and irreversible damage to vital organ systems (Malik, 2004). HMs bioaccumulate in aquatic environments and magnified through food chain, resulting in increased toxicity to organisms at higher trophic levels. Approximately 20 metals are highly persistent and resistant to degradation like lead (Pb), mercury (Hg), hexavalent chromium (Cr [VI]), cadmium (Cd), arsenic (As), zinc (Zn), and nickel (Ni) are considered toxic from ecotoxicological perspective (Balali-Mood et al., 2021).

Various soil, plant and metal-related factors significantly influence the interaction and uptake of heavy metals by crop plants (Njoku and Nwani, 2022). Crop factor encompass type (species, cultivar, genotype), growth stage, prevailing edaphic/climatic conditions, metabolic processes and physiological capacities. Primary soil factors comprise pH, organic matter content, rhizosphere biogeochemistry, cation exchange capacity, and microbial community dynamics. Secondary soil attributes include texture, moisture status, aeration/compaction state, and temperature. Heavy metal determinants encompass speciation (organic/inorganic), concentration, oxidation states, mobility, solubility, bioavailability, interaction with soil colloids, and associations with essential plant nutrients (Ca, Mg, Zn) or non-essential elements (Hg, Cd, Pb) (Hasan et al., 2017).

Plants employ diverse mechanisms in mitigating the toxic effects of HMs by sequestration and binding to cell wall, active transport of HMs into vacuolar compartments, synthesis of metal binding proteins such as cysteine rich metallothioneins and phytochelatins. These proteins play critical roles in maintaining metal ion homeostasis, chelating and sequestering excess metal ions, and detoxifying surplus HMs within plant cells, thereby preventing cellular damage and ensuring metal tolerance (Hasan et al., 2017). Reduced glutathione, a tripeptide composed of glycine, cysteine and glutamic acid, exhibits a strong affinity for HMs ions such as Cu, Cd, Zn, Hg, Ni, Pb, and As. Acting as a ligand, GSH chelates these metals, thereby mitigating their toxic effects on plants. Based on their binding affinities to GSH, the heavy metals can be ranked in the following order: Cd > Pb > Zn > Hg > As > Cu (Pal and Rai, 2010). Certain proteins within the mitogen-activated protein kinase (MAPK) family are activated in response to copper (Cu) or cadmium (Cd) accumulation. These Cu- or Cd-induced MAPKs facilitate the upregulation of transporter proteins involved in the sequestration and efflux of heavy metals, thereby promoting their removal from plant cells (Jonak et al., 2004). Based on proteomic and complementary analyses, a study indicated that hemp plants can acclimate to elevated levels of lead (Pb) toxicity by enhancing cellular respiration, photosynthetic efficiency (primary photochemistry), and intercellular carbon and nitrogen assimilation. Additionally, they mitigate Pb-induced stress by preventing the aggregation of unfolded proteins, promoting the degradation of misfolded proteins, and increasing transmembrane ATP transport (Xiao et al., 2019). Plants exposed to soils with elevated heavy metal (HM) concentrations release chemical signaling molecules such as ethylene and jasmonic acid, which play crucial roles in mitigating HM toxicity by modulating stress responses and enhancing tolerance mechanisms (Thao et al., 2015).

HMs enter plant roots via passive apoplastic diffusion through cell walls and intercellular spaces, or via active symplastic transport across plasma membranes into living cells (Yan et al., 2020). The extent of phytotoxicity is influenced not only by root absorption but also by the translocation of heavy metals to various plant tissues and their accumulation to toxic concentrations. Study demonstrated that after 20 days of exposure, mercury (Hg) translocation was less than 2% in leaves and less than 4% in shoots relative to the total Hg content ($\mu g\ g^{-1}$ dry weight) absorbed by the roots of tomato seedlings (Cho et al., 2000). Metal transporters are integral to the uptake, translocation, and detoxification of heavy metals in plants by facilitating their movement into cells, redistribution among tissues, and sequestration into vacuoles for detoxification (Feng et al., 2010).

Heavy metal elements can exhibit synergistic or antagonistic interactions during their absorption and translocation within plants. For instance, the presence of mercury (Hg) in the growth medium significantly inhibited arsenic (As) accumulation in roots, demonstrating an antagonistic effect of Hg on As uptake. Conversely, this interaction became synergistic during As translocation to the shoots, particularly at elevated Hg concentrations (Du et al., 2005). Cadmium uptake in rice plants was reduced in the presence of iron (Fe) plaque formation around the roots, indicating an antagonistic effect of Fe on Cd absorption (Siddique et al., 2021). Additionally, a study reported that chromium (Cr) and lead (Pb) concentrations in locally cultivated vegetable species at heavy metal-contaminated sites in Dhaka, Bangladesh, were approximately 10 and 2 times higher, respectively, than the permissible limits established by FAO/WHO for plants. Based on observations across multiple vegetable species, several studies have attributed variations in heavy metal toxicity to differences in their uptake and translocation within the plants (Siddique et al., 2021).

Nonetheless, overall HM phytotoxicity is contingent upon plant efficacy in executing physiological processes: rhizofiltration (root-mediated HM adsorption within the rhizosphere), phytostabilization (soil-based HM immobilization reducing bioavailability), phytoextraction (HM uptake and translocation to aerial tissues), phytoaccumulation (accumulation as metabolically active form), and phytovolatilization (volatilization of absorbed HMs into the atmosphere (Kafle et al., 2022). The prevalence and the bioavailability of heavy metals in soils act as a fundamental determinant of phytotoxic effects in the plants.

2.4. Case examples from recent studies (2020–2025)

Table 1: Summary of Key Findings from Recent Case Studies (2020-2025)

Region/ Context	Study Focus	Key Findings	Major Challenges Identified	Citation Examples
Israel (Negev)	Precision Irrigation + Advanced Treatment (MBR/RO)	>30% water savings, 15-25% fertilizer reduction, high water quality, positive ROI for large farms.	High initial capital cost, energy demand for RO.	Gross et al., (2023)
Ghana (Kumasi)	Decentralized Nature-Based Treatment	Effective pathogen reduction (>95% helminths), high farmer WTP (~20% premium).	Limited heavy metal removal, maintenance funding, land tenure.	Amoah et al., (2022)
India (Delhi Peri-urb)	Policy-Practice Gap & Health Risks	Widespread use of untreated water despite STPs; heavy metal/pathogen accumulation; farmer awareness but no alternatives.	Infrastructure gaps, unreliable treated supply, enforcement.	Thomas and Roy (2024)
Mexico (Mezquital)	Transition from Untreated to Treated Water	Reduced salinity/ pathogens; Altered soil microbiome; Variable yield impacts; Increased farmer costs.	Ecosystem adaptation, economic viability for farmers.	Heyde et al., (2025); Acosta-Gonzalez et al., (2022)
Global	Antibiotic Resistance Genes (ARGs)	Conventional WW irrigation enriches soil ARGs/MGEs; Persistence/transfer risks. Advanced treatment needed.	Cost of ARG-targeting treatment, lack of regulations.	Chen et al., (2021); Manaia (2023)
Australia/ Europe	PFAS Contamination	Uptake into crops/forage, livestock exposure, contamination of food chain. Source control critical.	Persistence, remediation difficulty, lack of cost-effective advanced treatment.	Gallen et al., (2022); Gredelj et al., (2025)

3. Biochar: Properties, Mechanisms, and Agricultural Role

3.1. Origin and production from various feedstocks

Biochar is a pyrogenic carbon material produced from diverse feedstocks including agricultural residues, food processing waste, woody biomass, animal manure and municipal solid waste (Singh et al., 2020), and it derives from the pyrolysis of these biomasses under oxygen-limited conditions (Lopez et al., 2020). The notable characteristics of biochar, including its extensive surface area, chemical recalcitrance, elevated sorption capacity, and unique microstructure, render it a multifunctional material efficacy for diverse environmental applications (environmental contaminant immobilization, soil restoration, wastewater treatment, climate change mitigation and renewable energy production) (Ye et al., 2017; Zhang et al., 2020). Biochar application to land has attracted worldwide attention (Shen et al., 2022). Numerous studies have demonstrated that biochar application to soil could increase soil-organic-matter (SOM) content (Liang et al., 2021), boost crop yield (Kizito et al., 2019) soil fertility, improve soil structure (Siedt et al., 2021) and decrease greenhouse-gas emissions (Kalu et al., 2022)

Organic material can serve as a feedstock for biochar production regulations (Tripathi et al., 2016) as the availability of feedstocks maybe constrained by production costs and regulatory considerations (Shackley et al., 2011).While biochar production and composting utilize organic biomass as feedstocks, there is no inherent competition between them; rather these processes improve the management and disposal of organic solid waste. Feedstocks with high moisture content are unsuitable for biochar production because additional energy is required to evaporate water during pyrolysis, whereas such materials are ideal for composting, which requires a moisture content of approximately 60-70% (Camps and Tomlinson, 2015).

Biochar produced through the thermochemical conversion of biomass feedstocks (Fig. 1). Gasification, pyrolysis, and hydrothermal carbonization are techniques in which biomass is heated at relatively low temperature (300-900 °C) under oxygen deficient condition is the cost effective and efficient approach for biochar production (Initiative, 2012; Cha et al., 2016). Pyrolysis is further classified into slow and fast based on heating rates. Despite certain drawbacks including lower energy efficiency and longer processing times, slow pyrolysis continues to be the most widely employed method for biochar production due to its relatively higher yield (Tripathi et al., 2016).

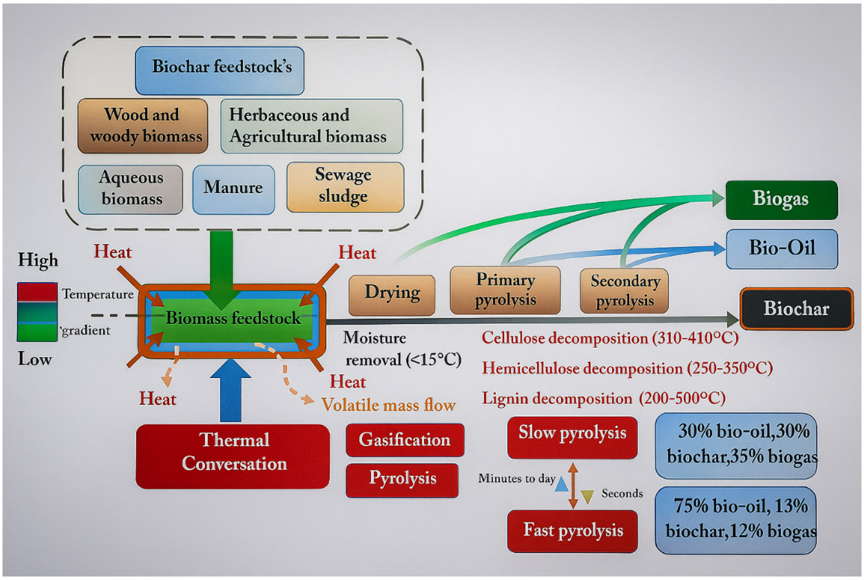


Fig.1. Introduction of biochar feedstock and its production processes (slightly modified from Xiao et al., 2017)

3.2. Key properties affecting soil and plant responses

3.2.1. Biochar Application and Soil Health:

Biochar application improves soil physical/chemical properties, crop yield, produce quality, and removes pollutants (Medynska-Juraszek et al., 2021; Kamali et al., 2022). Soil health, defined as the capacity to sustain plant development/production (Doran and Zeiss, 2000), relies on physical, biological and chemical characteristics (Igalavithana et al., 2017). Low fertility is widespread, especially in arid/semi-arid regions (low water/nutrient storage) (Khalifa and Yousef, 2015) and rainforests (nutrient leaching, high SOM mineralization) (Bruun et al., 2015). Biochar enhances soil health by improving properties, increasing water retention/protection, preventing degradation, increasing nutrient content/sequestration, attenuating toxins, promoting soil organism well-being, and boosting plant growth/biomass/yield/profits (Brtnicky et al., 2021).

3.2.1.1. Physical Properties:

Biochar reduces soil bulk density (average 12% reduction) and compaction (>10%), increases porosity (average 8.4%), improves water holding capacity (15.1%), and enhances saturated hydraulic conductivity (25%), thereby improving water/air/heat transport (Balconi-Canqui, 2017). These effects depend on biochar amount, soil type, pyrolysis temperature (<450°C can cause hydrophobicity), and feedstock (Jien et al., 2021; Zhang and You, 2013). Biochar can promote aggregation and structural stability, particularly in clay soils (Jien et al., 2021; Sun and Lu, 2014).

3.2.1.2. Chemical Properties:

Biochar (BC) alkalinity combats soil acidification, increasing pH and availability of cations (K, Mg, Ca, Na). Long-term increases are documented (e.g., pH 3.89 to 4.05 after 4 years; pH 3.9 to 5.1 in Sumatra) (Major et al., 2010). BC mitigates salinity/sodicity by improving soil structure (enhancing infiltration), balancing ions via CEC, and fostering salt-tolerant microbial activity (Dahlawi et al., 2018). BC application generally increases soil CEC due to surface oxidation and reactive functional groups (e.g., COOH, OH) (Rogovska et al., 2011). Effects vary with soil type (stronger increases in non-calcareous soils) (Laird et al., 2010). BC reduces nutrient leaching (N, NO_3, K, P, Mg, Na, Ca), increases nutrient availability (especially P and K), enhances soil organic carbon (SOC) sequestration, and improves nutrient use efficiency (Luo et al., 2020). Field trials show significant improvements in soil P, K, Na, Mg, C, and N content (Martinsen et al., 2014).

3.2.1.3. Soil Biological Properties:

Biochar impacts microbial biomass carbon (MBC) and nitrogen (MBN), generally increasing MBC (15.2–71.8%) but having variable effects on MBN depending on depth/dose (Zou et al., 2016). It enhances microbial diversity and activity by providing carbon, nutrients, habitats (pores), and favorable microenvironments (Lu et al., 2020; Ge et al., 2019). Increases in specific microbial groups (e.g., denitrification genes, ammonia oxidizers) are reported (Xiao et al., 2019). Effects on microbial biomass and community composition (bacteria, fungi, AMF) are highly variable, depending on biochar type/feedstock, dose, soil type, and time (Zou et al., 2016). Negative effects can occur due to toxins (polyphenols), reduced nutrient availability, or physical changes (Das et al., 2018).

3.2.2. Crop Growth, Development, and Yield:

Field studies show biochar increases yields (e.g., maize 16-35%, durum wheat up to 30%, cumulative rice/sorghum ~75%) in degraded, acidic, or nutrient-poor soils, linked to improved nutrient availability, soil structure, and moisture (Yi et al., 2023). Effects are often greater in acidic soils and may increase over time (long-term impact) (Major et al., 2010). Meta-analyses confirm significant average yield increases (13-20%) (Chen et al., 2023). Negative or neutral effects occur in some contexts, sometimes due to nutrient leaching or reduced alkalinity over time (Jin et al., 2019).

Biochar and Regenerative Agriculture: Biochar enhances regenerative agriculture by improving nutrient retention/availability, soil structure and water-holding capacity. It acts as a stable carbon sink for long-term sequestration, mitigating climate change. It fosters beneficial soil microbial communities and symbiotic relationships (e.g., mycorrhizae), aids in contaminant remediation (e.g., immobilizing heavy metals), and improves water quality by reducing nutrient runoff/leaching (Woolf et al., 2010).

3.3. Mechanisms of heavy metal immobilization and nutrient retention

Heavy metal contamination in environmental water contains toxic metals such as Cu, Cd, Hg, Pu, Cr, Ni, Zn and U as well a metalloid such as As and Se, emerged as global challenge (Yang et al., 2021; Li et al., 2021). HMs cause health disorders such as cancer while biochar serves as effective and eco friendly adsorbent for water purification and its surface modifications can markedly enhance porosity, reactivity and sorption capacity. The primary method by which biochar removes HMs from wastewater include complexation, electrostatic attraction and ion exchange. Consequently, biochar application in heavy metal remediation is considered a promising approach (Liang et al., 2021; Chen et al., 2021).

Heavy metal removal efficiency and mechanism of biochar largely depend on the modification technique applied (Cai et al., 2022) as properly executed modification can enhance the stability of heavy metals bound to biochar, thereby strengthening chemisorption and overall removal. For instance, pyrolyzed sulfate lignin biochar modified with CO_2 at 800 °C and impregnated with FeOx significantly improved arsenic adsorption from aqueous solutions (Cha et al., 2021). Similarly, microwave assisted modification of reed straw biochar with nano magnetite increased its arsenic sorption capacity to 9.92 $mg \cdot g^{-1}$, compared to 8.03 $mg \cdot g^{-1}$ for unmodified biochar (Song et al., 2020).

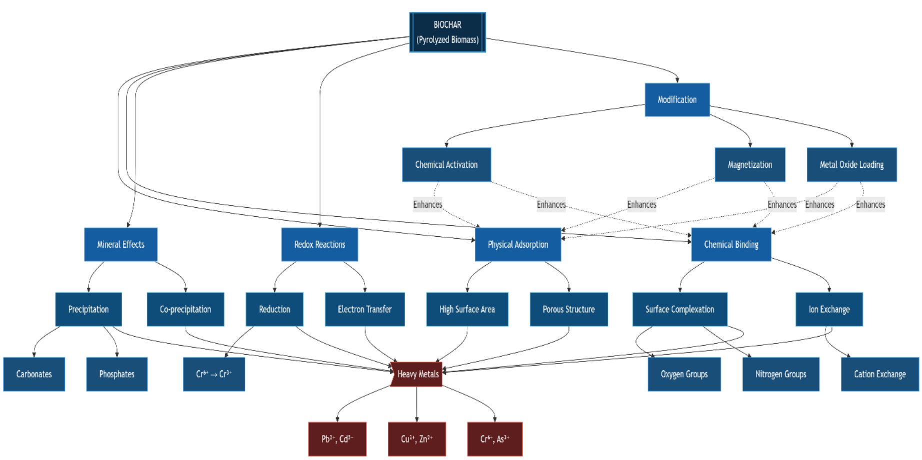


Fig.2. Biochar mechanism to remove heavy metals

Conclusion

Biochar amended wastewater irrigation represents a sustainable strategy to address the dual challenges of water scarcity and soil contamination in modern agroecosystems. By modifying soil physicochemical properties, biochar improves nutrient dynamics, enhances cation exchange capacity, and stabilizes organic carbon while reducing the phytoavailability of toxic heavy metals such as Cd, Pb, Cr, and Co. Its multifunctional role extends to supporting microbial activity, improving soil structure, and fostering crop growth under stress conditions. Despite these benefits, variations in biochar feedstock, pyrolysis conditions, and site-specific soil responses highlight the need for tailored application strategies. Long-term field studies are essential to better understand the persistence of biochar effects on soil fertility and metal immobilization. Integrating biochar into wastewater-based irrigation systems can not only mitigate environmental risks but also contribute to resilient, nutrient-efficient, and climate-smart agriculture, ensuring sustainable crop production in regions facing freshwater scarcity.

References

Acosta-Gonzalez, U., Silva-Rojas, H. V., Fuentes-Aragon, D., Hernandez-Castrejon, J., Romero-Bautista, A., & Rebollar-Alviter, A. (2022). Comparative performance of fungicides and biocontrol products in the management of Fusarium wilt of blackberry. *Plant Disease*, *106*(5), 1419-1427.

Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S. and Ok, Y.S. (2014). Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere*, *99*, 19-33.

Ahmed, M., Matsumoto, M., Ozaki, A., Thinh, N. V., & Kurosawa, K. (2019). Heavy metal contamination of irrigation water, soil, and vegetables and the difference between dry and wet seasons near a multi-industry zone in Bangladesh. *Water*, *11*(3), 583.

Akpor, O. B., Ohiobor, G. O., & Olaolu, D. T. (2014). Heavy metal pollutants in wastewater effluents: sources, effects and remediation. *Advances in Bioscience and Bioengineering*, *2*(4), 37-43.

Amoah, P., Keraita, B., Drechsel, P., Cofie, O. O., & Raschid-Sally, L. (2022)**.** Performance and adoption of decentralized nature-based wastewater treatment systems in urban Ghana. *Journal of Environmental Management, 310*, 114661. https://doi.org/10.1016/j.jenvman.2022.114661

Angelakis, A. N., & Snyder, S. A. (2015). Wastewater treatment and reuse: Past, present, and future. *Water*, *7*(9), 4887-4895.

Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in pharmacology*, *12*, 643972.

Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal*, *81*(4), 687-711.

Brtnicky, M., Datta, R., Holatko, J., Bielska, L., Gusiatin, Z. M., Kucerik, J., Hammerschmiedt, T., Danish, S., Radziemska, M., Mravcova, L. and Fahad, S. (2021). A critical review of the possible adverse effects of biochar in the soil environment. *Science of the Total Environment*, *796*, 148756.

Bruun, T. B., Elberling, B., de Neergaard, A., & Magid, J. (2015). Organic carbon dynamics in different soil types after conversion of forest to agriculture. *Land Degradation & Development*, *26*(3), 272-283.

Cai, Y., Zhang, Y., Lv, Z., Zhang, S., Gao, F., Fang, M., Kong, M., Liu, P., Tan, X., Hu, B. and Wang, X. (2022). Highly efficient uranium extraction by a piezo catalytic reduction-oxidation process. *Applied Catalysis B: Environmental*, *310*, 121343.

Camps, M., & Tomlinson, T. (2015). The use of biochar in composting. *International Biochar Initiative*, 1-4.

Cha, J. S., Jang, S. H., Lam, S. S., Kim, H., Kim, Y. M., Jeon, B. H., & Park, Y. K. (2021). Performance of CO2 and Fe-modified lignin char on arsenic (V) removal from water. *Chemosphere*, *279*, 130521.

Cha, J. S., Park, S. H., Jung, S. C., Ryu, C., Jeon, J. K., Shin, M. C., & Park, Y. K. (2016). Production and utilization of biochar: A review. *Journal of Industrial and Engineering Chemistry*, *40*, 1-15.

Chaw, R., & Reves, A. S. (2001). Effect of Wastewater on Mentha piperita and Spinacia oleracea. *J. Environ. Biol*, *51*, 131-145.

Chen, H., Yang, X., Liu, Y., Lin, X., Wang, J., Zhang, Z., Li, N., Li, Y. and Zhang, Y. (2021). KOH modification effectively enhances the Cd and Pb adsorption performance of N-enriched biochar derived from waste chicken feathers. *Waste Management*, *130*, 82-92.

Chen, J., Wang, T., Zhang, K., Luo, H., Chen, W., Mo, Y., & Wei, Z. (2021). The fate of antibiotic resistance genes (ARGs) and mobile genetic elements (MGEs) from livestock wastewater (dominated by quinolone antibiotics) treated by microbial fuel cell (MFC). *Ecotoxicology and Environmental Safety*, *218*, 112267.

Chen, Z., Liu, J., Sun, H., Xing, J., Zhang, Z., & Jiang, J. (2023). Effects of biochar applied in either rice or wheat seasons on the production and quality of wheat and nutrient status in paddy profiles. *Plants*, *12*(24), 4131.

Cho, U. H., & Park, J. O. (2000). Mercury-induced oxidative stress in tomato seedlings. *Plant science*, *156*(1), 1-9.

Dahlawi, S., Naeem, A., Rengel, Z., & Naidu, R. (2018). Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Science of the Total Environment*, *625*, 320-335.

Das, S. K., Avasthe, R. K., Singh, M., & Yadav, A. (2018). Soil health improvement using biochar application in Sikkim: a success story. *Innov Farming*, *3*(1), 48-50.

Dawson, C. J., & Hilton, J. (2011). Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. *Food Policy*, *36*, S14-S22.

Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: managing the biotic component of soil quality. *Applied soil ecology*, *15*(1), 3-11.

Drechsel, P. (Ed.). (2010). *Wastewater irrigation and health: assessing and mitigating risk in low-income countries*. IWMI.

Du, X., Zhu, Y. G., Liu, W. J., & Zhao, X. S. (2005). Uptake of mercury (Hg) by seedlings of rice (Oryza sativa L.) grown in solution culture and interactions with arsenate uptake. *Environmental and experimental botany*, *54*(1), 1-7.

Enaime, G., Bacaoui, A., Yaacoubi, A., & Lubken, M. (2020). Biochar for wastewater treatment—conversion technologies and applications. *Applied Sciences*, *10*(10), 3492.

Feldlite, M., Juanico, M., Karplus, I., & Milstein, A. (2008). Towards a safe standard for heavy metals in reclaimed water used for fish aquaculture. *Aquaculture*, *284*(1-4), 115-126.

Feng, J. I. N., Cui, W. A. N. G., Hai-Jian, L., Ya-Ou, S., Zhi-Ming, Z., Mao-Jun, Z., & Guang-Tang, P. (2010). Heavy metal-transport proteins in plants: A review. *Chinese Journal of Applied Ecology/ Yingyong Shengtai Xuebao*, *21*(7).

Foster, E. J., Hansen, N., Wallenstein, M., & Cotrufo, M. F. (2016). Biochar and manure amendments impact soil nutrients and microbial enzymatic activities in a semi-arid irrigated maize cropping system. *Agriculture, Ecosystems & Environment*, *233*, 404-414.

Gallen, C., Bignert, A., Taucare, G., O'Brien, J., Braeunig, J., Reeks, T., Thompson, J. and Mueller, J.F. (2022). Temporal trends of perfluoroalkyl substances in an Australian wastewater treatment plant: A ten-year retrospective investigation. *Science of The Total Environment*, *804*, 150211.

Ge, X., Cao, Y., Zhou, B., Wang, X., Yang, Z., & Li, M. H. (2019). Biochar addition increases subsurface soil microbial biomass but has limited effects on soil CO_2 emissions in subtropical moso bamboo plantations. *Applied Soil Ecology*, *142*, 155-165.

Gredelj, A., Roberts, J., Kearney, E. M., Barrett, E. L., Haywood, N., Sheffield, D., Hodges, G. and Miller, M.A. (2025). Predicting aquatic toxicity of anionic hydrocarbon and perfluorinated surfactants using membrane-water partition coefficients from coarse-grained simulations. *Environmental Science: Processes & Impacts*, *27*(4), 1131-1144.

Gross, A., Azulay, C., & Ronen, Z. (2023). Precision irrigation combined with advanced wastewater treatment: Economic and environmental benefits in arid agriculture. *Agricultural Water Management, 283*, 108292. https://doi.org/10.1016/j.agwat.2023.108292

Hasan, M. K., Cheng, Y., Kanwar, M. K., Chu, X. Y., Ahammed, G. J., & Qi, Z. Y. (2017). Responses of plant proteins to heavy metal stress—a review. *Frontiers in plant science*, *8*, 1492.

Hasnine, M. T., Huda, M. E., Khatun, R., Saadat, A. H. M., Ahasan, M., Akter, S., Uddin, M.F., Monika, A.N., Rahman, M.A. and Ohiduzzaman, M. (2017). Heavy metal contamination in agricultural soil at DEPZA, Bangladesh. *Environment and ecology research*, *5*(7), 510-516.

Heyde, B. J., Braun, M., Soufi, L., Luneberg, K., Gallego, S., Amelung, W. Axtmann, K., Bierbaum, G., Glaeser, S.P., Grohmann, E. and Arredondo-Hernandez, R. (2025). Transition from irrigation with untreated wastewater to treated wastewater and associated benefits and risks. *npj Clean Water*, *8*(1), 6.

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., & Richter, B. D. (2012). Global monthly water scarcity: blue water footprints versus blue water availability. *PloS one*, *7*(2), e32688.

Igalavithana, A. D., Lee, S. E., Lee, Y. H., Tsang, D. C., Rinklebe, J., Kwon, E. E., & Ok, Y. S. (2017). Heavy metal immobilization and microbial community abundance by vegetable waste and pine cone biochar of agricultural soils. *Chemosphere*, *174*, 593-603.

Initiative, I. B. (2012). Standardized product definition and product testing guidelines for biochar that is used in soil. *IBI biochar Stand*.

Jien, S. H., Kuo, Y. L., Liao, C. S., Wu, Y. T., Igalavithana, A. D., Tsang, D. C., & Ok, Y. S. (2021). Effects of field scale in situ biochar incorporation on soil environment in a tropical highly weathered soil. *Environmental Pollution*, *272*, 116009.

Jimenez, B., & Asano, T. (2008). *Water reuse: An international survey of current practice, issues and needs*. IWA publishing.

Jin, J., Kang, M., Sun, K., Pan, Z., Wu, F., & Xing, B. (2016). Properties of biochar-amended soils and their sorption of imidacloprid, isoproturon, and atrazine. *Science of the Total Environment*, *550*, 504-513.

Jin, Z., Chen, C., Chen, X., Hopkins, I., Zhang, X., Han, Z., Jiang, F. & Billy, G. (2019). The crucial factors of soil fertility and rapeseed yield-A five year field trial with biochar addition in upland red soil, China. *Science of the Total Environment*, *649*, 1467-1480.

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances*, *8*, 100203.

Kalavrouziotis, I. K., Robolas, P., Koukoulakis, P. H., & Papadopoulos, A. H. (2008). Effects of municipal reclaimed wastewater on the macro-and micro-elements status of soil and of Brassica oleracea var. Italica, and B. oleracea var. Gemmifera. *Agricultural water management*, *95*(4), 419-426.

Kalu, S., Kulmala, L., Zrim, J., Peltokangas, K., Tammeorg, P., Rasa, K., Kitzler, B., Pihlatie, M. & Karhu, K. (2022). Potential of biochar to reduce greenhouse gas emissions and increase nitrogen use efficiency in boreal arable soils in the long-term. *Frontiers in Environmental Science*, *10*, 914766.

Kamali, M., Sweygers, N., Al-Salem, S., Appels, L., Aminabhavi, T. M., & Dewil, R. (2022). Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chemical Engineering Journal*, *428*, 131189.

Kazmi, A. A., Tyagi, V. K., Trivedi, R. C., & Kumar, A. (2008). Coliforms removal in full-scale activated sludge plants in India. *Journal of Environmental Management*, *87*(3), 415-419.

Khalifa, N., & Yousef, L. F. (2015). A short report on changes of quality indicators for a sandy textured soil after treatment with biochar produced from fronds of date palm. *Energy Procedia*, *74*, 960-965.

Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z., & Zhu, Y. G. (2008). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environmental pollution*, *152*(3), 686-692.

Kizito, S., Luo, H., Lu, J., Bah, H., Dong, R., & Wu, S. (2019). Role of nutrient-enriched biochar as a soil amendment during maize growth: Exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand. *Sustainability*, *11*(11), 3211.

Kumar, D., Singh, D. P., Barman, S. C., & Kumar, N. (2016). Heavy metal and their regulation in plant system: an overview. *Plant responses to xenobiotics*, 19-38.

Kuppusamy, S., Thavamani, P., Megharaj, M., Venkateswarlu, K., & Naidu, R. (2016). Agronomic and remedial benefits and risks of applying biochar to soil: current knowledge and future research directions. *Environment international*, *87*, 1-12.

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., & Karlen, D. L. (2010). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma*, *158*(3-4), 443-449.

Layani, G., Bakhshoodeh, M., Zibaei, M., & Viaggi, D. (2021). Sustainable water resources management under population growth and agricultural development in the Kheirabad river basin, Iran. *Bio-based and Applied Economics*, *10*(4), 305-323.

Lehmann, J., & Joseph, S. (Eds.). (2012). *Biochar for environmental management: science and technology*. Routledge.

Lehmann, J., Pereira da Silva Jr, J., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and soil*, *249*(2), 343-357.

Li, P., Wang, X., Allinson, G., Li, X., & Xiong, X. (2009). Risk assessment of heavy metals in soil previously irrigated with industrial wastewater in Shenyang, China. *Journal of Hazardous Materials*, *161*(1), 516-521.

Li, S., Hu, Y., Shen, Z., Cai, Y., Ji, Z., Tan, X., Liu, Z., Zhao, G., Hu, S. & Wang, X. (2021). Rapid and selective uranium extraction from aqueous solution under visible light in the absence of solid photocatalyst. *Science China Chemistry*, *64*(8), 1323-1331.

Liang, J. F., Li, Q. W., Gao, J. Q., Feng, J. G., Zhang, X. Y., Hao, Y. J., & Yu, F. H. (2021). Biochar-compost addition benefits Phragmites australis growth and soil property in coastal wetlands. *Science of the Total Environment*, *769*, 145166.

Liang, L., Xi, F., Tan, W., Meng, X., Hu, B., & Wang, X. (2021). Review of organic and inorganic pollutants removal by biochar and biochar-based composites. *Biochar*, *3*(3), 255-281.

Lopez, J. E., Builes, S., Heredia Salgado, M. A., Tarelho, L. A., Arroyave, C., Aristizabal, A., & Chavez, E. (2020). Adsorption of cadmium using biochars produced from agro-residues. *The Journal of Physical Chemistry C*, *124*(27), 14592-14602.

Lu, H., Yan, M., Wong, M. H., Mo, W. Y., Wang, Y., Chen, X. W., & Wang, J. J. (2020). Effects of biochar on soil microbial community and functional genes of a landfill cover three years after ecological restoration. *Science of the total Environment*, *717*, 137133.

Luo, C., Yang, J., Chen, W., & Han, F. (2020). Effect of biochar on soil properties on the Loess Plateau: Results from field experiments. *Geoderma*, *369*, 114323.

Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and soil*, *333*(1), 117-128.

Malik, A. (2004). Metal bioremediation through growing cells. *Environment international*, *30*(2), 261-278.

Małkowski, E., Sitko, K., Zieleźnik-Rusinowska, P., Gieroń, Ż., & Szopiński, M. (2019). Heavy metal toxicity: Physiological implications of metal toxicity in plants. In *Plant metallomics and functional omics: a system-wide perspective* (pp. 253-301). Cham: Springer International Publishing.

Manaia, C. M. (2023). Framework for establishing regulatory guidelines to control antibiotic resistance in treated effluents. *Critical Reviews in Environmental Science and Technology*, *53*(6), 754-779.

Martinsen, V., Mulder, J., Shitumbanuma, V., Sparrevik, M., Børresen, T., & Cornelissen, G. (2014). Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *Journal of Plant Nutrition and Soil Science*, *177*(5), 681-695.

Maryam, B., & Buyukgungor, H. (2019). Wastewater reclamation and reuse trends in Turkey: Opportunities and challenges. *Journal of Water Process Engineering*, *30*, 100501.

Medynska-Juraszek, A., Latawiec, A., Krolczyk, J., Bogacz, A., Kawalko, D., Bednik, M., & Dudek, M. (2021). Biochar improves maize growth but has a limited effect on soil properties: Evidence from a three-year field experiment. *Sustainability*, *13*(7), 3617.

Metcalf and Eddy, Inc, Asano, T., Burton, F. L., Leverenz, H., Tsuchihashi, R., & Tchobanoglous, G. (2007). *Water reuse* (pp. 6-15). United States of America: McGraw-Hill Professional Publishing.

Mourato, M. P., Moreira, I. N., Leitao, I., Pinto, F. R., Sales, J. R., & Louro Martins, L. (2015). Effect of heavy metals in plants of the genus Brassica. *International journal of molecular sciences*, *16*(8), 17975-17998.

Naz, S., Anjum, M. A., Siddique, B., Naqvi, S. A. H., Sajid, A., Sardar, H., Haider, S.T.A., Zulfiqar, M.A., Azeem, H., Ullah, S. & Pasand, S. (2020). Effect of sewage water irrigation frequency on growth, yield and heavy metals accumulation of tomato and okra. *Pakistan Journal of Agricultural Research*, *33*(4), 798.

Njoku, K. L., & Nwani, S. O. (2022). Phytoremediation of heavy metals contaminated soil samples obtained from mechanic workshop and dumpsite using Amaranthus spinosus. *Scientific African*, *17*, e01278.

Olunusi, S. O., Ramli, N. H., Fatmawati, A., Ismail, A. F., & Okwuwa, C. C. (2024). Revolutionizing tropical fruits preservation: Emerging edible coating technologies. *International Journal of Biological Macromolecules*, *264*, 130682.

Pal, R., & Rai, J. P. N. (2010). Phytochelatins: peptides involved in heavy metal detoxification. *Applied biochemistry and biotechnology*, *160*(3), 945-963.

Pellegrini, G., Ingrao, C., Camposeo, S., Tricase, C., Conto, F., & Huisingh, D. (2016). Application of water footprint to olive growing systems in the Apulia region: a comparative assessment. *Journal of Cleaner Production*, *112*, 2407-2418.

Pituya, P., Sriburi, T., & Wijitkosum, S. (2017). Properties of biochar prepared from acacia wood and coconut shell for soil amendment. *Engineering Journal*, *21*(3), 63-75.

Pourret, O., & Hursthouse, A. (2019). It's time to replace the term "heavy metals" with "potentially toxic elements" when reporting environmental research. *International journal of environmental research and public health*, *16*(22), 4446.

Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P. G., Drechsel, P., Bahri, A., & Minhas, P. S. (2010). The challenges of wastewater irrigation in developing countries. *Agricultural water management*, *97*(4), 561-568.

Qian, L., & Chen, B. (2013). Dual role of biochars as adsorbents for aluminum: the effects of oxygen-containing organic components and the scattering of silicate particles. *Environmental Science & Technology*, *47*(15), 8759-8768.

Rogovska, N., Laird, D., Cruse, R., Fleming, P., Parkin, T., & Meek, D. (2011). Impact of biochar on manure carbon stabilization and greenhouse gas emissions. *Soil Science Society of America Journal*, *75*(3), 871-879.

Rong-Guang, S. H. I., Sheng-Wei, P. E. N. G., Yue-Hua, W. A. N. G., Hao, Z. H. A. N. G., Yu-Jie, Z. H. A. O., Feng-Zhi, L. I. U., & Qi-Xing, Z. H. O. U. (2008). Countermeasures of reclaimed municipal wastewater for safety of agricultural use in China. *Agricultural Sciences in China*, *7*(11), 1365-1373.

Rutkowski, T., Raschid-Sally, L., & Buechler, S. (2007). Wastewater irrigation in the developing world—two case studies from the Kathmandu Valley in Nepal. *Agricultural Water Management*, *88*(1-3), 83-91.

Sanchez-Garcia, M., Cayuela, M. L., Rasse, D. P., & Sanchez-Monedero, M. A. (2019). Biochars from mediterranean agroindustry residues: physicochemical properties relevant for C sequestration and soil water retention. *ACS Sustainable Chemistry & Engineering*, *7*(5), 4724-4733.

Sarfraz, R., Shakoor, A., Abdullah, M., Arooj, A., Hussain, A., & Xing, S. (2017). Impact of integrated application of biochar and nitrogen fertilizers on maize growth and nitrogen recovery in alkaline calcareous soil. *Soil science and plant nutrition*, *63*(5), 488-498.

Satyanarayana, C., Rao, S. R., & Hossain, K. (2010). Assessment of water quality of freshwater resources along the coast of Andhra Pradesh. *Nature Environ. Pollut. Technol*, *9*, 19-23.

Scott, C. A., Zarazua, J. A., & Levine, G. (2004). *Indicators of wastewater irrigation in the Mezquital Valley, Mexico* (IWMI Research Report No. 127). International Water Management Institute.

Shackley, S., Hammond, J., Gaunt, J., & Ibarrola, R. (2011). The feasibility and costs of biochar deployment in the UK. *Carbon Management*, *2*(3), 335-356.

Shahid, M., Khalid, S., Abbas, G., Shahid, N., Nadeem, M., Sabir, M., Aslam, M. & Dumat, C. (2015). Heavy metal stress and crop productivity. In *Crop production and global environmental issues* (pp. 1-25). Cham: Springer International Publishing.

Shahzad, K., Ali, A., Ghani, A., Nadeem, M., Khalid, T., Nawaz, S., Jamil, M. & Anwar, T. (2023). Exogenous application of proline and glycine betaine mitigates nickel toxicity in mung bean plants by up-regulating growth, physiological and yield attributes. *Pak J Bot*, *55*(10.30848).

Shen, X., Meng, H., Shen, Y., Ding, J., Zhou, H., Cong, H., & Li, L. (2022). A comprehensive assessment on bioavailability, leaching characteristics and potential risk of polycyclic aromatic hydrocarbons in biochars produced by a continuous pyrolysis system. *Chemosphere*, *287*, 132116.

Siddique, A. B., Rahman, M. M., Islam, M. R., & Naidu, R. (2021). Varietal variation and formation of iron plaques on cadmium accumulation in rice seedling. *Environmental Advances*, *5*, 100075.

Siedt, M., Schaffer, A., Smith, K. E., Nabel, M., Roß-Nickoll, M., & Van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, *751*, 141607.

Singh, A. (2021). A review of wastewater irrigation: Environmental implications. *Resources, Conservation and Recycling*, *168*, 105454.

Singh, S., Kumar, V., Dhanjal, D. S., Datta, S., Bhatia, D., Dhiman, J., Samuel, J., Prasad, R. & Singh, J. (2020). A sustainable paradigm of sewage sludge biochar: valorization, opportunities, challenges and future prospects. *Journal of Cleaner Production*, *269*, 122259.

Song, X., Zhang, Y., Cao, N., Sun, D., Zhang, Z., Wang, Y., Wen, Y., Yang, Y. & Lyu, T. (2020). Sustainable chromium (VI) removal from contaminated groundwater using nano-magnetite-modified biochar via rapid microwave synthesis. *Molecules*, *26*(1), 103.

Srinivasan, P., & Sarmah, A. K. (2015). Characterisation of agricultural waste-derived biochars and their sorption potential for sulfamethoxazole in pasture soil: A spectroscopic investigation. *Science of the Total Environment*, *502*, 471-480.

Sun, F., & Lu, S. (2014). Biochars improve aggregate stability, water retention, and pore-space properties of clayey soil. *Journal of Plant Nutrition and Soil Science*, *177*(1), 26-33.

Tan, X., Zhu, S., Show, P. L., Qi, H., & Ho, S. H. (2020). Sorption of ionized dyes on high-salinity microalgal residue derived biochar: Electron acceptor-donor and metal-organic bridging mechanisms. *Journal of Hazardous Materials*, *393*, 122435.

Thao, N. P., Khan, M. I. R., Thu, N. B. A., Hoang, X. L. T., Asgher, M., Khan, N. A., & Tran, L. S. P. (2015). Role of ethylene and its cross talk with other signaling molecules in plant responses to heavy metal stress. *Plant Physiology*, *169*(1), 73-84.

Thomas, N. T., & Roy, S. (2024). Advancing health equity in India: the intersection of social work and policy practice. *Indian Journal of Health Social Work*, *6*, 2.

Tiwari, S., & Lata, C. (2018). Heavy metal stress, signaling, and tolerance due to plant-associated microbes: An overview. *Frontiers in Plant Science, 9,* 452. https://doi.org/10.3389/fpls.2018.00452

Toze, S. (2006). Reuse of effluent water—benefits and risks. *Agricultural Water Management, 80*(1–3), 147–159. https://doi.org/10.1016/j.agwat.2005.07.010

Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews, 55,* 467–481. https://doi.org/10.1016/j.rser.2015.10.122

United Nations. (2017). *World population prospects: 2017 revision population database.*

UN-Water. (2021). *The United Nations World Water Development Report 2021: Valuing water.* UNESCO.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications, 1,* 56.

World Bank. (2007). *Making the most of scarcity: Accountability for better water management results in the Middle East and North Africa* (MENA Development Report). World Bank.

World Health Organization. (2006). *WHO guidelines for the safe use of wastewater, excreta and greywater: Volume 2—Wastewater use in agriculture.* WHO Press.

Xiao, R., Awasthi, M. K., Li, R., Park, J., Pensky, S. M., Wang, Q., Wang, J.J. & Zhang, Z. (2017). Recent developments in biochar utilization as an additive in organic solid waste composting: A review. *Bioresource Technology, 246,* 203–213.

Xiao, R., Sun, X., Wang, J., Feng, J., Li, R., Zhang, Z., Wang, J.J. & Amjad, A. (2015). Characteristics and phytotoxicity assay of biochars derived from a Zn-rich antibiotic residue. *Journal of Analytical and Applied Pyrolysis, 113,* 575–583.

Xiao, Z., Rasmann, S., Yue, L., Lian, F., Zou, H., & Wang, Z. (2019). The effect of biochar amendment on N-cycling genes in soils: A meta-analysis. *Science of the Total Environment, 696,* 133984.

Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Frontiers in Plant Science, 11,* 513099.

Yang, H., Liu, X., Hao, M., Xie, Y., Wang, X., Tian, H., Waterhouse, G.I., Kruger, P.E., Telfer, S.G. & Ma, S. (2021). Functionalized iron–nitrogen–carbon electrocatalyst provides a reversible electron transfer platform for efficient uranium extraction from seawater. *Advanced Materials, 33*(51), 2106621.

Ye, S., Zeng, G., Wu, H., Liang, J., Zhang, C., Dai, J., Xiong, W., Song, B., Wu, S. & Yu, J. (2019). The effects of activated biochar addition on remediation efficiency of co-composting with contaminated wetland soil. *Resources, Conservation and Recycling, 140,* 278–285.

Ye, S., Zeng, G., Wu, H., Zhang, C., Dai, J., Liang, J., Yu, J., Ren, X., Yi, H., Cheng, M. & Zhang, C. (2017). Biological technologies for the remediation of co-contaminated soil. *Critical Reviews in Biotechnology, 37*(8), 1062–1076.

Yi, Z., Jeyakumar, P., Yin, C., & Sun, H. (2023). Effects of biochar in combination with varied N inputs on grain yield, N uptake, NH_3 volatilization, and N_2O emission in paddy soil. *Frontiers in Microbiology, 14,* 1174805.

Zaid, A., Bhat, J. A., & Wani, S. H. (2020). Influence of metalloids and their toxicity impact on photosynthetic parameters of plants. In *Metalloids in plants: Advances and future prospects* (pp. 113–124). Elsevier.

Zhang, J., & You, C. (2013). Water holding capacity and absorption properties of wood chars. *Energy & Fuels, 27*(5), 2643–2648.

Zhang, W., Tan, X., Gu, Y., Liu, S., Liu, Y., Hu, X., Li, J., Zhou, Y., Liu, S. & He, Y. (2020). Rice waste biochars produced at different pyrolysis temperatures for arsenic and cadmium abatement and detoxification in sediment. *Chemosphere, 250,* 126268.

Zhou, Q., Yang, N., Li, Y., Ren, B., Ding, X., Bian, H., & Yao, X. (2020). Total concentrations and sources of heavy metal pollution in global river and lake water bodies from 1972 to 2017. *Global Ecology and Conservation, 22,* e00925.

Zou, Y., Wang, X., Khan, A., Wang, P., Liu, Y., Alsaedi, A., Hayat, T. & Wang, X. (2016). Environmental remediation and application of nanoscale zero-valent iron and its composites for the removal of heavy metal ions: A review. *Environmental Science & Technology, 50*(14), 7290–7304.

19

FUTURE PERSPECTIVES ON TISSUE NUTRIENT SAMPLING, ANALYSIS AND INTERPRETATION IN FRUIT TREES

Gustavo Brunetto[1], Danilo Eduardo Rozane[2], William Natale[3], Paola Daiane Welter[4], Antonio João de Lima Neto[5], Betânia Vahl de Paula[6], Korkmaz Bellitürk[7]

1. Introduction

The world population has increased eightfold over the past two centuries, rising from 1 billion people in 1804 to 8 billion in 2022. Considering these numbers, Malthus's 1798 prediction, that the demand for "food" would never diminish, proves accurate with each passing day. Moreover, the growing demand for food is not only driven by population growth but also by increased human longevity, shifts in dietary habits, and the pursuit of higher quality of life, which includes fruit consumption. The major agricultural challenge of the 21st century lies in increasing crop yield per unit area while simultaneously improving the efficiency of water and nutrient use to meet the escalating global demand for food.

Despite all scientific progress, technological development, and innovation, according to the FAO (2015), 95% of the world's food is still produced from the soil, thanks to plants. However, soils have natural limitations in their ability to supply nutrients and sustain primary productivity, being highly complex and interactive systems. After water, nutrient deficiency is the factor that most severely limits plant productivity, particularly in tropical and subtropical regions of the globe. Therefore, it is unrealistic to assume that land, even when fertile, can be exploited indefinitely by crops without nutrient replenishment. It is also important to consider that a significant portion of food is produced in highly weathered soils with inherently low fertility, as is the case in Brazil, where fertilizer use is essential to achieve high yields. In the 20th century, 50%

1 Federal University of Santa Maria, Santa Maria, Rio Grande do Sul, Brazil. https://orcid.org/0000-0002-3174-9992. E-mail: brunetto.gustavo@gmail.com
2 State University Paulista "Julio Mesquita Filho", Campus Registro. Registro, São Paulo, Brazil. https://orcid.org/0000-0003-0518-3689. E-mail: danilo.rozane@unesp.br
3 National Research Center for Tropical Agroindustry (Embrapa), Fortaleza, Ceará, Brazil. https://orcid.org/0000-0001-9572-4463. E-mail: natale@ufc.br
4 Federal University of Santa Maria, Santa Maria, Rio Grande do Sul, Brazil. https://orcid.org/0000-0001-6778-993X. E-mail: paoladwelter@gmail.com
5 Federal University of Ceará, Fortaleza, Ceará, Brazil. https://orcid.org/0000-0001-9019-562X. E-mail: limanetoagro@hotmail.com
6 Federal University of Santa Maria, Santa Maria, Rio Grande do Sul, Brazil. https://orcid.org/0000-0002-2348-1527. E-mail: behdepaula@hotmail.com
7 Faculty of Agriculture, Tekirdag Namık Kemal Universit, Tekirdag, Turkey. https://orcid.org/0000-0003-4944-3497. E-mail: kbelliturk@nku.edu.tr

of the global increase in crop productivity was attributed to improvements in plant nutrition through fertilizer application (FAO, 2015).

On the other hand, it is crucial to emphasize that global reserves of nutrients used in the production of mineral fertilizers, particularly phosphorus (P) and potassium (K), are limited, scarce, and finite, making the more efficient use of these natural resources imperative in agricultural production systems (Cordell et al., 2009). In the case of nitrogen (N), although the element is abundant in the atmosphere (approximately 78%), petroleum is required for fertilizer synthesis. Global fertilizer production is concentrated in a few countries with access to raw materials and technology, such as Russia, China, Canada, and Morocco. In terms of energy consumption, the production of 1 kg of N, P_2O_5, and K_2O fertilizers requires approximately 16,800, 3,040, and 2,100 Kcal, respectively (Malavolta, 1981). In Brazil, fertilizer use accounts for 25–30% of orchard production costs. Conversely, fertilizer use efficiency is estimated to average 60% for N and 70% for K, according to Malavolta (1980), and around 50% for P, as reported by Roy et al. (2016). Thus, in order to minimize nutrient losses (via leaching, volatilization, denitrification, erosion, etc.) and enhance fertilizer use efficiency, all available agronomic tools should be employed, such as soil and leaf analysis, to accurately determine orchard nutrient requirements.

2. Importance of nutritional diagnosis in fruit crops

Although Brazil is one of the world's largest food producers, it remains the fourth-largest importer of fertilizers for agribusiness. In 2024, imported fertilizers accounted for approximately 97%, 73%, and 97% of national consumption of N, P_2O_5, and K_2O, respectively (ANDA, 2025). Furthermore, the global supply of these inputs is dominated by a few countries; and because fertilizers are traded as commodities, nations such as Brazil are highly dependent on international market fluctuations. The growing reliance on imported fertilizers makes the Brazilian economy, strongly based on agribusiness, including fruit production, vulnerable to external shocks. This was evident in the recent increases in fertilizer prices caused by events such as the COVID-19 pandemic and the conflict in Ukraine.

The production of high-value and nutritionally rich foods that promote consumer health and well-being, in addition to supporting proper plant development, depends on appropriate management of crop mineral nutrition. Fruit crops, in particular, must maintain a balance of essential elements within their tissues to achieve satisfactory yields and high fruit quality, while ensuring rational input use and environmental stewardship (Parent and Natale, 2020). Moreover, agricultural practices throughout the crop cycle can significantly influence postharvest fruit quality and storability.

Nutritional management plays a particularly important role in the fruit production chain, as mineral elements directly affect fruit quality, a key requirement for meeting increasing consumer demand and ensuring competitiveness in export markets. The global rise in demand for fresh fruits and natural juices is largely associated with the proven health benefits of fruit consumption, growing awareness of healthy lifestyles, and longer human life expectancy, which increases the number of elderly consumers. This trend is also driven by preferences for foods that are low in calories and rich in fiber, vitamins, and minerals, as well as by medical community campaigns encouraging fruit consumption. Consequently, there has been continuous interest in expanding fruit production areas, both for health-related reasons and for the sensory appeal of fruit consumption. However, fruit quality results from the combined effects of several factors, particularly the individual and synergistic roles of nutrients. Proper fulfillment of plant nutritional requirements allows fruit crops to express their full genetic potential in terms of yield and fruit quality. Nutritional balance determines key fruit quality attributes such as appearance, color, size, flavor, aroma, postharvest storage capacity, and resistance to pests and diseases. A synthesis of these effects has been compiled for several tropical fruit crops (Aular and Natale, 2013; Aular et al., 2014; Aular et al., 2017). Therefore, it is essential to establish effective diagnostic criteria for assessing the nutritional status of orchards, with the goal of defining rational fertilizer application rates (Natale and Rozane, 2024).

In addition to influencing fruit quality, nutrients play key roles in plant defense. Regarding the ability of plants to tolerate or resist attacks by phytopathogens such as bacteria, fungi, nematodes, and viruses, nutritional balance is a central factor in mitigating these biotic stresses. Throughout evolution, plants have developed defense mechanisms that enable them to reduce infection severity (Sun et al., 2020), and proper nutrient balance supports overall plant health.

Balanced nutrition can be considered the first line of defense against pathogens, due to the direct involvement of mineral elements in plant defense systems against a wide range of pathogenic organisms. Mineral nutrients critically influence plant defense mechanisms by modulating enzyme activity or indirectly improving plant vigor, altering root exudates, affecting microbial population dynamics in the rhizosphere, changing soil nutrient concentrations and pH, and enhancing lignin deposition and the biosynthesis of secondary metabolites (Tripathi et al., 2022). Marschner (2012) notes that the effects of nutrients on plant growth and yield are generally explained by the physiological and metabolic functions of essential elements. However, nutrition can also have secondary, sometimes unpredictable, effects on plant development, morphology, anatomy, and chemical composition, which may increase or decrease plant resistance or tolerance to pathogen attack. Resistance is primarily determined by the host plant's ability to limit the penetration, development, and/or reproduction of invading pathogens, or to restrict pest feeding. Tolerance, on the other hand, refers to the plant's capacity to maintain growth and productivity despite infection or pest pressure. Depending on the nutrient, pathogen, or pest, plant nutrition can affect both resistance and tolerance, as well as pathogen virulence. Plant diseases can also alter nutrient availability, uptake, distribution, and utilization, with disease symptoms often reflecting changes in the plant's nutritional status.

Mineral nutrients are directly and intrinsically involved in plant protection as structural components and metabolic regulators (Huber, 1980). Consequently, they can directly influence plant health by activating enzymes involved in the synthesis of defensive metabolites or indirectly by modifying the plant's surrounding environment. Balanced nutrition has always been a key component in disease control and management, although its full importance is not yet fully appreciated. In general, a well-nourished plant exhibits greater vigor and enhanced resistance, and thus mineral nutrients play a crucial role in defense against pathogen invasion and attack. Although resistance and tolerance are primarily under genetic control, these traits are strongly influenced by environmental factors. Nutritional status can be considered one such environmental factor, and it can be readily manipulated through nutrient application to mitigate biotic stresses. Although often overlooked, this aspect has always been a critical component of plant disease management. In the case of fruit crops, the role of certain nutrients is well established. For example, excessive nitrogen can negatively affect the plant's physical defense mechanisms, consequently increasing susceptibility to pathogenic infection. Similarly, calcium deficiency, due to its structural role, reduces the rigidity of cell walls and middle lamellae, facilitating pathogen penetration and colonization.

3. Advances and current practices in leaf sampling and analysis of orchards

The principles of plant analysis can be traced back to the pioneering work of De Saussure (1804), who examined the chemical composition of plant ashes from different species (Ulrich, 1952). As scientific understanding of plant nutrition evolved and the essentiality of various chemical elements for plant metabolism and growth was established, researchers began to use the chemical composition of plant tissues as an indirect means of assessing soil fertility (Lundegårdh, 1943; Ulrich, 1952). This scientific foundation set the stage for a more systematic approach to nutrient diagnosis in plants, linking the mineral composition of plant organs to soil nutrient availability and crop performance.

The development of plant tissue analysis as a diagnostic tool for evaluating plant nutritional status advanced substantially with the classical studies on grapevines conducted in Montpellier, France, by Lagatu and Maume (1934a). These researchers identified the leaf as the most representative tissue for diagnosis, given its central role in photosynthesis and metabolism, and termed their approach *diagnostic foliaire*. Their concept emphasized that the leaf functions as a "chemical laboratory" of the plant, integrating both root absorption and metabolic redistribution of nutrients, thereby providing a sensitive indicator of nutritional imbalances long before visual symptoms appear.

Because leaves generally exhibit the highest physiological activity among plant organs, they are particularly sensitive to variations in soil nutrient availability. Consequently, leaf analysis has become the most widely used method for predicting plant nutritional status (Natale and Rozane, 2024). The fundamental principle of foliar diagnosis is the existence of a quantitative relationship among fertilizer application rates, nutrient concentrations in leaves, and crop yield. This relationship enables the adjustment of fertilization practices to correct deficiencies and optimize productivity. Although leaves are the most commonly analyzed organ, recent studies have shown that flowers may also reflect nutrient interactions and serve as early indicators of plant nutritional status in several fruit crops, such as olive (Khelil et al., 2010), citrus (Gui et al., 2014), and guava (Oliveira et al., 2020). The potential use of floral tissues in nutrient diagnosis could allow for earlier detection and correction of nutritional problems, though additional research is required to standardize reference values for different species.

Foliar diagnosis involves several sequential steps, including tissue sampling, sample preparation, analytical determination, interpretation of results, and formulation of fertilizer recommendations (Natale et al., 2020). Among these, the sampling stage is considered the most critical, as any errors introduced during this step cannot be corrected later in the analytical process. Sampling must therefore be performed carefully, following specific protocols for each crop, developmental stage, and management system to ensure that the collected tissue accurately represents the nutritional condition of the orchard.

In Brazil, the main protocols for foliar diagnosis in fruit crops have been compiled by Natale and Rozane (2018). These protocols define the plant organ to be sampled, the physiological stage of sampling, the number of samples per plot, and the exact position of leaves on the branch. Differences among protocols arise mainly from species-specific traits and the influence of environmental conditions, phenology, and canopy architecture on nutrient distribution. Despite these advances, current foliar standards still have limitations: (i) the short time window available to correct nutrient deficiencies after sampling; (ii) the variability among interpretation systems, which results in different threshold concentrations for adequate nutrition; and (iii) the need for calibration of nutrient standards for crops under fertigation or other specific management systems (Srivastava and Malhorta, 2017).

The chemical analysis of plant tissues consists of the mineralization of organic matter and the subsequent quantification of total macro- and micronutrient concentrations, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn). Complete analyses enable a comprehensive assessment of nutrient balance and interactions, while partial analyses, though less costly, may provide insufficient information for precise nutritional evaluation. It is important to note that, unlike soil analyses, which estimate available or exchangeable nutrient fractions, foliar analysis measures total concentrations, including both metabolized and non-metabolized forms. Analytical methodologies are well established and reliable when conducted in laboratories under strict quality control, although certain elements such as molybdenum (Mo), nickel (Ni), and chlorine (Cl) present challenges due to low concentrations or analytical constraints (Malavolta, 2006).

In recent decades, the search for more efficient and precise methods for diagnosing plant nutritional status has intensified. Research has focused on defining the optimal sampling period, identifying the plant organ that best reflects nutritional condition, improving analytical extraction techniques, and refining the interpretation of foliar data, particularly for perennial fruit species that accumulate and remobilize nutrients across growing seasons (Rozane et al., 2009; Prado and Rozane, 2020). Furthermore, the integration of new technologies, such as optical sensors, multispectral and hyperspectral imaging, and unmanned aerial vehicles (UAVs), has expanded the possibilities for real-time nutrient monitoring. These tools enable the development of predictive models that integrate spatial and temporal variability, crop phenology, and environmental dynamics, thereby contributing to more sustainable and precise nutrient management in fruit production systems (Kuldeep et al., 2024).

4. Evolution and trends in nutrient analysis of fruit crop tissues

4.1 Integrated approaches: combined soil and tissue analysis

Soil and plant diagnostic techniques are not mutually exclusive but rather complementary. Their determinations should be conducted in accredited laboratories, using reference populations from high-yielding orchards established under modern cultivation technologies for the evaluated crop. This approach enables the definition of parameters that support decision-making in fertilization practices, contributing to environmentally responsible management while maximizing the economic return of production systems.

The nutrient concentrations obtained from soil and tissue sampling, when correlated with yield data, allow the development and subsequent calibration of mathematical models for predicting multifactorial nutritional indices. These indices assist in assessing plant nutritional status and establishing proper nutrient balances that reflect the intrinsic multivariate nature of soil–plant interactions, characterized by well-defined nutrient ratios in plant tissues (Parent et al., 2013a; Rozane et al., 2025). Field trials conducted under ceteris paribus assumptions form the backbone of fertilizer rate recommendations. However, climatic conditions, fertilizer sources and application schedules, soil quality, irrigation, tillage management, and crop rotation systems are critical factors determining yield and may vary widely from year to year (Stefanello et al., 2021).

The classical purpose of fertilizer experiments is to establish critical and maintenance levels of soil fertility, either to "feed the plant," by ensuring sufficient nutrient availability, or to "feed the soil," by maintaining proper cation proportions and nutrient reserves (Lagatu and Maume, 1934b; Prévot and Ollagnier, 1956).

Uncertainty regarding adequate nutrient rates often leads growers to apply unbalanced or excessive fertilizer amounts (Oliveira et al., 2024b), frequently exceeding crop requirements to minimize the risk of yield loss from nutrient deficiency (Kyveryga et al., 2011; Nowaki et al., 2017). Both nutrient deficiency and excess are detrimental to agricultural productivity and environmental integrity, not only because they fail to meet plant nutritional demands, resulting in direct economic losses (Natale et al., 2011), but also because excessive fertilization increases the incidence of plant diseases (Martinez et al., 2021), postharvest losses, and environmental impacts such as nitrate leaching, N_2O emissions (Stewart and Lal, 2017), and surface-water eutrophication caused by phosphate runoff (Pellerin et al., 2006).

Although multiple factors interact to influence yield within agroecosystems, a predictable relationship often exists between the concentration or centered log ratio (clr) of an element in plant tissue (dependent variable) and the nutrient dose applied (independent variable), even under limiting conditions (Wallace and Wallace, 1993). Such predictions require precise classification and regression models constructed using machine learning approaches (Hahn et al., 2024; Lima Neto et al., 2022; Nowaki et al., 2017; Yamane et al., 2022).

It is important to emphasize that Liebig's Law of the Minimum, proposed by the German biologist Justus von Liebig in the 19th century, states that crop productivity is determined by the nutrient available in the smallest proportion relative to plant demand, that is, the most deficient nutrient. Therefore, the deficiency of a single nutrient can compromise crop performance even when all other elements are present at adequate levels.

It should be noted, however, that each production factor performs optimally only when the others are near their ideal conditions, and the optimum of any individual factor cannot be considered in isolation. Consequently, an integrative evaluation of all nutrients, preferably through multivariate methods such as the Compositional Nutrient Diagnosis (CND) (Parent and Dafir, 1992), provides a more accurate assessment of plant nutritional status than any single-nutrient index. This is because nutrient concentrations in plant tissues are expressed within a closed compositional space in which all elements interact (Prévot and Ollagnier, 1956).

Since plants maintain electrical neutrality (a balance between negative and positive charges), they exhibit a nominal equilibrium between monovalent and bivalent nutrients. Any reduction in one group is automatically compensated by an increase in the other. Thus, changes in the concentration of a single element alter the proportional relationships among nutrients, affecting the overall equilibrium of the system (Parent et al., 2013a; 2013b). For this reason, the integrative CND approach accounts for the interactive behavior among all nutrients detected in the analytical results of the sampled plant organ.

4.2 Evaluation of nutritional status through multielement diagnosis and nutrient balance

Most current scientific datasets are multivariate in nature. These data mutually influence one another within a closed system, generally constrained by the measurement unit. For example, in a ternary soil texture diagram, the sum of sand, silt, and clay is limited to 100%. If the proportion of one component changes, it necessarily affects the others, producing "resonance," spurious correlations, and redundancy of information. Thus, there are D–1 degrees of freedom in a composition consisting of D components. Compositional data analysis provides a solid theoretical foundation for multivariate statistical analysis of this type of data, using logarithmic ratios (Aitchison, 1986). Interactions, dilutions, and concentrations are resonance phenomena within plant tissues. The centered log ratio (*clr*) transformation was used to develop the Compositional Nutrient Diagnosis (CND) method (Parent and Dafir, 1992). The *clr* is a mean of pairwise log ratios, calculated as the logarithm of the concentration of a given component divided by the geometric mean (G) of all components, as follows:

$$G = [N \times P \times K \times \ldots \times R_d]^{\frac{1}{d+1}}$$

$$ln\left(\frac{N}{g(x)}\right) = ln\left(\frac{N}{N} \times \frac{N}{P} \times \frac{N}{K} \times \frac{N}{Ca} \times \frac{N}{Mg} \times \frac{N}{S} \times \frac{N}{B} \times \frac{N}{Cu} \times \frac{N}{Zn} \times \frac{N}{Mn} \times \frac{N}{Fe} \times \ldots \times \frac{N}{x_D}\right)^{\frac{1}{D}} =$$

$$\frac{1}{D}\left[ln\left(\frac{N}{N}\right) + ln\left(\frac{N}{P}\right) + ln\left(\frac{N}{K}\right) + ln\left(\frac{N}{Ca}\right) + ln\left(\frac{N}{Mg}\right) + ln\left(\frac{N}{S}\right) + ln\left(\frac{N}{B}\right) + \cdots + ln\left(\frac{N}{x_D}\right)\right]$$

After division by the geometric mean (G) of the d + 1 components, including Rd, nutrient proportions become scale-invariant (Aitchison, 1986). This transformation places *clr* values in Euclidean geometry, allowing calculation of the Euclidean distance (Ɛ) between two compositions as follows:

$$\mathcal{E} = \sqrt{\sum_{j=1}^{D}\left(clr_j - clr_j^*\right)^2}$$

where clr^*_j is the *clr* of a reference sample located near the diagnosed sample but without any deficiency symptoms.

When a composition is compared with a reference group that exhibits variance, the Mahalanobis distance (M^2) (Parent et al., 2009) is calculated as:

$$\mathcal{M}^2 = \sum_{j=1}^{D}\frac{\left(clr_j - clr_j^*\right)^2}{COV_j^*}$$ assuming *clr* values are correlated, or

$$\mathcal{M}^2 = \sum_{j=1}^{D}\frac{\left(clr_j - clr_j^*\right)^2}{VAR_j^*}$$ assuming *clr* values are independent.

If the variance represents the mean variance of all *clr* values (Greenacre et al., 2023), the Mahalanobis distance becomes a weighted Euclidean distance, as follows:

$$\mathcal{E} = \sqrt{\frac{1}{VAR}\sum_{j=1}^{D}\left(clr_j - clr_j^*\right)^2}$$

When evaluating a database, it is desirable to maximize the number of specimens that unequivocally belong to the low-yield subpopulation (Walworth and Sumner, 1987). Accordingly, Khiari et al. (2001) proposed that low- and high-yield subpopulations be established through variance ratio functions for nutrient indices across a descending order of yield values. At the yield cutoff, a proportion of the total population is assigned to the low-yield subpopulation. This proportion represents an exact probability corresponding to a CND-r^2 threshold between low- and high-yield subpopulations. The selected approach is then linked to the chi-square distribution function. As exact probabilities increase with higher yield targets, CND-r^2 decreases according to the chi-square distribution function. Therefore, the variance ratio should be low when comparing nutrient variance for the lowest yields against that for the remainder of the population. Consequently, a curvilinear relationship between yield and nutrient concentration should exhibit a yield cutoff between the low- and high-yield subpopulations at the point where the cumulative variance ratio function changes concavity – that is, at its inflection point, as exemplified by Trapp et al.

(2025) for apple crops (Figure 1). The inflection point is determined by the first derivative of the function $\frac{-b}{3a}$, representing the minimum yield value separating the two subpopulations.

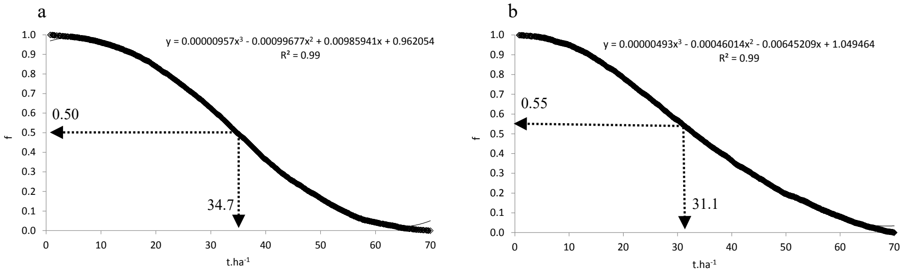


Figure 1. Inflection points based on the association between f (cumulative functions) and fruit yield for apple cultivars Gala (a) and Fuji (b).

CND indices, calculated to diagnose various major, fruit, and vegetable crops using computer-based tools, have been in use since 2012 (Rozane et al., 2012). These indices are weighted by the variance of each *clr* (https://www.registro.unesp.br/sites/cnd), as illustrated for phosphorus (P):

$$\text{P index} = \frac{clr_P - clr_P^*}{\sigma_P^*}$$

Nutrient indices can be visualized using a histogram (Figure 2). A positive sign indicates a relative excess, whereas a negative sign indicates a relative deficiency. Importantly, the closer an index is to zero, the more balanced that nutrient is relative to the others; conversely, the farther from zero, the greater the imbalance.

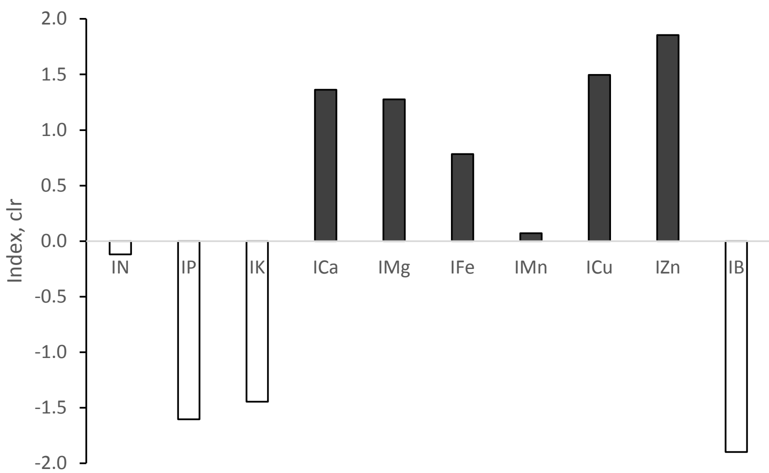


Figure 2. Histogram showing nutrients in relative deficiency (negative indices) or relative excess (positive indices) in grapevines. Source: Rozane et al. (2015).

The global imbalance index (CND-r^2), independent for each sample, allows assessment of the deviation from the ideal nutritional balance. The closer the CND-r^2 value is to zero, the more balanced the nutrient composition is in relation to high-yield standards. The index is calculated as follows:

$$CND{-}r^2 = I^2N + I^2P + I^2K + \cdots + I^2R$$

Rozane et al. (2017), analyzing the nutritional composition of commercial pear (*Pyrus communis* L.) orchards in São Joaquim, SC, Brazil, observed the necessity of using the integrative nutritional measure (CND-r^2) to more accurately express nutritional status rather than relying on a single nutrient index. This is because nutrient concentrations, as expressed by the analytical results of the evaluated organ, are constrained within a closed compositional space, bounded only by the measurement unit, in which all nutrients interact. The calculated CND-r^2 ($p < 0.001$) indicated that the nutritional balance of the current dataset explained 20% of the yield variation, while other non-nutritional factors influenced 80% of productivity. This finding corroborates Lima Neto et al. (2022) for banana crops grown in Ceará, Brazil, where the CND-r^2 index explained 30% of yield variation, reinforcing the need to establish appropriate nutrient balances within current production systems using advanced compositional analysis techniques. For the same dataset, the DRIS index explained only 20% of yield variation.

5. Use of techniques and equipment for non-destructive assessment of nutritional status

Leaf samples can be collected in orchards, prepared, and analyzed in a laboratory. The resulting nutrient concentrations can be interpreted using fertilization guidelines and reference tables to determine whether fertilization is necessary. These analyses also support decisions on the appropriate fertilizer rates to be applied (Tassinari et al., 2022; Ayres et al., 2023; Trapp et al., 2025). In addition, results may help explain visual symptoms of nutrient deficiencies or toxicities in fruit crops. However, many fruit-producing regions worldwide face a shortage of personnel for leaf sampling. Moreover, not all regions have laboratories capable of performing foliar analyses, and in some locations, analytical costs remain high. Considering these and other constraints, there is a growing need to propose new methodologies and equipment, preferably non-destructive, capable of generating information to support the estimation of the nutritional status of fruit crops.

The SPAD (Soil Plant Analysis Development) technique is based on measuring light absorbance by chlorophyll molecules in leaves using a portable chlorophyll meter that emits light in the red (approximately 650 nm) and near-infrared (approximately 940 nm) wavelengths (Zhang et al., 2022). The device measures light transmittance through the leaf and calculates an index related to chlorophyll content, which correlates with leaf nitrogen concentration, an essential nutrient for photosynthesis and plant growth. Field operation is relatively simple: the operator positions the sensor on the leaf surface, avoiding damaged or shaded areas, and records the readings (Süß et al., 2015). The selection of leaves is critical for ensuring accuracy; fully expanded, healthy leaves located in the middle canopy are recommended, as very young or old leaves exhibit physiological variations that may distort readings (Süß et al., 2015; Zhang et al., 2022). In olive trees, studies have shown that mid-canopy leaves provide more representative data on nutritional status (Boussadia et al., 2011). Research conducted in Italian olive orchards found significant correlations between SPAD values and spectral indices obtained by drones, demonstrating the feasibility of this technique for rapid, non-destructive assessment of chlorophyll and nitrogen content (Caruso et al., 2019). In other fruit crops, such as citrus and grapevines, SPAD has been widely used for monitoring nutritional status, although the need for species- and cultivar-specific calibration remains a recognized limitation (Trentin et al., 2009; Huang et al., 2024; Niaz et al., 2023). It is important to emphasize that the success of SPAD use for nutrient estimation, particularly nitrogen, depends on methodological adjustments, including defining plant quadrants for readings, the number of leaves and readings per leaf, and the leaf position on the branch. Additionally, it is advisable to evaluate statistical models that best fit the relationship between SPAD readings and nutrient concentrations, such as nitrogen.

The use of unmanned aerial vehicles (UAVs or drones) equipped with multispectral or hyperspectral sensors has expanded the possibilities for nutritional monitoring in orchards. These devices capture images in the visible and near-infrared spectral ranges, enabling calculation of vegetation indices such as the Normalized Difference Vegetation Index (NDVI), which relates near-infrared and red reflectance to estimate plant vigor and health. NDVI has been shown to correlate with chlorophyll content and leaf area index (LAI), key parameters for nutritional assessment. For example, in both irrigated and rainfed olive orchards in Italy, UAV-derived NDVI showed significant correlations with leaf chlorophyll and LAI, demonstrating the sensitivity of the technique in detecting nutritional and water stress variations (Caruso et al., 2019). Drone operation requires flight planning with standardized altitude (typically 30–70 m), appropriate image overlap for canopy 3D reconstruction, and subsequent data processing to extract spectral indices. Field validation using leaf samples is essential to ensure reliability. In other fruit crops, such as mango and citrus, the combination of multispectral imagery and artificial intelligence algorithms has enabled accurate prediction of nutrient concentrations.

Near-infrared (NIR) spectroscopy is based on the interaction of infrared radiation with the chemical constituents of leaves, such as water, proteins, and carbohydrates. Portable NIR instruments emit light in the 780–2500 nm range and record the reflected or transmitted spectrum, allowing the construction of predictive models for foliar nutrient quantification. In the field, the sensor is positioned directly on the leaf or on collected samples, with care to avoid external interference (Borges et al., 2020). In fruit crops such as apple and pear, NIR spectroscopy has proven effective in predicting soluble solids, dry matter, and nutrient contents, with relative errors below 8%, highlighting its potential for rapid and non-invasive evaluations (Vilvert et al., 2023).

Other emerging techniques include active optical sensors and chlorophyll fluorescence. Chlorophyll fluorescence measures light emission by chlorophyll molecules when excited by light, reflecting the physiological and nutritional status of plants. This technique is sensitive to both environmental and nutritional stress and has been used to detect deficiencies and monitor fruit ripening. In tomato and mango crops, fluorescence has been applied for assessing nutritional and physiological stress (Abdelhamid et al., 2024; Lechaudel et al., 2010). Active optical sensors, such as LiDAR and Vis/NIR systems, allow acquisition of three-dimensional canopy and fruit structure data, supporting precision management (Borges et al., 2020; Farhan et al., 2024). For instance, in olive trees, manual and electronic methods for canopy volume estimation have been compared, and techniques such as the ellipsoidal volume method have shown good correlation with LiDAR measurements, facilitating canopy characterization for integrated management (Miranda-Fuentes et al., 2015).

Therefore, non-destructive techniques for assessing the nutritional status of fruit crops provide valuable tools for sustainable management, offering different levels of complexity and operational requirements. The SPAD meter is a fast and accessible technique but requires careful calibration and sampling; drones with multispectral sensors enable large-scale monitoring but demand data processing and field validation; NIR spectroscopy provides rapid chemical analyses but depends on robust predictive models; and emerging techniques such as fluorescence and LiDAR complement physiological and structural diagnostics. The integrated application of these methodologies, adapted to local conditions and validated under field conditions, is essential and may contribute to improving orchard productivity and sustainability.

6. Challenges in the interpretation of results and regional variability in calibration criteria

The interpretation of chemical analysis results from soil and plant samples represents one of the most complex and decisive stages in the nutritional management of fruit crops. All knowledge regarding soil reactions and nutrient availability is fundamentally derived from laboratory analyses, whose reliability depends directly on proper sampling procedures in the field. Errors made during this stage cannot be corrected later, highlighting the importance of strictly following technical standards and recommendations. Soil and plant tissue analyses are complementary and indispensable tools, enabling the monitoring of soil acidity, fertility, and plant nutritional status, as well as supporting more precise recommendations for fertilizers and soil amendments.

Nutrient management is, therefore, one of the main factors influencing the growth and productivity of fruit crops, directly affecting fruit quality and orchard profitability. However, determining crop nutritional requirements remains a persistent challenge, since although the essential elements are the same for all plant species, the required quantities vary according to genetic traits, edaphoclimatic conditions, productive capacity, soil characteristics, and the plant's life cycle. In fruit production, these challenges are magnified by the perennial nature of the species, the influence of practices such as pruning, and the extensive root systems that explore soil layers beyond those typically analyzed.

Leaf analysis, based on the relationship between nutrient concentrations available in the soil, their contents in well-defined leaves, and yield magnitude (Natale et al., 2012), has been established as an essential diagnostic tool. Leaves, due to their intense physiological activity and rapid response to nutritional variations, are the preferred organs for diagnosis. However, the interpretation of leaf nutrient concentrations requires caution, as nutrient levels may vary depending on leaf age, position on the branch, environmental conditions, and plant health.

Among the main challenges is the lack of cultivar- and region-specific critical ranges. In a country as large as Brazil, characterized by extensive climatic and edaphic diversity, it is unfeasible to apply uniform recommendations. Most of the values presented in technical bulletins remain generic (Brunetto et al., 2016; Teixeira et al., 2022), encompassing multiple species and varietal groups, and are often based on international references such as Failla et al. (2000) and Porro et al. (2001), developed under different edaphoclimatic conditions. Consequently, the nutritional standards commonly adopted may not accurately reflect regional realities, potentially overestimating or underestimating the optimal nutrient levels in leaf tissues.

The misconception that nutritional diagnostic "standards" – such as the DRIS method – are universally applicable has been refuted by numerous recent studies. Research conducted on crops such as soybean (Ferreira et al., 2024; Souza et al., 2023), banana (Oliveira et al., 2024a; Lima Neto et al., 2022), pineapple (Amorim et al., 2024; Rodrigues et al., 2022), and citrus (Yamane et al., 2022) demonstrates wide variability in adequate nutrient concentrations across regions and cultivation conditions, indicating that critical ranges are strongly dependent on both environment and genotype.

Most soils, particularly those in tropical regions, are unable to supply sufficient and balanced amounts of all nutrients required by fruit crops. It is also important to consider that countries or regions with vast territorial extension, such as Brazil, characterized by wide climatic and biological variation, may present distinct fertility constraints among different areas. Therefore, it is evident that defining uniform management strategies is highly challenging, since lime and fertilizer application programs, once established, must be distinct and tailored to the conditions of each producing region.

In general, the nutrient values indicated in official bulletins are generic (Brunetto et al., 2016; Teixeira et al., 2022), encompassing different cultivars (epibiotes), rootstocks (hypobiotes), soil and climate conditions, and management systems. Thus, the available databases provide broad, generalized patterns. However, the idea that these "standards" are universal is a myth, as demonstrated by Rozane et al. (2025) and evidenced in the following examples:

- For soybean grown in the western region of Bahia, Brazil, Ferreira et al. (2024) reported adequate leaf nutrient concentrations of 35.5 g kg^{-1} N, 2.5 g kg^{-1} P, and 14.6 g kg^{-1} K, whereas Souza et al. (2023) estimated suitable levels of 46.3 g kg^{-1} N, 3.7 g kg^{-1} P, and 19.2 g kg^{-1} K for crops grown in southern Piauí and eastern and southern Maranhão, Brazil.

- For banana cv. 'Grande Naine', Oliveira et al. (2024a) found adequate concentrations of 26.0 g kg^{-1} N, 2.1 g kg^{-1} P, and 33.0 g kg^{-1} K in the Vale do Ribeira region, São Paulo, Brazil, while Lima Neto et al. (2022) reported 20.7 g kg^{-1} N, 1.6 g kg^{-1} P, and 32.0 g kg^{-1} K for the same variety cultivated in Ceará, Brazil.

- Regarding pineapple cv. Pérola, Amorim et al. (2024) reported adequate leaf concentrations of 14.9 g kg^{-1} N, 0.8 g kg^{-1} P, and 28.8 g kg^{-1} K for conditions in the Triângulo Mineiro region, Minas Gerais, Brazil, whereas Rodrigues et al. (2022) found adequate values of 12.5 g kg^{-1} N, 1.4 g kg^{-1} P, and 39.2 g kg^{-1} K for the same cultivar grown in Paraíba, Brazil.

- For 'Valencia' orange (*Citrus sinensis* (L.) Osb.), adequate leaf nutrient concentrations also diverge when comparing orchards established in California, United States (Beverly, 1987), and São Paulo, Brazil (Yamane et al., 2022).

These examples highlight that nutritional recommendations vary widely among regions, confirming that the universality of diagnostic norms is a myth. Nevertheless, the interpretation of nutritional diagnosis extends far beyond reference values. Adequate nutrient balance must take into account the characteristics of each genotype, as well as the specific edaphoclimatic conditions under which orchards are managed. It is also worth noting that fruit trees tend to reach a certain nutritional stability in their adult phase, reflecting the identity of the region and/or cultivation method.

Sharpe et al. (1989) observed that nutritional status, evaluated at different times, affected the nutrient balance of peach trees grown in the United States, a finding corroborated by results obtained under Brazilian conditions for guava crops (Rozane et al., 2016). However, even under the same edaphoclimatic conditions and at the same evaluation time, divergent nutritional balances are observed within a given species whenever there is variation in cultivar or variety, as reported by Parent et al. (2013b), Rozane et al. (2015, 2016), and Botelho et al. (2025) for several fruit crops. This suggests that nutrient balance norms should be established not only at the species level but also for each cultivation system, considering the specific soil and climate conditions.

Although differences exist among nutritional patterns according to species, cultivar, and orchard environment, similarities can also be found among genotypes (Parent et al., 2013a; Rozane et al., 2015). Thus, nutritional parameters already considered adequate can be used as reference for other varieties that exhibit comparable nutrient concentrations and demands, provided that appropriate adjustments are made.

Therefore, the interpretation of analytical results should not rely solely on isolated comparisons of individual nutrient levels but rather on the assessment of the overall nutrient balance, considering interactions among elements and the specific characteristics of each species, cultivar, and production environment. The adoption of integrative approaches, such as the Compositional Nutrient Diagnosis (CND), represents a promising advance, enabling more accurate and applicable diagnoses under real cultivation conditions. Nonetheless, significant knowledge gaps persist, particularly for perennial and tropical fruit crops, where long-term experimentation and substantial research investment are required.

In summary, overcoming the challenges associated with the interpretation of analytical results requires the establishment of regional databases, expansion of calibration studies, and development of diagnostic criteria that account for the genetic and environmental specificities of each production system. Only through such efforts will it be possible to establish more consistent nutritional recommendations that ensure productivity, fruit quality, and orchard sustainability.

7. Future perspectives and the importance of nutritional diagnosis for orchard sustainability

Food autonomy is a crucial factor in the twenty-first century. The growing demand for food, driven by population increase and longer life expectancy, represents one of the greatest challenges humanity will face in the coming decades. Increasing production, and especially productivity, depends on adopting advanced agricultural technologies and the rational use of inputs such as soil amendments and fertilizers, particularly in tropical and subtropical regions.

Advances in plant mineral nutrition have been key drivers of productivity growth. However, many countries, including Brazil, remain highly dependent on imported fertilizers to supply nitrogen (N), phosphorus (P), and potassium (K). Phosphorus and potassium reserves are scarce, while nitrogen fertilizer synthesis depends on hydrogen (H) derived from petroleum, underscoring the importance of efficient and sustainable use of these resources in agriculture.

Fruit production stands out as a strategic sector in Brazilian agribusiness due to its economic importance, high added value, and profitability per cultivated area. In addition to its productive potential, fruit tree cultivation contributes to carbon (C) cycling and may, in the near future, generate carbon credits and environmental services as economic assets. Although fruit crops are grown under diverse edaphoclimatic conditions, research consistently demonstrates strong yield responses to adequate soil fertility. Proper nutritional management is essential, as excessive or insufficient fertilization can reduce productivity, compromise fruit quality, increase costs, and cause environmental contamination. Thus, the integrated use of soil and leaf analyses remains fundamental for sustainable and efficient orchard management, given the perennial nature of fruit crops and their capacity to recycle nutrients through extensive root systems.

Although plant nutritional diagnosis was first proposed nearly a century ago (Lagatu and Maume, 1934a; 1934b), its objectives remain highly relevant amid the growing need to achieve higher productivity and quality with lower environmental impact. Each nutrient plays specific roles in plant metabolism, directly influencing physiological processes that determine yield and fruit quality. The concentration of nutrients in plant tissues reflects the integration of soil and plant factors affecting crop performance (Munson and Nelson, 1990). Nonetheless, universal diagnostic standards often fail to account for the influence of local climate and management conditions (Beaufils, 1973), making regional or local calibration more consistent (Rozane et al., 2020). Given the immense number of potential interactions among soil, climate, and plant factors identified by Tisdale et al. (1985), large, well-documented databases derived from commercial orchards have become essential for understanding and managing nutritional variability (Rozane et al., 2015; Lima Neto et al., 2020; Trapp et al., 2025).

The creation of such databases enables the use of multivariate models, such as Compositional Nutrient Diagnosis (CND) (Parent and Dafir, 1992), which integrate soil, climate, cultivar, and management variables to provide more reliable recommendations and enhance diagnostic precision (Parent and Natale, 2020). However, building robust databases is the most demanding phase of diagnosis development, requiring meticulous data collection, verification, and organization to avoid errors or missing information. The accuracy of nutritional interpretation depends on reliable reference standards that reflect local soil, climatic, and management conditions. Therefore, improving foliar diagnosis and fertilization strategies requires integrated efforts combining plant physiology, soil science, and data analytics. Accurate diagnosis, strategic planning, and technical training will enable producers to adopt practices that harmonize productivity, fruit quality, and environmental sustainability.

8. Final considerations

Future perspectives on nutrient sampling, analysis, and interpretation in fruit crops point to steady advances integrating traditional methods with emerging technologies to improve diagnostic efficiency and reliability. Non-destructive tools, such as optical sensors, NIR spectroscopy, and drone-based multispectral imaging, are expanding monitoring capabilities while reducing costs and response time. However, their full potential relies on developing local calibrations and robust databases that reflect species, cultivar, and environmental diversity. Integrating leaf and soil analyses with multielement models like Compositional Nutrient Diagnosis (CND) can better guide management practices balancing yield and fruit quality. Yet, the absence of standardized sampling procedures and region-specific critical ranges limits broader application, emphasizing the need for local research and validation. Ultimately, advances in fruit crop nutrition depend on an integrated approach combining plant physiology, soil science, and data analytics to support sustainable and efficient production systems.

References

Amorim, D.A.de, Favero, A.C., Conceição, M.P.D., Vilela Rodrigues, M.G., Belarmino Rodrigues, J. B., Natale, W., Rozane, D.E. (2024). DRIS nutritional norms and sufficiency range for the perola pineapple cultivation. *Journal of Plant Nutrition*, 47(20), 3998-4007.

Abdelhamid, M.A., Rawdhan, S.A., Shalaby, S.S., Atia, M.F. (2024). Assessment of tomato ripeness using chlorophyll fluorescence. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 28.

Aitchison, J. (1986). The statistical analysis of compositional data (1st ed.). Chapman and Hall.

ANDA (2025). *Anuário Estatístico do Setor de Fertilizantes 2024.* Associação Nacional para Difusão de Adubos, São Paulo, Brazil, 178 p.

Aular, J.U., Casares, M., Natale, W. (2014). Nutrição mineral e qualidade do fruto do abacaxizeiro e do maracujazeiro. *Revista Brasileira de Fruticultura*, 36 (4): 1046-1054.

Aular, J.U., Casares, M., Natale, W. (2017). Factors affecting citrus fruit quality: Emphasis on mineral nutrition. *Científica*, 45 (1): 64-72, 2017.

Aular, J.U., Natale, W. (2013). Nutrição mineral e qualidade do fruto de algumas frutíferas tropicais: goiabeira, mangueira, bananeira e mamoeiro. *Revista Brasileira de Fruticultura*, 35 (4): 1214-1231.

Ayres, G., Simao, F., Rozane, D. E., Bueno, J.M.M., Berghetti, A.L.P., Dotto, L., Nunes, F., Marques, A.C.R., Silva L.O.S., Paula, B.V., Krug, A., Marques, A.L.L., Papalia, D., Hindersmann, J., Brunetto, G. (2023). Proposition of critical levels and nutrient sufficiency ranges in leaves of 'White Moscato' (*Vitis vinifera* 'Muscat') and 'Bordeaux' (*Vitis labrusca* 'Ives'). *VITIS*, 62: 125-135.

Beaufils, E.R. (1973). *Diagnosis and Recommendation Integrated System (DRIS).* Soil Science, Bulletin 1. Pietermaritzburg: University of Natal.

Beverly, R.B. (1987). Modified DRIS method for simplified nutrient diagnosis of 'Valencia' oranges. *Journal of Plant Nutrition*, 10(9), 1401–1408.

Borges, C.S., Weindorf, D.C., Carvalho, G.S., Guilherme, L.R.G., Takayama, T., Curi, N., Lima, G.J.E.O., Ribeiro, B.T. (2020). Foliar elemental analysis of Brazilian crops via portable X-ray fluorescence spectrometry. *Sensors*, 20: 2509.

Botelho, S.M., Viégas, I.D.J.M., Galvão, J.R., Santos, C.R.C.dos, Fontes, E.A.de O., Lobo, V.M.Q., Oliveira, B.M.de., Oliveira, J.P.de. (2025). Potential response to fertilization for interpreting the DRIS indices of the black pepper crop. *Journal of Plant Nutrition*, 1-12.

Boussadia, O., Steppe, K., Zgallai, H., El Hadj, S.B., Braham, M., Lemeur, R., Van Labeke, M. C. (2011). Nondestructive determination of nitrogen and chlorophyll content in olive tree leaves and the relation with photosynthesis and fluorescence parameters. *Photosynthetica*, 49: 149–153.

Brunetto, G., Ernani, P. R., Melo, G. W. B. de, & Nava, G. (2016). Frutíferas. In *Manual de calagem e adubação para os estados do Rio Grande do Sul e de Santa Catarina* (11th ed., pp. 189–232). Comissão de química e fertilidade do solo RS/SC.

Caruso, G., Zarco-Tejada, P.J., González-Dugo, V., Moriondo, M., Tozzini, L., Palai, G., Rallo, G., Hornero, A., Primicerio, J., Gucci, R. (2019). High-resolution imagery acquired from an unmanned platform to estimate biophysical and geometrical parameters of olive trees under different irrigation regimes. PloS one, 14(1), e0210804.

Cordell, D., Drangert, J.O., White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change,* 19, 292–305.

Costa, L.G.A.F., Rozane, D.E., Silva, S.A., Oliveira, C.T., Pavarin, L.G.F., Silva, S.H.M.G. (2019). Seasonality in nutrient content of banana diagnostic leaf. *Revista Brasileira de Fruticultura*, 41(4), e-151.

De Saussure, N. T. (1804). *Recherches chimiques sur la vegetation*. Nyon.

Failla, O., Santucci, S., Del Turco, C., Di Francesco, L., Chiuchiarelli, I. (2000). Tree Nutritional Status in Relation to Soil Pedogenetic Description: A Case Study. In *IV International Symposium on Mineral Nutrition of Deciduous Fruit Crops* 564: 229-234).

FAO – Food and Agriculture Organization of the United Nations (2015). *International Year of Soils: Healthy soils are the foundation for healthy food production.* FAO, Rome. Available at: http://www.fao.org/3/a-i4405f.pdf (Accessed: 05 May 2024).

Farhan, S.M., Yin, J., Chen, Z., Memon, M.S. (2024). A comprehensive review of LiDAR applications in crop management for precision agriculture. *Sensors*, 24: 5409.

Ferreira, E., Medeiros, F.C., Rozane, D.E., Lindsey, L., Amadori, C., Rocha, C.da.S. (2024). Assessment of nutritional status of soybean by the DRIS method in western of Bahia State. *Revista Brasileira de Ciência Do Solo*, 48.

Greenacre, M., Grunsky, E., Bacon-Shone, J., Erb, I., Quinn, T. (2023). Aitchison's Compositional Data Analysis 40 Years on: A Reappraisal. *Statistical Science*, 38(3).

Gui, H.P., Tan, Q.L., Hu, C.X., Zhang, Y., Zheng, C.-S., Sun, X.C., Zhao, X.H. (2014). Floral analysis for *Satsuma* mandarin (*Citrus unshiu* Marc.) nutrient diagnosis based on the relationship between flowers and leaves. *Scientia Horticulturae*, 169, 51–56.

Hahn, L., Kurtz, C., de Paula, B. V., Feltrim, A. L., Higashikawa, F. S., Moreira, C., Rozane, D. E., Brunetto, G., Parent, L.-É. (2024). Feature-specific nutrient management of onion (*Allium cepa*) using machine learning and compositional methods. *Scientific Reports*, 14(1), 6034.

Huang, Y., Li, D., Liu, X., Ren, Z. (2024). Monitoring canopy SPAD using UAV multispectral imaging over fruit tree growth stages and species. *Frontiers in Plant Science*, 15.

Huber, D.M. (1980). "The role of mineral nutrition in defense," in Plant Disease, An Advanced Treatise, Volume 5, *How Plants Defend Themselves*, eds J. G. Horsfall and E. B. Cowling (New York, NY: Academic Press), 381–406.

Khelil, M.B., Sanaa, M., Sallem, M., Larbi, A. (2010). Floral analysis as a new approach to evaluate the nutritional status of olive trees. *Journal of Plant Nutrition*, 33(5), 627–639.

Khiari, L., Parent, L.-É., Tremblay, N. (2001). Selecting the High-Yield Subpopulation for Diagnosing Nutrient Imbalance in Crops. *Agronomy Journal*, 93(4), 802–808.

Kyveryga, P. M., Blackmer, T. M., Caragea, P. C. (2011). Categorical Analysis of Spatial Variability in Economic Yield Response of Corn to Nitrogen Fertilization. *Agronomy Journal*, 103(3), 796–804.

Kuldeep, Singh, A.K., Sajwan, A., Kamboj, A.D., Joshi, G., Gautam, R., Kumar, M., Mani, G., Lal, S., Kaur, J. (2024). Advances in precision nutrient management of fruit crops. *Journal of Plant Nutrition*, 47(19), 3251–3271.

Lagatu, H., Maume, L. (1934a). Le diagsontic foliaire de la pomme de terre. *Annual Ecole Nationale Superieure Agronomique de Montpellier,* 22:50-158.

Lagatu, H., Maume, L. (1934b). Recherches sur lê diagnostic foliaire. *Annual Ecole Nationale Superieure Agronomique de Montpellier*, 22:257-306.

Lechaudel, M., Urban, L., Joas, J. (2010). Chlorophyll fluorescence, a nondestructive method to assess maturity of mango fruits (Cv. 'Cogshall') without growth conditions bias. *Journal of Agricultural and Food Chemistry*, 58: 7532–7538.

Lima Neto, A.J., Deus, J.A.L., Rodrigues Filho, V.A., Natale, W., Parent, L.E. (2020). Nutrient Diagnosis of Fertigated "Prata" and "Cavendish" Banana (*Musa* spp.) at Plot-Scale. *Plants,* 9: 1467.

Lima Neto, A.J., Natale, W., Rozane, D.E., de Deus, J.A.L., Rogrigues Filho, V.A. (2022). Establishment of DRIS and CND Standards for Fertigated 'Prata' Banana in the Northeast, Brazil. *Journal of Soil Science and Plant Nutrition*, 765–777.

Lundegårdh, H. (1943). Leaf analysis as a guide to soil fertility. *Nature*, 151, 310–311.

Malavolta, E. (1980). *Elementos da nutrição mineral de plantas.* Editora Agronômica Ceres, São Paulo, Brazil, 251 p.

Malavolta, E. (1981). *Manual de química agrícola: adubos e adubação* (3rd ed.). Editora Agronômica Ceres, São Paulo, Brazil, 594 p.

Malavolta, E. (2006). *Manual de nutrição mineral de plantas*. São Paulo: Editora Agronômica Ceres Ltda., 638 p.

Marschner, P. (2012). *Marschner's Mineral Nutrition of Higher Plants*. Academic Press, 3.ed. 651p.

Martinez, D.A., Loening, U.E., Graham, M.C., Gathorne-Hardy, A. (2021). When the Medicine Feeds the Problem; Do Nitrogen Fertilisers and Pesticides Enhance the Nutritional Quality of Crops for Their Pests and Pathogens? *Frontiers in Sustainable Food Systems*, 5.

Miranda-Fuentes, A., Llorens, J., Gamarra-Diezma, J., Gil-Ribes, J., Gil, E. (2015). Towards an optimized method of olive tree crown volume measurement. *Sensors*, 15: 3671–3687.

Munson, R.D., Nelson, W.L. (1990). Principles and practices in plant analysis. R.L Westerman (Ed.) *Soil testing and plant analysis*. Soil Science Society of America, Stillwater, Oklahoma. 359-388.

Natale, W., Brunetto, G., Rozane, D.E., Melo, G.W.B., Corrêa, M.C.M., Lima Neto, A.J. (2020). Amostragem e preparo de amostras de solo e folhas em frutíferas. In: Brunetto, G., Melo, G.W.B., Girotto, E., Tassinari, A., Krug, A.V., Marques, A.C.R., Paula, B.V., Marchezan, C., Betemps, D.L., Trentin, E., Silva, I.C.B., Silva, L.O.S. (Eds.), *Atualização sobre calagem e adubação em frutíferas*. Porto Alegre: NRS-SBCS, Gráfica e Editora RJR, pp. 32–44.

Natale, W., Rozane, D.E. (2018). *Análise de solo, folhas e adubação de frutíferas*. Registro: UNESP, 124 p.

Natale, W., Rozane, D.E. (2024). *Recomendações de calagem e adubação para a goiabeira 'Paluma' cultivada no estado de São Paulo*. Santa Maria: Editora Pallotti, 136 p.

Natale, W., Rozane, D.E., Parent, L.E., Parent, S.É. (2012). Acidez do solo e calagem em pomares de frutíferas tropicais. *Revista Brasileira de Fruticultura*, 34, 1294-1306.

Natale, W., Rozane, D.E., Prado, R. de M., Romualdo, L.M., Souza, H.A. de, Hernandes, A. (2011). Dose econômica de calcário na produtividade de caramboleiras. *Revista Brasileira de Fruticultura*, 33(4), 1294–1299.

Nowaki, R.H.D., Parent, S.-É., Cecílio Filho, A.B., Rozane, D.E., Meneses, N.B., Silva, J.A. dos S. da, Natale, W., Parent, L.E. (2017). Phosphorus over-fertilization and nutrient misbalance of irrigated tomato crops in Brazil. *Frontiers in Plant Science*, 8, 825.

Niaz, N., Gulzar, S., Kazmi, J.H., Aleem, S.A., Pham, M.P.P., Mierzwa-Hersztek, M.M.H., Ahmed, S.R., Lahori, A.H., Mushtaq, Z.N. (2024). Assessment of chlorophyll content in leaves of crops and orchards based on spad, multispectral, and hyperspectral techniques. *Ecological Questions*, 35(2), 161-174.

Oliveira, C.T., Rozane, D.E., Amorim, D.A., Souza, H.A., Fernandes, B.S., Natale, W. (2020). Diagnosis of the nutritional status of 'Paluma' guava trees using leaf and flower analysis. *Revista Brasileira de Fruticultura*, 42(3), 1–9.

Oliveira, C.T.de, Rozane, D.E., Deus, J.A.L. de, Lima, J.D., Lopes, M.D.C., Souza, W.J.O.de. (2024a). Establishment of DRIS standards and sufficiency range for 'nanica' banana trees in Vale do Ribeira. *Acta Scientiarum. Agronomy*, 46(1), e67171.

Oliveira, C.T. de, Rozane, D.E., Lima Neto, A.J. de, Natale, W. (2024b). Nutrient parameters limiting banana plant development in Vale do Ribeira, São Paulo State, Brazil. *Ciência Rural*, 54(6).

Parent, L.E., Dafir, M. (1992). A Theoretical Concept of Compositional Nutrient Diagnosis. *Journal of the American Society for Horticultural Science*, 117(2), 239–242.

Parent, L.E., Natale, W. (2020). Perspectivas futuras da nutrição mineral para frutíferas. *In:* Brunetto, G. et al. *Atualização sobre calagem e adubação em frutíferas*. Bento Gonçalves, RS. NRS-SBCS, 13-31.

Parent, L.E., Natale, W., Ziadi, N. (2009). Compositional nutrient diagnosis of corn using the Mahalanobis distance as nutrient imbalance index. *Canadian Journal of Soil Science*, 89(4), 383–390.

Parent, S.-É., Parent, L.E., Egozcue, J.J., Rozane, D.E., Hernandes, A., Lapointe, L., Hébert-Gentile, V., Naess, K., Marchand, S., Lafond, J., Mattos, D., Barlow, P., Natale, W. (2013a). The plant ionome revisited by the nutrient balance concept. *Frontiers in Plant Science*, 4, 39.

Parent, S.-É., Parent, L.E., Rozane, D.-E., Natale, W. (2013b). Plant ionome diagnosis using sound balances: case study with mango (*Mangifera Indica*). *Frontiers in Plant Science*, 4, 449.

Pellerin, A., Parent, L.-É., Fortin, J., Tremblay, C., Khiari, L., Giroux, M. (2006). Environmental Mehlich-III soil phosphorus saturation indices for Quebec acid to near neutral mineral soils varying in texture and genesis. *Canadian Journal of Soil Science*, 86(4): 711–723.

Porro, D., Dorigatti, C., Ramponi, M. (2001). Can foliar application modify nutritional status and improve fruit quality results on apple in northeastern Italy. In *International Symposium on Foliar Nutrition of Perennial Fruit Plants* 594: 521-526.

Prado, R.M., Rozane, D.E. (2020). Leaf analysis as a diagnostic tool for balanced fertilization in tropical fruits. In: Srivastava, A.K., Hu, C. (Eds.), *Fruit Crops: Diagnosis and Management of Nutrient Constraints*. Amsterdam: Elsevier, 131–143.

Prévot, P., Ollagnier, M. (1956). Méthode d'utilisation du diagnostic foliaire. In IRHO (Ed.), *Analyse des plantes et problèmes de fumures minérales*, 171–192.

Rodrigues, J.B.B., da Silva, A.P., Rozane, D.E., Natale, W., de Melo Silva, S. (2022). Leaf reference values for 'Pérola' pineapple quality using compositional nutrient diagnosis. *Journal of Plant Nutrition*, 45(20): 3066–3079.

Rozane, D.E., Mattos, J.R., D., Parent, S.-É., Natale, W., Parent, L.E. (2015). Meta-analysis in the Selection of Groups in Varieties of Citrus. *Communications in Soil Science and Plant Analysis*, 46:1948–1959.

Rozane, D.E., Natale, W., Brunetto, G., Ciotta, M.N., Nowaki, R.H.D., Melo, G.W.B.de. (2017). Diagnose da composição nutricional (CND) como critério de predição do estado nutricional de pereiras. In Ciotta, M.N., Brunetto, G., Comin, J., Pasa, M.da S., Sete, P. B. (Eds.), I Workshop sobre frutificação e adubação de pereiras (Epagri, pp. 103–120).

Rozane, D.E., Natale, W., Parent, L.E., dos Santos, E.M.H. (2012). The CND-Goiaba 1.0 software for nutritional diagnosis of guava (Psidium guajava L.)'Paluma', in Brazil. In *III International Symposium on Guava and other Myrtaceae* 959:161-166.

Rozane, D.E., Natale, W., Prado, R.M., Barbosa, J.C. (2009). Tamanho da amostra foliar para avaliação do estado nutricional de goiabeiras com e sem irrigação. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 13(3): 233–239.

Rozane, D.E., Parent, L.E., Natale, W. (2016). Evolution of the predictive criteria for the tropical fruit tree nutritional status. Científica, 44(1): 102-112.

Rozane, D.E., Paula, B.V., Melo, G.W.B., Santos, E.M.H, Trentin, E., Marchezan, C., Silva, L.O.S., Tassinari, A., Dotto, L., Oliveira, F.N., Natale, W., Baldi, E., Toselli, M., Brunetto, G. (2020). Compositional Nutrient Diagnosis (CND) applied to grapevines grown in subtropical climate region. *Horticulturae*, 6: 1-13.

Rozane, D.E., Toselli, M., Brunetto, G., Baldi, E., Natale, W., Paula, B.V.de, Lima, J.D., Medeiros, F.C., Ayres, G., Gobi, S.F. (2025). Proposal of Nutritional Standards for the Assessment of the Nutritional Status of Grapevines in Subtropical and Temperate Regions. *Plants*, 14(5): 698.

Roy, E.D., Richards, P.D., Martinelli, L.A., Coletta, L.D., Lins, S.R.M., Vazquez, F.F., Willig, E., Spera, S.A., VanWey, L.K., Porder, S. (2016). The phosphorus cost of agricultural intensification in the tropics. *Nature Plants,* 2: 16043.

Sharpe, R.R., Reilly, C.C., Nyczepir, A.P., Okie, W.R. (1989). Establishment of peach in a replant site as affected by soil fumigation, rootstock, and pruning date. *Plant Dis*, 73(5), 412-415.

Smith, P.F. (1962). Mineral analysis of plant tissues. *Annual Review of Plant Biology*, 13, 81–108.

Souza, H.A.de, Rozane, D.E., Vieira, P.F.de M.J., Sagrilo, E., Leite, L.F.C., Brito, L.C.R. de, Conceição, M.P., Ferreira, A. C. M. (2023). Accuracy of DRIS and CND methods and nutrient sufficiency ranges for soybean crops in the Northeast of Brazil. *Acta Scientiarum. Agronomy*, 45, e59006.

Srivastava, A.K., Malhotra, S.K. (2017). Nutrient use efficiency in perennial fruit crops – A review. *Journal of Plant Nutrition*, 40(13), 1928–1953.

Stefanello, L.O., Schwalbert, R., Schwalbert, R.A., Drescher, G.L., De Conti, L., Pott, L.P., Tassinari, A., Kulmann, M.S.de.S., da Silva, I.C.B., Brunetto, G. (2021). Ideal nitrogen concentration in leaves for the production of high-quality grapes cv 'Alicante Bouschet' (*Vitis vinifera* L.) subjected to modes of application and nitrogen doses. *European Journal of Agronomy*, 123, 126200.

Stewart, B.A., Lal, R. (2017). The nitrogen dilemma: Food or the environment. *Journal of Soil and Water Conservation*, 72(6).

Süß, A., Danner, M., Obster, C., Locherer, M., Hank, T., Richter, K., Consortium, E. (2015). Measuring leaf chlorophyll content with the Konica Minolta SPAD-502Plus. 1. ed. Potsdam: GFZ Data Services.

Sun, Y., Wang, M., Mur, L. A., Shen, Q., Guo, S. (2020). Unravelling the roles of nitrogen nutrition in plant disease defenses. *Int. J. Mol. Sci.* 21:572.

Tassinari, A., Silva, L.O.S., Schwalbert, R.A., Vitto, B., Kulmann, M., Jung, J.P., Arruda, W.S., Schwalbert, R., Tiecher, T.L., Ceretta, C.A., De Conti L., Schumacher, R.L., Brunetto, G. (2022). Nitrogen Critical Level in Leaves in `Chardonnay' and `Pinot Noir' Grapevines to Adequate Yield and Quality Must. Agronomy-Baselimage, 12:1132.

Teixeira, L. A. J., Quaggio, J. A., Mattos Jr., D., Boaretto, R. M., & Cantarella, H. (2022). Frutíferas. In H. Cantarella, J. A. Quaggio, D. Mattos Jr., R. M. Boaretto, & B. Van Raij (Eds.), *Boletim 100: Recomendações de adubação e calagem para o estado de São Paulo*, 259–264.

Tisdale, S.L., Nelson, W.L., Beaton, J.D. (1985). *Soil fertility and fertilizers*. 4. ed. Macmillan Publishing, 754p.

Trapp, T., Moura-Bueno, J.M., Siqueira, G.N. de, Hahn, L., Rozane, D.E., Lima Neto, A.J.de, Natale, W., Loss, A., Brunetto, G. (2025). Nutrients' critical level propositions and sufficiency ranges aimed at high apple yield under subtropical climate. *European Journal of Agronomy*, 164, 127523.

Trentin, G., Brunetto, G., Ceretta, C.A., Kaminski, J., Melo, G.W.de., Girotto, E., Lorensini, F., Lourenzi, C.R., Moser, G., De Conti, L., Tiecher, T., Miotto, A. (2009). Uso do SPAD no diagnóstico do teor total de nitrogênio na folha em videiras submetidas à adubação nitrogenada na Serra Gaúcha do Rio Grande do Sul. Viçosa, MG: *Sociedade Brasileira de Ciência do Solo*, p. 745.

Tripathi, R., Tewari, R., Singh, K. P., Keswani, C., Minkina, T., Srivastava, A.K., Corato, U., Sansinenea, E. (2022). Plant mineral nutrition and disease resistance: A significant linkage for sustainable crop protection. *Frontiers Plant Sci*., 13.

Ulrich, A. (1952). Physiological bases for assessing the nutritional requirements of plants. *Annual Review of Plant Biology*, 3, 207–228.

Vilvert, J.C., Santos, L.F. dos, Cardoso, A.D., Lopes, P.R.C., Amarante, C.V.T. do, Freitas, S.T. de. (2023). Non-destructive assessment of quality traits in apples and pears using near-infrared spectroscopy and chemometrics. *Revista Brasileira de Fruticultura*, 45.

Wallace, A., Wallace, G.A. (1993). Limiting factors, high yields, and the law of the minimum. In J. Janick (Ed.), *Horticultural Reviews*, 1st ed., pp. 409–448.

Walworth, J.L., Sumner, M.E. (1987). The Diagnosis and Recommendation Integrated System (DRIS). *Advances in Soil Science*, 6, 149–188.

Yamane, D.R., Parent, S.-É., Natale, W., Cecílio Filho, A.B., Rozane, D.E., Nowaki, R.H.D., Mattos Junior, D. de, Parent, L.E. (2022). Site-Specific Nutrient Diagnosis of Orange Groves. *Horticulturae*, 8(12), 1126.

Zhang, R., Yang, P., Liu, S., Wang, C., Liu, J. (2022). Evaluation of the methods for estimating leaf chlorophyll content with SPAD chlorophyll meters. *Remote Sensing*, 14: 5144.

20

REMOTE SENSING-BASED SMART IRRIGATION FOR SUSTAINABLE SOIL AND CROP PRODUCTIVITY

Muhammad Safdar[1,2], Fahd Rasul[3], Muhammad Adnan Shahid[1,2], Kashif Mehmood[1], Hafiz Muhammad Bilawal Akram[3]

Abstract

Global water scarcity, impacting two-thirds of the world's population, is exacerbated by inefficient traditional irrigation practices, posing a significant threat to food security. This challenge necessitates a holistic and robust irrigation system to optimize crop yields judiciously. An integrative approach is essential to enhance water use efficiency (WUE) and agricultural productivity. Smart irrigation emerges as an innovative solution, leveraging wireless communication, advanced monitoring devices, and data analytics to optimize irrigation scheduling. The integration of remote sensing (RS) satellite data with real-time field monitoring is particularly transformative for data-scarce regions, providing critical spatial and temporal information on crop and soil conditions. These systems rely on fundamental components like precision monitoring and closed-loop control, utilizing Internet of Things (IoT) sensors, deep learning, and fuzzy logic to calibrate and validate data on crops, soil, and water. Numerous global research experiments demonstrate the profound impact of these practices, showing significant increases in WUE and crop yield alongside substantial water conservation. Widespread adoption of these advanced irrigation systems at the farm level, especially in developing countries, is critical to securing sustainable water for agriculture and ensuring long-term global food security.

1 Research Assistant[*1] Department of Irrigation & Drainage, University of Agriculture, Faisalabad 38000, Punjab, Pakistan, [*2] Agricultural Remote Sensing Lab (ARSL), University of Agriculture, Faisalabad 38000, Punjab, Pakistan, m.safdar@uaf.edu.pk ,

Associate Professor [**3] Department of Agronomy, University of Agriculture, Faisalabad 38000, Punjab, Pakistan, drfahdrasul@uaf.edu.pk

Professor [*1] Department of Irrigation & Drainage, University of Agriculture, Faisalabad 38000, Punjab, Pakistan, [*2] Agricultural Remote Sensing Lab (ARSL), University of Agriculture, Faisalabad 38000, Punjab, Pakistan, muhammad.shahid@uaf.edu.pk

Lecturer [*1] Department of Irrigation & Drainage, University of Agriculture, Faisalabad 38000, Punjab, Pakistan,

PhD Scholar [*****3] Department of Agronomy, University of Agriculture, Faisalabad 38000, Punjab, Pakistan, bilawalakram48@gmail.com

Correspondence Email: drfahdrasul@uaf.edu.pk

1 Introduction

Nowadays we are facing biggest water scarcity problems. Due to which farm productivity is decreasing day by day and the food security issue is becoming major concern. Water scarcity and food security have become the major obstacles to sustainable development (Mishra 2023). Climate change projections as predicted by the rising in temperature, the rising of temperature and deficiency in precipitation near future (Alotaibi et al. 2024). Severe droughts in large numbers are also impacting agriculture production. Agriculture utilizes major sources of water, about 70 percent to 95 percent of the abstraction coming from farming activities (Ingrao et al. 2023). If this usage of water resources continues like this then in coming days two thirds of world's community may survive in water stressed nations (du Plessis 2019). If we want to achieve the Sustainable development goals SDG, s "Zero Hunger" we should take some decisions regarding implementation of integrated water resources management techniques in smart ways of irrigation methods. To mitigate water scarcity, we should move to judicious use of water on all levels of water management i.e. on farm level and off farm level as well.

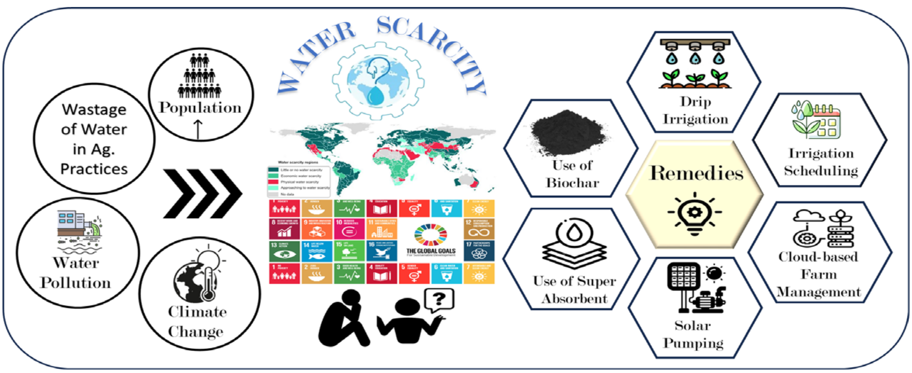
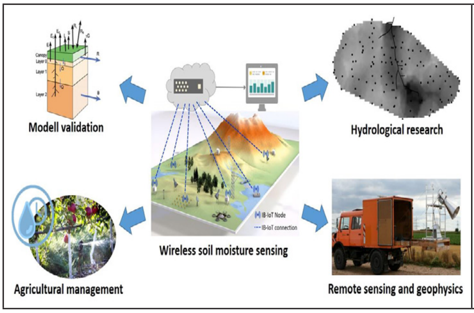


Figure 1 Overview of the various sources of water scarcity and the remedial strategies through innovation and water-efficient agricultural practices

Irrigation system is being adopted to mitigate climate change impacts on crop productivity. Irrigation has contributed about 40 percent of global food production (Ahmed et al. 2023). Irrigated agriculture is facing major issues regarding poor management of hydraulic structures on farm level and at reservoir/dams' level by lacking in improper management of sediments control to water losses due to poor irrigation scheduling on farm level. There is urgent need to move towards high efficiency system especially in water scarce regions (Kywe & Aye, 2019). Therefore, for sustainable crop production there should be smart irrigation system which utilizes holistic and robust techniques, software to improve water use efficiency and crop productivity (Bwambale et al., 2022). Excessive irrigation, often used in traditional agriculture, leads to environmental and agronomic issues, including soil salinity, nutrient leaching, fertilizer waste, eutrophication, and ecosystem degradation. Conventional irrigation is energy-intensive, leading to water wastage and increased costs. It disregards soil, topography, and crop requirements, resulting in uneven watering and decreased yields. The below figures show the agricultural revolution from traditional to smart irrigation system. Remote Sensing is an art science and technology to acquire useful data and information without any physical contact either by drones or Unmanned Aerial Vehicle UAV's, satellites and radars as well (Patel et al. 2025). In this modern era satellite and sensor-based irrigation practices provide real time monitoring of crops, water, and soil to achieve the effective management of smart irrigation systems. RS with Smart Irrigation is very helpful to provide us with crop growth water stress and variable rate irrigation scheduling to gain maximum water use efficiency and crop productivity. For water resources insights different indices are being used like NDVI for vegetation health, NDWI for water resources and CWSI for water stressed conditions of crops (Safdar et al., 2023). The possible way forward is combination of satellites and Unmanned aerial vehicles UAVs with real time monitoring various sensors on ground level. By applying these practices with precision irrigation systems and techniques to optimize soil and water resources conservation for achieving best crop yield.

2 Remote Sensing and GIS Technologies for Irrigation

Soil moisture is a very important factor that affects agriculture, hydrology, and climate as it can significantly influence water and energy exchange of the ground and the atmosphere. Balancing temporal and spatial resolution and the effect of surface roughness and vegetation remain a problem (Corradini, 2014). The present review paper is a synthesis of the current developments in the field of soil moisture remote sensing, with a wide range of interested readers, such as researchers and practitioners in the environmental science, agriculture, hydrology, and climatology fields. It will explain the physical concepts of the remote sensing methods, demonstrate the transformative use in other areas, assess the current constraints and limitations, and address the new technologies in the future of soil moisture monitoring. The paper is organized with the discussion of optical, thermal, and microwave remote sensing principles and then specific sections devoted to the applications in agriculture, hydrology, and climate science. Thermal techniques based on the use of Land Surface Temperature (LST) in the 3.5-14 mm band are useful in estimating soil moisture. The temperature rising rate vegetation dryness index (TRRVDI) is a satellite-based index that uses Meteo sat-SEVRI satellite data to reduce the ambiguity of estimations by using the temporal LST variations, but it needs additional data to be accurate. The correlation between the diurnal LST cycles and net shortwave radiation is useful in modelling bare soil moisture (Li et al. 2023). An innovative algorithm that integrates optical and thermal infrared data is better than the past in estimating soil moisture. Abbas et al. 2025, suggested a synergistic method of combining Sentinel-1 and Landsat thermal bands, which boosts the high-resolution soil moisture and enhances the ground measurement correlations in VV polarization as shown in figure (2). Precision irrigation is no longer uniform water application, but a variable, data-driven approach, which applies to the appropriate amount of water at the right place and time. Variable-rate irrigation (VRI) systems, which operate sprinkler heads which are controlled by GPS, are used to maximize water use by sprinkling more where it is drier and less where it is wetter (Anjum et al. 2023). This method is able to conserve 15-30 percent of water, increase crop yields through water stress and waterlogging reduction, decrease energy pumping, and decrease fertilizer and pesticide runoff, which has significant environmental advantages as shown in figure (3).



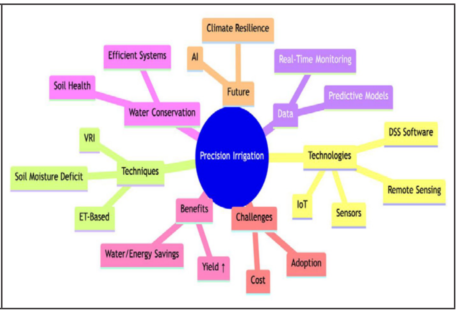


Figure 2 Emergence and evolution of remote sensing for soil moisture monitoring.
Figure 3 Precision irrigation scheduling and water management

Suitability analysis is a technique of identifying the most appropriate sites of goods or conservation, which is affected by site-specific factors. These studies are done with the help of geographic information systems (GIS) that have suitability modelers that offer an interactive platform to create and test models. The most recent uses of GIS in land suitability evaluations of irrigated agriculture include the evaluation of soil, land use, climate, and water resources data to produce suitability maps that categorize land according to several factors. GIS has been used by several researchers to analyze land suitability. AL-Taani et al. (2023) evaluated land suitability to agriculture in Jordan and found that only 0.2% of the land in Ma'an can be used in rainfed agriculture and 1.4% in irrigated crops, which is due to low soil fertility and water scarcity. On the same note, Paul et al. (2020) used geospatial multi-criteria decision analysis to assess the irrigation potential of reclaimed water and found that there is a strong relationship between the geographical distribution of the areas favorable to water reuse in agriculture. GIS is also important in precision irrigation as it involves mapping of irrigated lands with the help of satellite data sources such as MODIS, Landsat and AVHRR. GIS can be used to classify irrigated and non-irrigated lands and evaluate spatio-temporal changes in irrigation through the analysis of spectral patterns. The SPOT6 imagery of Ethiopia has been useful in tracking the smallholder agriculture and GIS tools are necessary in mapping of soil salinity using software such as Excel and ArcMap to produce continuous surface maps based on the sampled points (AL-Taani et al., 2023).

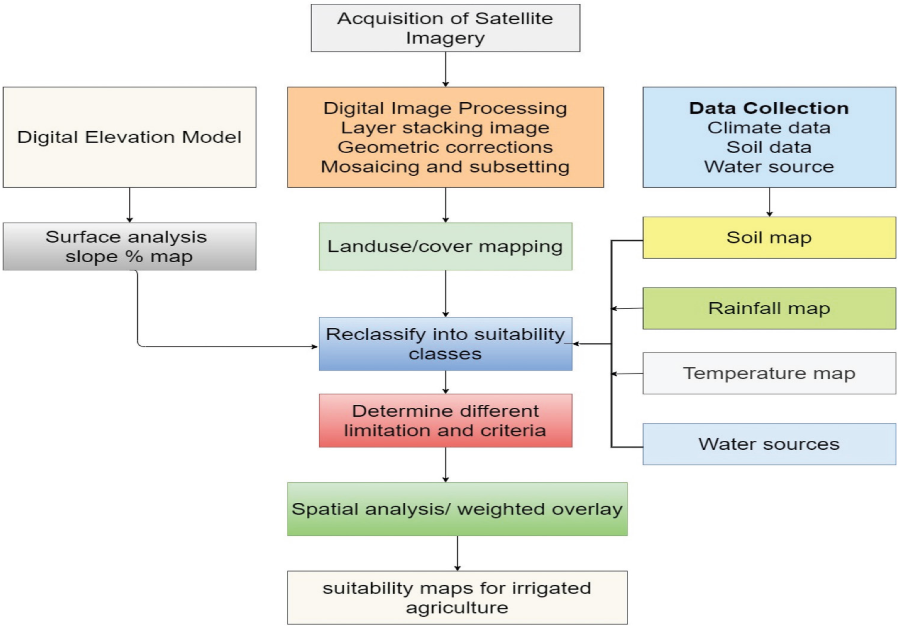
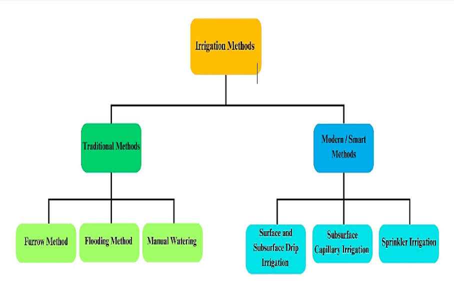


Figure 4 Flowchart for land suitability for irrigation. adapted from (AL-Taani et al., 2023)

3 Smart Irrigation Systems and Decision Support System

Climate-related events are not predictable and certain areas experience droughts and heat waves whereas others experience heavy rainfall and floods. The recent developments in agricultural technology, especially precision farming and controlled environment agriculture, have enhanced water resource management and farming efficiency (Ahmed et al. 2024). Precision farming involves the use of new tools to ensure that natural resources are used in the best way possible, and controlled environments enable the growth factors to be regulated with precision, resulting in an increase in crop yields and water use efficiency (WUE). The irrigation techniques are classified into gravity-based (traditional) and pressure-based (modern) techniques with the latter having higher WUE due to the application of water and nutrients in a specific area thereby reducing water stress in crops (Mustafa et al. 2024).



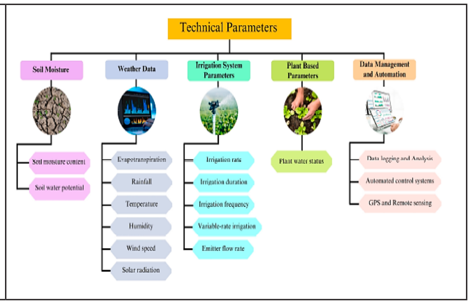


Figure 5 Irrigation methods used in agriculture.
Figure 6 Technical parameters in precision irrigation for Water Use Efficiency (WUE).

Smart or digital irrigation has revolutionized the process of water management using different sensors and actuators that detect and control the soil and weather conditions. Precision irrigation systems are a great way to improve the efficiency of water use because they can measure the most important parameters, including soil moisture, weather conditions, details of irrigation systems, and the water condition of plants. The moisture content of soil is measured using different sensors, whereas weather data encompasses evapotranspiration and rain, which are used to schedule irrigation (Ahmed et al. 2023). The irrigation parameters such as rate, duration, and frequency and other advanced irrigation technologies such as variable rate irrigation (VRI) are used to guarantee the efficient distribution of water. Logging, automation, and GPS help in the optimization of irrigation practices. The paper relies on the data of 2005-2024 to evaluate the smart irrigation technologies in the framework of water conservation and sustainable agriculture. It reduces unnecessary use of water, which may cause erosion of nutrients and pollution. To practice effective irrigation, one needs to know how land water is used and the incorporation of technology such as meteorological sensors, variable rate irrigation, remote sensing, and decision support system (Ali et al. 2025). The increased efficiency of irrigation can fulfil half of the projected increase in water demand, and this will lead to food security and resilience to environmental challenges like climate change and water shortage in the long run. The developments are in line with different United Nations Sustainable Development Goals such as clean water (SDG 6), climate action (SDG 13), and sustainable urban development (SDG 11).

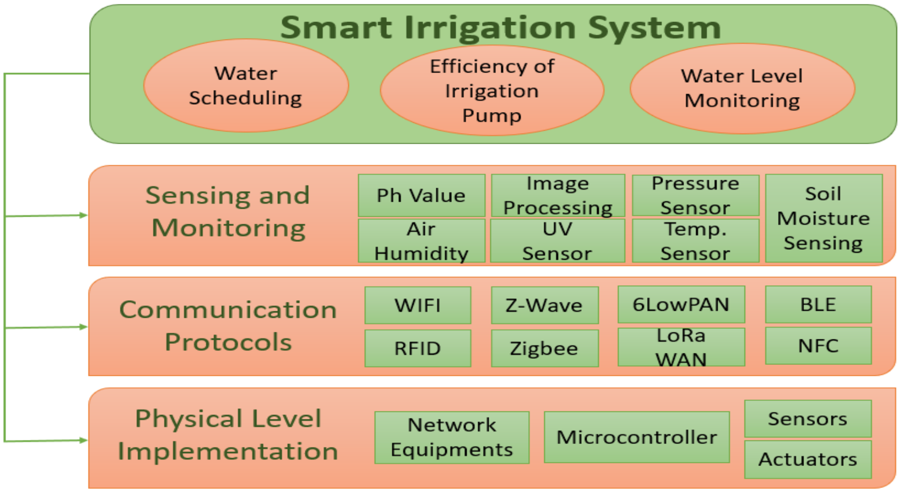
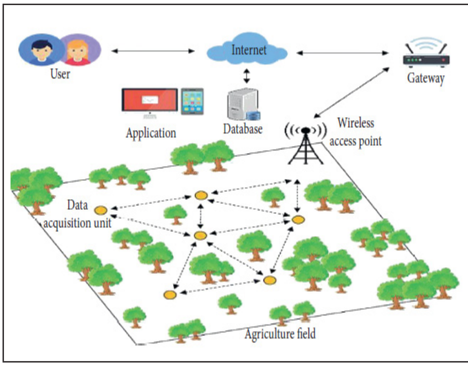


Figure 7 Smart irrigation systems building layers

Automatic irrigation systems are necessary to enhance efficiency of agriculture by conserving energy and resources. They allow water to be applied in time with little labor since sensor-based valves and controllers are used to control the flow of water. There were problems with traditional irrigation methods, such as the use of wired data collection methods, but now it is possible to monitor soil moisture accurately with rainfall and evapotranspiration data. Although technology has improved, scientists are tackling challenges such as memory and security of data in sensor networks. This review explains the current sensor irrigation management methods, environmental monitoring and is meant to guide future studies in this field (Askaraliev et al. 2024).

Site-specific irrigation control systems make use of different technologies to measure and transmit physical characteristics like soil moisture to optimize irrigation management and improve crop yield. These systems have difficulties in software design, sensor integration, data interface and communication protocol. Examples of solutions are GSM-SMS remote control systems of greenhouses and various methods of soil moisture measurement which can be divided into modern (e.g., TDR, FDR) and classical (e.g., tensiometers) methods. The wireless relay of soil moisture information will enable farmers to receive real-time data, which will help them manage water better and possibly boost production by 25-30 percent (Evans & Sadler, 2013).



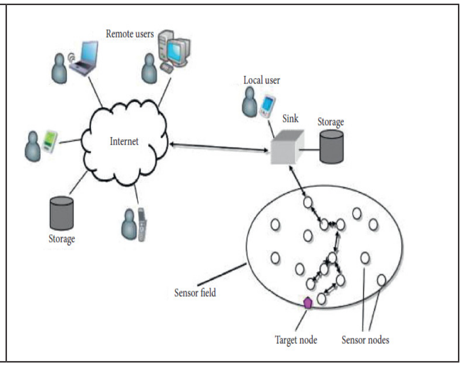


Figure 8 Wireless sensor network layout for the automated irrigation system.
Figure 9 Sensor network application in 1eld source

Remote sensing is a new method of gathering information with the help of satellite sensor technologies to examine vast territories in the form of aerial photographs. The technique assists in the identification and mapping of agricultural resources and water data pertaining to forests, water bodies, and crop areas. Agriculture is a common application of optical remote sensing, in which sensors such as NIR and SWIR are used to measure surface reflections. Thermal sensors detect temperature using the radiation of the surface, and this helps to evaluate the health and stress of crops without physical contact (Khanal et al. 2017). The thermal remote sensing data on temperature and energy transfer is essential to the study of landscape processes. Such data together with agrometeorological data can improve the estimations of crop yields and guide agricultural practices, such as soil moisture monitoring, which is essential in the management of irrigation. The modern irrigation systems have sensors that monitor the environmental conditions and optimize the inputs such as water and fertilizers.

Irrigation systems such as sprinkler and drip irrigation are more efficient in the use of water than the old systems, though they also need the supervision of the operators. Modern technologies allow automated irrigation based on real-time data on soil and plants, which will support sustainable water management and boost food production during climate change. The combination of existing agriculture with the new technologies of IoT, GPS, and automation is essential to make informed decisions and implement the use of green energy in agriculture (Hadidi et al. 2022)

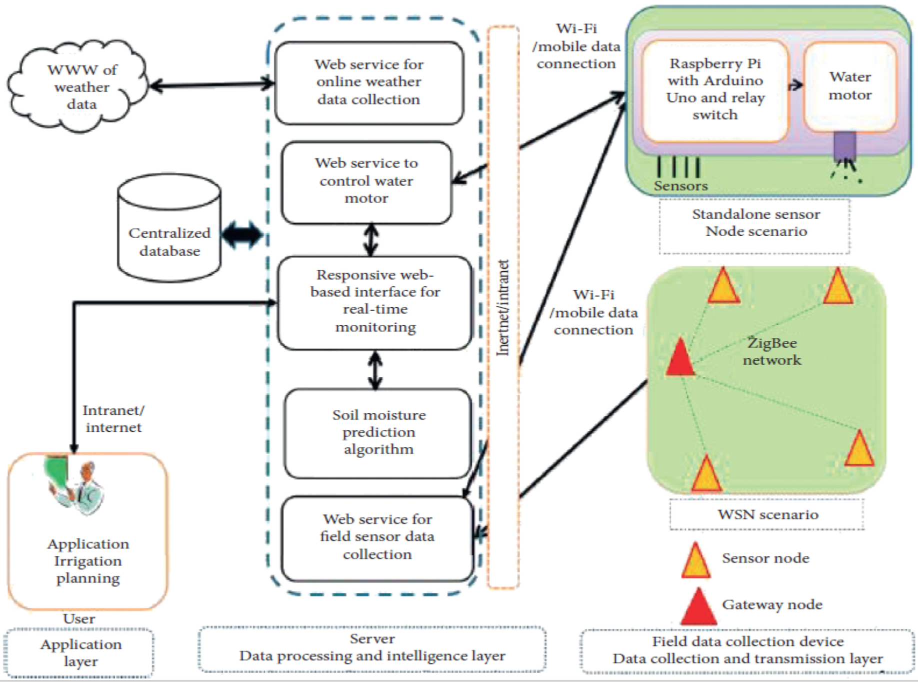


Figure 10 -e architecture of the proposed system.

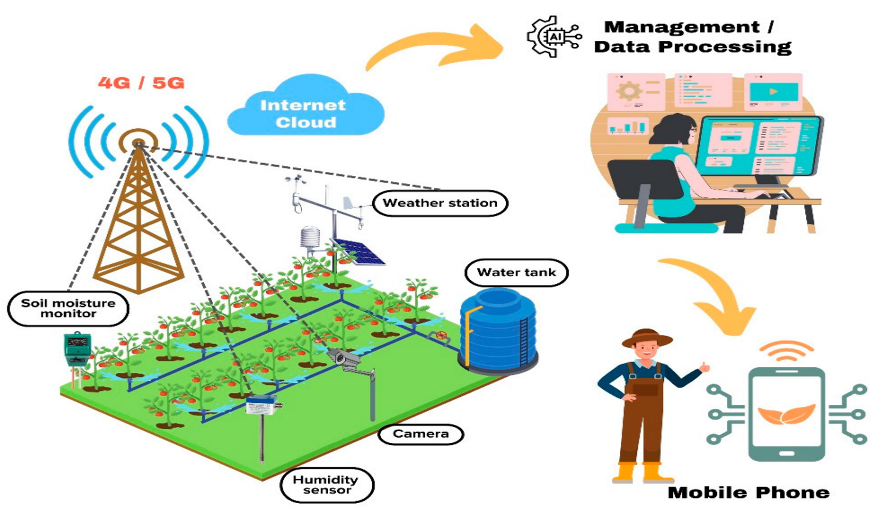


Figure 11 Advanced irrigation hub assisted with real-time weather and moisture sensors and decision

Smart irrigation is a concept that aims at minimizing the cost of operation in agriculture and enhancing resource efficiency to ensure sustainable practices. It uses data mining on various datasets (agronomical, genomics, and meteorological), which improves decision-making and operational efficiency

(Zhang, 2024). The systems are based on a three-layer architecture of real-time monitoring to gather important data on soil, weather, and plants with the use of high-end sensors and communication technologies, and its main components are sensors, connectivity, automation, and user interaction.

The choice of the best architecture is complicated by the different sizes and the particular needs of smart irrigation systems such as soil conditions and weather dynamics. The IoT systems in agriculture produce large amounts of data, which pose a problem in real-time management and analysis. The smart agriculture IoT architecture is usually composed of three to five layers, such as perception, connectivity, application, middleware, and processing layers. Wireless sensor networks (WSNs) are essential, which are composed of nodes, gateways, and base stations, and the common architecture is separated into five layers: physical, data link, network, transport, and application. These systems consist of autonomous and low power sensor nodes that are connected to send data to a central node to process it (Li et al. 2020).

Open-loop control systems (OCS) operate without feedback with simple On/Off signals, and are easy to maintain, but do not provide much automation because they are based on timers. The process of CLS consists of implementation and engineering stages, such as simulation. There are types of CLS model predictive control, intelligent control (based on fuzzy logic and neural networks), and linear control schemes, which make systems such as irrigation more efficient in automation (Nahar et al. 2019).

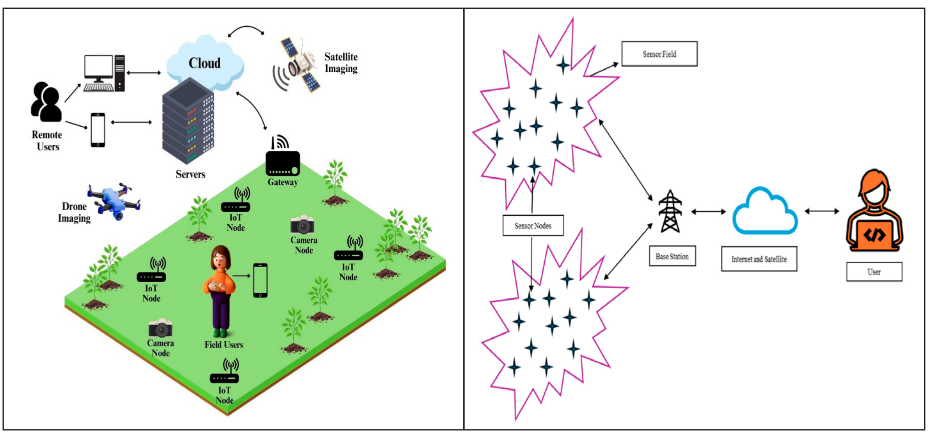


Figure 12 &13 Smart Farm Irrigation and Structure of wireless sensor network.

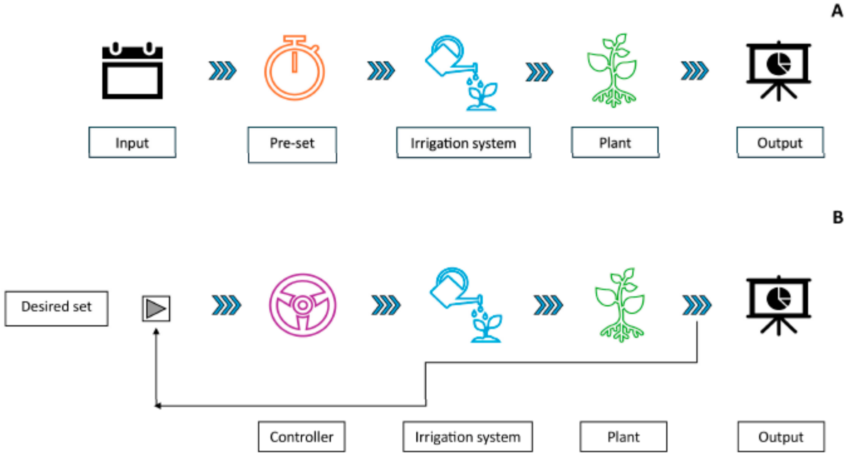


Figure 14 Block diagram: (A)Open-loop control irrigation system(B)Closed-loop control irrigation system

4 Case Studies and Practical Applications with their Impact

The document provides an overview of the different research on soil moisture management and irrigation systems used on the various crops in different areas.

Isik et al. (2017), a Turkish study on the use of walnut, with a DS200 drip irrigation system, reported a reduction in the number of employees by 60 percent, as the system is efficient. In Nigeria, Bodunde et al. (2019) studied a YL-69 sprinkler irrigation robot, stating that the installation of this robot caused minimal crop and farm damage. Panigrahi et al. (2019) presented the case of banana farming in Bhubaneswar, India, and their drip irrigation system produced 15% more fruits than conventional ones, which proved to be more productive. Liao et al. (2021) concentrated on tomato cultivation in Beijing, China, where a TMH-2000 drip irrigation system was more effective in irrigation management with a water-use efficiency of 41.23 kg/m3 than the control system.

In India, Kumar et al. (2025) utilized a DHT11 soil moisture and rain sensor system and drip irrigation, which turned the motor a total of 9.72% of the time the water was needed, maximizing water consumption. All these studies emphasize the developments in irrigation technology that enhance crop production and minimize the use of labor by means of automated systems that are adjusted to different environmental factors. The impacts of irrigation treatments in terms of evapotranspiration coefficients (ETc) have been examined in different agricultural studies in different regions and crops to establish their effects on crop yields. Zhang et al. (2006) studied spring wheat in Gansu province, China, in arid conditions and found that the application of 80 percent ETc at the jointing and filling stages led to the significant improvement of grain yield of 16.6 percent to 25.0 percent over a control treatment at the same stages.

In comparative research by in Spain, Marti et al. (2018) examined tomatoes and found that the application of 50% ETc to tomatoes after the fruit set stage led to an increase in L-ascorbic acid levels, but carotenoid content was not affected by the experimental condition. Zou et al. (2021) conducted a study on maize in Shaanxi province, China, whereby the 80% application of ETc between V8 (8-leaf) and R6 (maturity) growth stages yielded the highest total yield and water use efficiency (WUE) of about 34.8 kg ha-1 mm-1 as compared to control plots.

Shrestha et al. (2020) examined winter wheat in Texas, USA and discovered that when 0% ETc was applied at the booting and grain filling stages, the yield reduction was less by 16%. Perez-Pastor et al. (2009) evaluated apricot trees in Murcia, Spain, where 50% ETc resulted in drastic yield and fruit per tree reductions relative to controls but 100% ETc at critical growth stages and 40% ETc at non-critical stages produced similar results to control trees. Finally, Elmetwalli and Elnemr (2020) achieved a 39.8 percent potato yield reduction with 50 percent ETc in Egypt and a water productivity of 28 kg m -3.

5 Conclusion and Future Prospects

This analysis concludes that smart irrigation systems are paramount for advancing sustainable agriculture and mitigating global water scarcity. The evidence confirms the superior efficacy of these technologies: soil moisture sensors (SMS) can achieve water savings of 20-92%, while Evapotranspiration (ET) controllers and remote sensing (RS) techniques offer savings of 20-71% and 7-50%, respectively. Strategies like Continuous Deficit Irrigation (CDI) can save approximately 13% water with minimal yield reduction, underscoring the potential for careful water management. The critical role of precise instrumentation, such as the accurate frequency emission of handheld soil moisture sensors, is highlighted as a cornerstone for reliable data and effective system control. Furthermore, the development of user-friendly, self-powered control systems promises to bring the benefits of precision agriculture to smallholder farmers in vulnerable semi-arid regions. Despite this promise, significant challenges impede widespread implementation. Key obstacles include high initial costs, a lack of financial incentives for farmers, and the need for extensive training on technology operation and data interpretation. The escalating pressures of climate change further amplify the urgency for real-time, adaptive monitoring and control.

Future directions must focus on overcoming these barriers through multi-faceted strategies. First, policy interventions and subsidies are required to make these technologies financially accessible. Second, research must prioritize the development of more affordable, robust, and standardized sensor networks and data analysis units to streamline resource management and crop growth modeling. Third, future systems should integrate hybrid approaches that fuse RS data with dense in-situ Wireless Sensor Networks (WSN) to minimize errors and enhance decision-making accuracy. Finally, fostering interdisciplinary collaboration among agronomists, data scientists, and engineers is crucial to refining predictive models using AI and machine learning, ultimately creating closed-loop systems that are not only water-efficient but also resilient to changing climatic conditions, thereby securing global food production.

References

Abbas, U., Maqbool, Z., Shahid, M. A., Safdar, M., & Khan, S. U. (2025). Retrieval of Surface Soil Moisture Using Landsat 8 TIRS Data: A Case Study of Faisalabad. *Revue Internationale de Géomatique*, 34.

Ahmed, M. M., Sharif, U., Raza, A., Safdar, M., Ali, W., Asim, M., ... & Zaheer, M. (2024). Climate-smart agriculture for resilience and profitability. In *Sustainable practices for agriculture and marketing convergence* (pp. 27-50). IGI Global Scientific Publishing.

Ahmed, Z., Gui, D., Murtaza, G., Yunfei, L., & Ali, S. (2023). An overview of smart irrigation management for improving water productivity under climate change in drylands. *Agronomy*, *13*(8), 2113.

Ahmed, Z., Gui, D., Murtaza, G., Yunfei, L., & Ali, S. (2023). An overview of smart irrigation management for improving water productivity under climate change in drylands. *Agronomy*, *13*(8), 2113.

Ali, A., Hussain, T., & Zahid, A. (2025). Smart irrigation technologies and prospects for enhancing water use efficiency for sustainable agriculture. *AgriEngineering*, *7*(4), 106.

Alotaibi, B. A., Xu, W., Shah, A. A., & Ullah, W. (2024). Exploring climate-induced agricultural risk in Saudi Arabia: Evidence from farming communities of Medina region. *Sustainability*, *16*(10), 4245.

Al-Taani, A., Al-husban, Y., & Ayan, A. (2023). Assessment of potential flash flood hazards. Concerning land use/land cover in Aqaba Governorate, Jordan, using a multi-criteria technique. *The Egyptian Journal of Remote Sensing and Space Science*, *26*(1), 17-24.

Anjum, M. N., Cheema, M. J. M., Hussain, F., & Wu, R. S. (2023). Precision irrigation: challenges and opportunities. *Precision agriculture*, 85-101.

Askaraliev, B., Musabaeva, K., Koshmatov, B., Omurzakov, K., & Dzhakshylykova, Z. (2024). Development of modern irrigation systems for improving efficiency, reducing water consumption and increasing yields. *Machinery & Energetics*, *15*(3).

Bodunde, O. P., Adie, U. C., Ikumapayi, O. M., Akinyoola, J. O., & Aderoba, A. A. (2019). Architectural design and performance evaluation of a ZigBee technology based adaptive sprinkler irrigation robot. *Computers and Electronics in Agriculture*, *160*, 168-178.

Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agricultural Water Management*, *260*, 107324.

Corradini, C. (2014). Soil moisture in the development of hydrological processes and its determination at different spatial scales. *Journal of Hydrology*, *516*, 1-5.

du Plessis, A. (2023). Water resources from a global perspective. In *South Africa's Water predicament: Freshwater's unceasing decline* (pp. 1-25). Cham: Springer International Publishing.

Evans, R. G., & Sadler, E. J. (2013). Site-specific irrigation water management. In *Precision Agriculture for Sustainability and Environmental Protection* (pp. 172-190). Routledge.

Hadidi, A., Saba, D., & Sahli, Y. (2022). Smart irrigation system for smart agricultural using IoT: concepts, architecture, and applications. *The digital agricultural revolution: innovations and challenges in agriculture through technology disruptions*, 171-198.

Ingrao, C., Strippoli, R., Lagioia, G., & Huisingh, D. (2023). Water scarcity in agriculture: An overview of causes, impacts and approaches for reducing the risks. *Heliyon*, *9*(8).

Işık, M. F., Sönmez, Y., Yılmaz, C., Özdemir, V., & Yılmaz, E. N. (2017). Precision irrigation system (PIS) using sensor network technology integrated with IOS/Android application. *Applied Sciences*, *7*(9), 891.

Khanal, S., Fulton, J., & Shearer, S. (2017). An overview of current and potential applications of thermal remote sensing in precision agriculture. *Computers and electronics in agriculture*, *139*, 22-32.

Kywe, K., & Aye, N. (2019). Possible solutions to the challenges of irrigation water pricing for saedawgyi irrigated area. *American Scientific Research Journal for Engineering, Technology, and Sciences ASRJETS*, *52*(1), 176-188.

Li, Z. L., Wu, H., Duan, S. B., Zhao, W., Ren, H., Liu, X., ... & Zhou, C. (2023). Satellite remote sensing of global land surface temperature: Definition, methods, products, and applications. *Reviews of Geophysics*, *61*(1).

Liao, H., Fan, H., Li, Y., & Yao, H. (2021). Influence of reductive soil disinfestation or biochar amendment on bacterial communities and their utilization of plant-derived carbon in the rhizosphere of tomato. *Applied Microbiology and Biotechnology*, *105*(2), 815-825.

Marti, R., Valcarcel, M., Leiva-Brondo, M., Lahoz, I., Campillo, C., Rosello, S., & Cebolla-Cornejo, J. (2018). Influence of controlled deficit irrigation on tomato functional value. *Food Chemistry*, *252*, 250-257.

Mishra, R. K. (2023). Fresh water availability and its global challenge. *British Journal of Multidisciplinary and Advanced Studies*, *4*(3), 1-78.

Mustafa, S., Sabir, R. M., Sarwar, A., Safdar, M., Al Ansari, M. S., & Hussain, S. (2024). Precision agriculture and unmanned aerial vehicles (UAVs). In *Agriculture and Aquaculture Applications of Biosensors and Bioelectronics* (pp. 83-108). IGI Global Scientific Publishing.

Nahar, J., Liu, S., Mao, Y., Liu, J., & Shah, S. L. (2019). Closed-loop scheduling and control for precision irrigation. *Industrial & Engineering Chemistry Research*, *58*(26), 11485-11497.

Panigrahi, B., Paramjita, D., & Paul, J. C. (2019). Impact of drip and furrow irrigation on tomato yield under mulch and non-mulch conditions. *IJCS*, *7*(5), 3202-3207.

Patel, J., Sharma, N., & Mohan, S. (2025). Introduction to Remote Sensing and GIS. In *Smart Buildings and Cities with Remote Sensing and GIS* (pp. 3-34). Chapman and Hall/CRC.

Paul, M., Negahban-Azar, M., Shirmohammadi, A., & Montas, H. (2020). Assessment of agricultural land suitability for irrigation with reclaimed water using geospatial multi-criteria decision analysis. *Agricultural Water Management*, *231*, 105987.

Pérez-Pastor, A., Domingo, R., Torrecillas, A., & Ruiz-Sánchez, M. C. (2009). Response of apricot trees to deficit irrigation strategies. *Irrigation Science*, *27*(3), 231-242.

Safdar M, Shahid MA, Sarwar A, Rasul F, Majeed MD, Sabir RM. Crop Water Stress Detection Using Remote Sensing Techniques. *Environmental Sciences Proceedings*. 2023; 25(1):20. https://doi.org/10.3390/ECWS-7-14198

Shrestha, R., Thapa, S., Xue, Q., Stewart, B. A., Blaser, B. C., Ashiadey, E. K., ... & Devkota, R. N. (2020). Winter wheat response to climate change under irrigated and dryland conditions in the US southern High Plains. *Journal of Soil and Water Conservation*, *75*(1), 112-122.

Touil, S., Richa, A., Fizir, M., Argente Garcia, J. E., & Skarmeta Gomez, A. F. (2022). A review on smart irrigation management strategies and their effect on water savings and crop yield. *Irrigation and Drainage*, *71*(5), 1396-1416.

Touil, S., Richa, A., Fizir, M., Argente Garcia, J. E., & Skarmeta Gomez, A. F. (2022). A review on smart irrigation management strategies and their effect on water savings and crop yield. *Irrigation and Drainage*, *71*(5), 1396-1416.

Vinod Kumar, S., Singh, C. D., Rao, K. R., Rajwade, Y. A., Kumar, M., Jawaharlal, D., & Asha, K. R. (2025). IoT-based smart drip irrigation scheduling and wireless monitoring of microclimate in sweet corn crop under plastic mulching. *Irrigation Science*, *43*(5), 1107-1126.

Zhang, Y. (2024). Application of big data in smart agriculture. *Advances in Resources Research*, *4*(2), 221-230.

Zhang, Y., He, Z., Zhang, A., van Ginkel, M., & Ye, G. (2006). Pattern analysis on grain yield performance of Chinese and CIMMYT spring wheat cultivars sown in China and CIMMYT. *Euphytica*, *147*(3), 409-420.

Zou, Y., Saddique, Q., Ali, A., Xu, J., Khan, M. I., Qing, M., ... & Siddique, K. H. (2021). Deficit irrigation improves maize yield and water use efficiency in a semi-arid environment. *Agricultural Water Management*, *243*, 106483.