

ENHANCING FOOD SECURITY THROUGH ORGANIC PRACTICES: INTEGRATED SOLUTIONS FOR CLIMATE-RESILIENT AGRICULTURE

Esther Fasina O¹, Muhammad Falalu Yahaya², Ahmad Hammanadama Kojoli³

^{1,2,3}American University of Nigeria Yola, Adamawa State Nigeria

esther.fasina@aun.edu.ng¹, muhammad.yahaya@aun.edu.ng², ahmad.hammanadama@aun.edu.ng³

Abstract

Climate change, rapid population expansion, and constrained natural resources are intensifying threats to global food security. Soil organic carbon (SOC) storage reflects a balance among plant residues, root exudates, and microbial decomposition, shaped by biological and physical processes—and strongly influenced by agricultural management. Conventional tillage and heavy use of synthetic fertilizers tend to deplete SOC and degrade soil structure and biodiversity. This paper examines how organic fertilizer can enhanced soil carbon storage, and how strategic land management can restore soil health and support sustainable agriculture. It outlines how amendments such as biochar, manure, fermented grass, cover crops, and diversified rotations improve soils' physical, chemical, and biological properties and how they foster beneficial microbial diversity for nutrient cycling and stability, and—when paired with novel organic fertilizer innovations—raise yields without harming the environment, thereby strengthening food safety and security.

Keywords: Soil management, organic farming, sustainable agriculture, soil carbon storage, organic fertilizer

Introduction

The global population is anticipated to increase to 8.9 billion by 2050, which will result in a substantial rise in the demand for agricultural products [1]. With new agricultural land, becoming scarce, increasing crop yields is essential to meet future food demand. Securing a safe, sustainable food supply is a key barrier: raising productivity while reducing climate impacts and protecting agroecosystems remains a central goal of sustainable agriculture [2]. Yet heavy reliance on synthetic fertilizers and pesticides has led to land degradation and pollution in many agroecosystems, with harmful effects on people, wildlife, and aquatic systems [3].

Zero contamination is vital for protecting public health and upholding consumer trust [4]. Moving toward this goal ensures a safer food supply through preventive measures against contamination [5], [6]. Understanding and maintaining soil health are central to sustainable agriculture, as healthy soils support diverse microbial life and robust crop growth [7]. Rising concerns about climate change and food security have increased global attention on soils as carbon reservoirs and on resilient farming systems. In this context, France's *4 per 1000* initiative, launched in 2015 ahead of COP21 (<http://4p1000.org/>), promotes global collaboration to enhance soil carbon management. Raising carbon stocks across agricultural landscapes—croplands, grasslands, and forests—on a global scale is expected to strengthen food security and help mitigate climate change. [8]. Maximizing soil carbon storage depends on adopting agricultural practices suited to local conditions.

The Sustainable Development Goals (SDGs) principally prioritize ending hunger, achieving food security, and promoting sustainable agriculture. When considered collectively, agricultural activities contribute—either directly or indirectly—to all 17 SDGs [9]. Realizing SDG 2 necessitates the

provision of adequate, safe, and affordable food for all, since robust health originates from appropriate nutrition and is intrinsically connected to effective learning.

Conventional agriculture marked by heavy use of pesticides (insecticides, herbicides, fungicides) poses a major obstacle to sustainable development [10]. Pesticide use also raises greenhouse-gas emissions, contributing to climate change [11]. Moreover, conventional synthetic fertilization has been reported to frequently “result in nutrient depletion, loss of microbial diversity, organic matter reduction, and deterioration” of soil structure [12]. Heavy tillage and chemical inputs also affect the soil health by diminishing organic matter, disrupting soil structure, reducing biodiversity, thus threatening the environment, food safety, and human health [11].

Sustainable agriculture that increases crop production without degrading the environment is urgently needed. Soil health restoration and improvement can be accomplished by applying organic amendments, cultivating diverse crop and cover crop systems, introducing beneficial microbiological agents, and implementing comprehensive soil-health management practices.

2. Literature Review

According to USDA organic agriculture is defined as a management system that minimizes or excludes synthetic fertilizers, pesticides, hormones, and feed additives, relying instead on practices such as crop rotations, crop residues, animal manures, off-farm organic inputs, mineral rock amendments, and biological mechanisms for nutrient mobilization and plant protection [13]. Complementing this, IFOAM frames organic agriculture as a production system dedicated to maintaining soil, ecosystem, and human health by leveraging ecological processes, biodiversity, and locally adapted cycles rather than detrimental external inputs; it deliberately integrates traditional methods, innovation, and scientific knowledge to advance shared environmental goals and social fairness [14].

By fostering practices that build soil health and biodiversity, organic farming increases agroecosystem resilience to climate-change impacts such as extreme temperature variability and drought and reduces erosion. Central to this approach are organic fertilizers, which deliver macronutrients (N, K, P, S) and essential micronutrients (e.g., Fe, Zn) in a more balanced form [15]. Their gradual mineralization supports a steady nutrient supply to the upper soil layers, stimulates microbial populations and activity, and enhances both water- and nutrient-holding capacity, thereby improving soil structure and root development. Additionally, these inputs can lower soil acidity, decrease the bioavailability of heavy metals, reduce incidence of pests and diseases, and curb nutrient leaching [16][17]. Because they do not emit hazardous gases or introduce synthetic contaminants, organic fertilizers also contribute to safer food production [18].

Given these advantages, organic agriculture has gained widespread popularity as a sustainable alternative to conventional chemical-based farming. The growing interest in organic fertilization methods reflects a global effort to mitigate the environmental damage caused by synthetic fertilizers and pesticides. Current innovations in organic soil fertility management include the use of unique organic amendments, cover crops, vermicomposting, and the cultivation of phytoaccumulator plants [19].

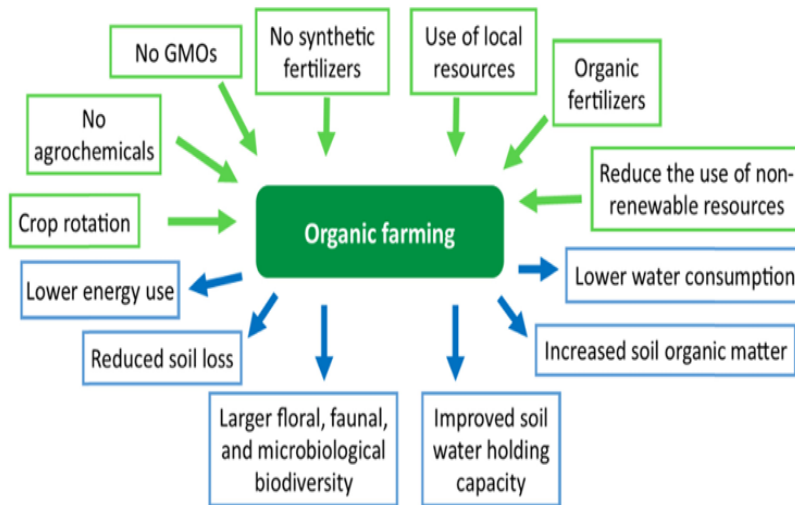


Figure1: Organic farming practices and effects

2.1 Organic practices

2.1.1 Crop rotation

Crop rotation is the systematic practice of cultivating different crops in the same field over successive periods. Alternating plant families helps break pest and disease cycles and supports soil fertility, food security, environmental recovery, and rural regeneration. It also strengthens climate resilience and reduces the vulnerability of cropping systems. [20]

2.1.2 Mixed Cropping

Mixed cropping also known as intercropping or polyculture is an agricultural practice, which involve more than one crop in the same field. This approach increases biodiversity, improve soil health by introducing varying nutrient from different crops, which can help to maintain soil fertility and structure [21]. Mixed cropping can lead to an increased overall yield; it promotes climate resilience and manage pest and disease [22].

2.1.3 Cover crops

Growing cover crops enhances soil nitrogen levels through nitrogen fixation, achieved via symbiotic relationships with rhizobia bacteria, and promotes carbon sequestration through photosynthesis, where organic carbon is eventually integrated into the soil from plant biomass [23]. Furthermore, deep-rooted cover crops are essential for retrieving nutrients from lower soil layers and relocating them to the surface [24]. These crops can be grown independently or interpolated alongside main cash crops. Research by [25] indicated that soils in organic farming systems incorporating winter cover crops exhibited improved pH, moisture content, and dissolved carbon and nitrogen levels relative to those in conventional farming practices.

2.1.4 Fermented grass

Fermented grass represents a popular organic fertilizer option, generated via anaerobic fermentation and functioning as a nutrient-packed soil enhancer [26]. It acts as a fast-acting nutrient provider, with the fermentation breaking down organic components to make nutrients instantly accessible [27]. As a result, these nutrients quickly enhance soil fertility and stimulate microbial proliferation. The use of fermented grass also aids in controlling soil diseases and cultivates a robust soil ecosystem. In addition, it supplies necessary organic matter to the soil, boosting its structure while mitigating compaction and erosion.

2.1.5 Farmyard manure

Farmyard manure represents a highly effective approach for improving soil structure through its application as an organic amendment. It is produced via the anaerobic decomposition of various materials, including food waste, plant residues, agricultural byproducts, or animal manure [28]. Farmyard manure supplies a well-proportioned quantity of organic matter to enhance soil fertility. Furthermore, it facilitates the gradual and consistent supply of essential macro- and micronutrients, promoting prolonged and environmentally sustainable nutrient availability. Consequently, the utilization of compost holds significant value in regions experiencing water scarcity. Compost is also abundant in microbial populations, such as bacteria, fungi, and actinomycetes, which play a vital role in facilitating soil nutrient cycling [29].

2.2.1. Addressing organic fertilizer constraints with emerging technologies

Organic farming emerges as a vital component in advancing toward a sustainable future, aimed at controlling the detrimental consequences of crop residue burning and global warming [30]. Conventional agricultural methodologies employ chemical fertilizers and pesticides to surmount the inherent difficulties of crop production. In reaction to the ecological degradation resulting from the application of chemical pesticides and synthetic fertilizers in conventional farming, modern organic farming was established, yielding a range of environmental advantages. The integration of organic fertilizers with emerging technologies is paramount for addressing the constraints and obstacles of organic fertilization [31]

2.2.1. Industrial waste matter

Industrial waste matter also known as sludge constitutes a semi-solid slurry derived from industrial water treatment, wastewater management. This material is enriched with beneficial organic compounds and essential nutrients, notably nitrogen and phosphorus, rendering it highly efficient as an organic fertilizer [32].

2.2.2. Organic fertilizer from Parolyzed biomass

Biochar is produced from a variety of carbon-rich feedstocks, animal and wastes from food, sludge, industrial residues, and chips from wood and agricultural and wastes from forestry each with distinct chemical and physical traits. Production technologies include pyrolysis, hydrothermal carbonization,

gasification, and flash carbonization. [33]. Among these, thermal decomposition stands as the predominant method for converting biomass into biochar [34]. In agricultural applications, organic fertilizers and biochar amendments have been employed to enhance soil health and boost crop yields. The integration of organic manure with bio char amendments demonstrates superior efficiency compared to unadulterated fertilizers, particularly in terms of crop yield and plant nutrient uptake relative to inorganic fertilizers [35].

2.2.3 Microbial fertilizer

Microbial fertilizers are formulations that contain one or more microbial species capable of mobilizing essential nutrients through biological processes. These methods include the decomposition in soil and compost, microbial nitrogen fixation, solubilizing phosphate, and producing substances that stimulate plant growth. Bioorganic fertilizers are a green technology that can reduce TSP requirements in crop production [37]. Their adoption in agriculture can lower reliance on chemical fertilizers—reducing both cost and the adverse impacts those fertilizers can have on soil health [36] [38].

2.2.4 Vermicomposting

Vermicomposting transforms decomposed waste into nutrient-rich organic manure through the activity of earthworms; it requires no pile turning, produces little odor, and generates compost quickly [39]. Earthworms are cultured on blends of animal waste, soil, crop residues, or biodegradable leaves, producing vermicompost that can be applied as an organic fertilizer for all types of plants. The flexible use of various earthworm-based methods — and the synergistic roles of earthworms and microbes in the process. [40] has also been highlighted the flexible use of various earthworm-based methods and the synergistic roles of earthworms' microbial communities.

2.2.5 Hybrid fertilizers

Hybrid fertilizers combine organic and mineral fractions and can be formulated in different N, P and K ratios to match specific crop requirements [41]. The final product is available as a powder, granule or pellet. These fertilizers boost soil fertility by improving soil physico-chemical properties, increasing nutrient availability and water-holding capacity, and promoting phosphate solubilization. They also enhance plant agro-physiological performance — increasing biomass and yield, improving nutrient assimilation, and supporting metabolic processes. [42]

2.2.6. Digital Innovations

Digital innovations and tools enable organic farmers to monitor and optimize crop and livestock health, raise resource-use efficiency, lower environmental impacts, and improve farm profitability [43]. They can be applied across farming operations such as tillage, irrigation, fertilization, post-harvest handling, storage, and transportation of produce. These technologies also hold promise for reducing poverty and food insecurity among the world's smallholder farmers [44]. However, advanced digital solutions are currently concentrated among large-scale producers, where they contribute substantially to sustainability; existing digital services for smallholders often lack suitability for organic farming and must be improved to promote future economic and environmental resilience [45].

2.3 Soil carbon mechanisms

2.3.1. Role of Microbial Biomass in Stabilizing Soil Health

Soil microorganisms are a vital, decisive determinant of soil health [46]. The communities of microbes in soil play central roles in nutrient cycling, in shaping the soil's physical and chemical properties, and in sequestering carbon [47]. For example, free-living nitrogen fixers such as *Clostridium* and *Azotobacter* convert atmospheric N₂ into ammonia (NH₃), making nitrogen biologically available to plants, while *Rhizobium* and *Bradyrhizobium* form symbiotic root nodules that also fix nitrogen for plant use. Other soil bacteria, including *Pseudomonas* and *Paracoccus*, function as denitrifiers under anaerobic conditions and help maintain the soil nitrogen balance. Phosphorus, another essential macronutrient, commonly occurs in soils as insoluble mineral forms or bound to organic matter; microbial activity and interactions with soil organic matter release phosphorus in plant-available forms [48].

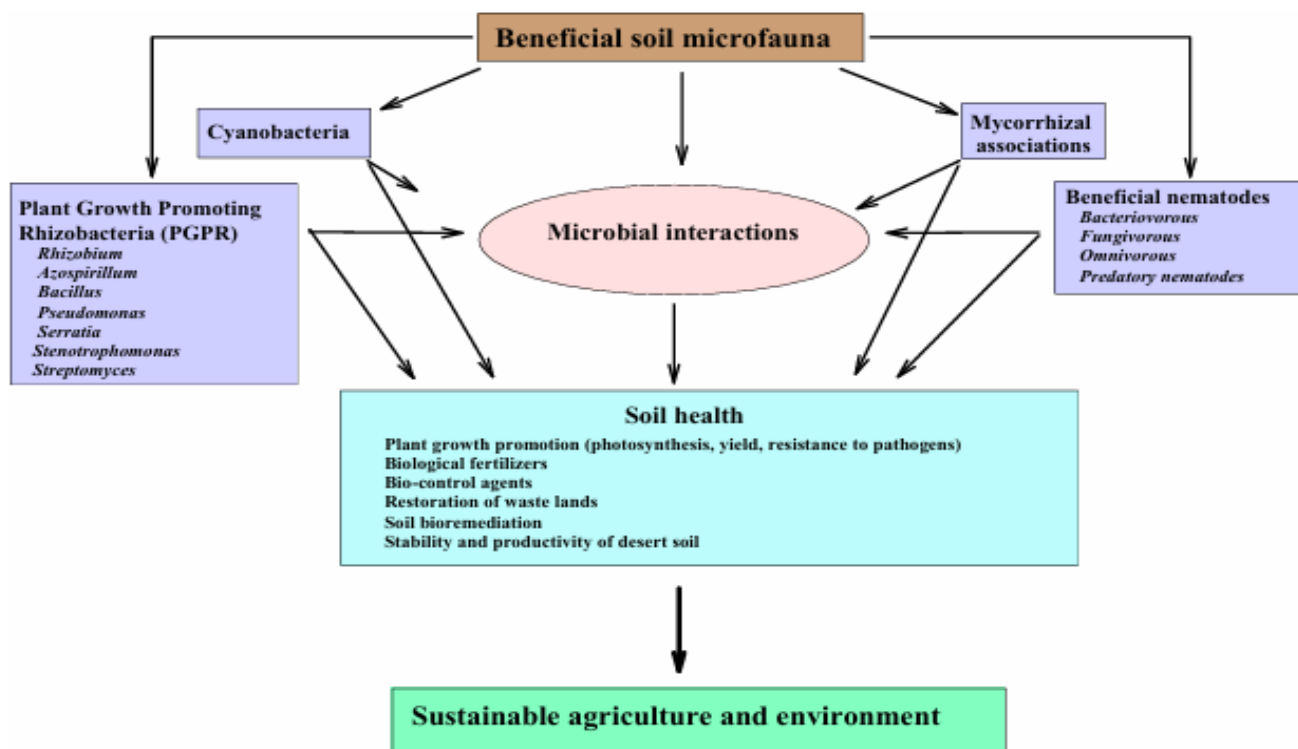


Fig. 2. Beneficial soil microbes and their interactions that support sustainable agriculture and environmental health.

Two primary types of mechanisms govern the stabilization and destabilization of soil organic C [49]: biotic mechanisms associated with living soil biomass and biodiversity (plants, soil fauna, and microorganisms), and abiotic mechanisms (physical localization within the soil, degradation/stabilization hotspots, and organomineral interactions).

2.3.2. Effect of living biomass on soil carbon cycling

Plants affect soil organic matter (OM) in two principal ways. Firstly, as autotrophs they are the primary source of soil organic C through litter fall, root exudation, and symbiotic associations [50]. Secondly, plants promote OM stabilization by producing relatively recalcitrant compounds and by encouraging the formation of stable soil aggregates; by reducing erosion they further conserve soil OM [12]. The influence of plants on OM also depends on species-specific root systems. It is also a function of the root morphology, physiology, chemical composition and symbiotic associations.

Soil macrofauna including millipedes, centipedes, woodlice, earthworms, some springtails, spiders, and numerous insects often form a large portion of soil biomass and strongly influence OM dynamics [51]. Long-term stabilization of OM is widely recognized to result from interactions among microorganisms, roots, macrofauna (earthworms, termites, ants), and the soil mineral matrix [52].

Microorganisms, through their activities, are central to the ecosystem services delivered by soils [53]. At the ecosystem scale, soil microbes are vital for: (i) nutrient recycling including nitrogen, phosphorus, sulfur, potassium and other elements essential for plant growth and ecosystem functioning; (ii) soil organic matter (OM) storage, which helps maintain soil structure and fertility; and (iii) soil OM decomposition, a process that can substantially affect the global climate balance by altering carbon fluxes.

2.4 Land Management Practices

2.4.1. Agricultural Tilling

Soil physical protection via aggregates is an important mechanism for stabilizing soil organic matter [54]. Conventional agricultural practices especially use of heavy machinery can cause structural degradation such as persistent compaction, often visible along former tractor routes and altering soil carbon dynamics. Tillage rapidly increases CO₂ emissions because it breaks soil aggregates, exposes labile organic matter, and stimulates microbial oxidation of SOM [55]. Mechanical disturbance also alters porosity, pore-size distribution and thermal conductivity, affecting soil temperatures at both the surface and subsurface. These changes often produce a degraded structure with low macroporosity and high moisture content, creating anaerobic microsites that can drive elevated N₂O emissions [56]. Soil compaction additionally reduces crop yield and photosynthesis, diminishing carbon sequestration while increasing the field's carbon footprint. Reducing tillage intensity or adopting no-till practices can restore structural stability and promote organic matter sequestration, enhancing both the labile fraction and long-term carbon stability [57].

2.4.2. Agricultural chemicals

Pesticide use in agriculture increases greenhouse-gas emissions and thereby contributes to climate change. Global pesticide application continues to rise day by day [58]. The routine use of herbicides and fungicides for example boscalid, bromoxynil, glyphosate, imazamox, imazethapyr, pyraclostrobin, and sethoxydim in field-crop production has been reported to elevate N₂O emissions. [59] The impact of herbicides can be reduced by timing applications to specific weed-growth stages and by combining their use with conservation tillage practices [60]

2.4.3. CO₂ (Tractors), Harvesting, and Runoff

On- and off-farm operations associated with crop production are important contributors to the agricultural carbon footprint. Farm machinery, in particular, generates greenhouse gases through its energy requirements [61]. Direct energy inputs include diesel, gasoline, electricity, and gas, while indirect energy demands arise from production inputs (seeds, fertilizers, feed) and manufactured inputs (buildings, machinery) [62]. In addition, tillage is an energy-intensive management practice.

Impact of Soil Organic Matter and Microbial Biomass on Soil Health and Productivity

3.1 Organic Soil Content

Organic soil content also known as soil organic matter (SOM) refers to the decomposing remains derived from plants or animals. This plant-based material can encompass dissolved or particulate substances, root exudates, leachates from leaf and needle litter, or deceased root and shoot residues [63]. As the biggest land-based storehouse of carbon on Earth, SOM holds more carbon than the combined amounts in plant life and the air [64]. It mainly consists of humic compounds and black carbon: humic compounds, which arise from the breakdown and alteration of organic biomass, featuring elements like humic and fulvic acids [65]. These humic elements play a key role in maintaining soil productivity. Black carbon, on the other hand, includes additional carbon remnants from biological sources, such as soot, char, and charcoal produced by wildfires, the combustion of agricultural leftovers, or fossil fuel use [66]. The carbon within SOM serves as energy source for soil microorganisms, enabling various chemical processes like the movement of carbon in the soil, carbon cycling between the atmosphere and soil, and the conversion of atmospheric nitrogen into usable mineral compounds. In the initial phases of forming soil organic carbon (SOC), soil microbes degrade fresh SOM along with plant root ends and foliage into beneficial forms that support plant development. Organic matter (OM) stands out as a vital element influencing overall soil quality and enhancing crop yields.

Soil organic matter enhances the physico-chemical and biological characteristics and functions in the soil. Consequently, it serves as a primary measure of soil quality [7]. Incorporating organic matter results in improved soil output, structural attributes, nitrogen levels, pore space, and water absorption. Therefore, these organic additions deliver a steady nutrient profile that boosts crop yields. Moreover, soil organic inputs promote the activity, variety, and proliferation of microbes, thereby converting inaccessible soil nutrients into forms that plants can readily utilize.

3.2 Soil living microbes

Soil living microbes refers to the active biological component of in the soil, excluding plant roots and soil animals. Soil microbes are a vital, essential, and determining factor in assessing soil health [47]. These microbial communities are critical for nutrient cycling, influencing the soil's physical and chemical properties, and aiding in carbon storage. For example, microbes like *Clostridium* contribute significantly to these processes. Although SMB constitutes only about 0.05% of soil organic matter, it plays a pivotal role in sustaining soil health by facilitating the cycling of carbon and other nutrients. Soil microbes enhance plant nutrient absorption through symbiotic relationships, suppress disease-

causing pathogens, and actively contribute to immobilizing heavy metals and breaking down foreign bio-compounds [12].

4. Discussions

Soil Biodiversity and Sustainability as Key for Food Security

Soil biodiversity refers to the different organisms inhabiting soil ecosystem. The roles played by microbial communities, along with their interactions with the soil and plants, can create a stable ecological system in the soil that promotes crop development, growth, and enduring harvests [67]. As a result, adequate knowledge into the roles, actions, and interaction mechanisms of these microbial groups in both soil and plants is vital to avoid unintended farming approaches that could cause irreversible harm to the agricultural ecosystem.

Research has demonstrated that robust soil can inhibit disease-causing agents, maintain living processes, break down organic materials, neutralize harmful substances, circulate nutrients, energy, and water [68]. According to Bouma *et al.*, soil quality is described as "the ability of a soil to perform its roles, within the limits of human ecosystem management, determines plant and animal productivity, water and air quality and human well-being" [69]. Soil health is intimately tied to biological activity. As highlighted in [47], [47] emphasize that a healthy soil sustains productivity and ecosystem functions through a rich microbiome.

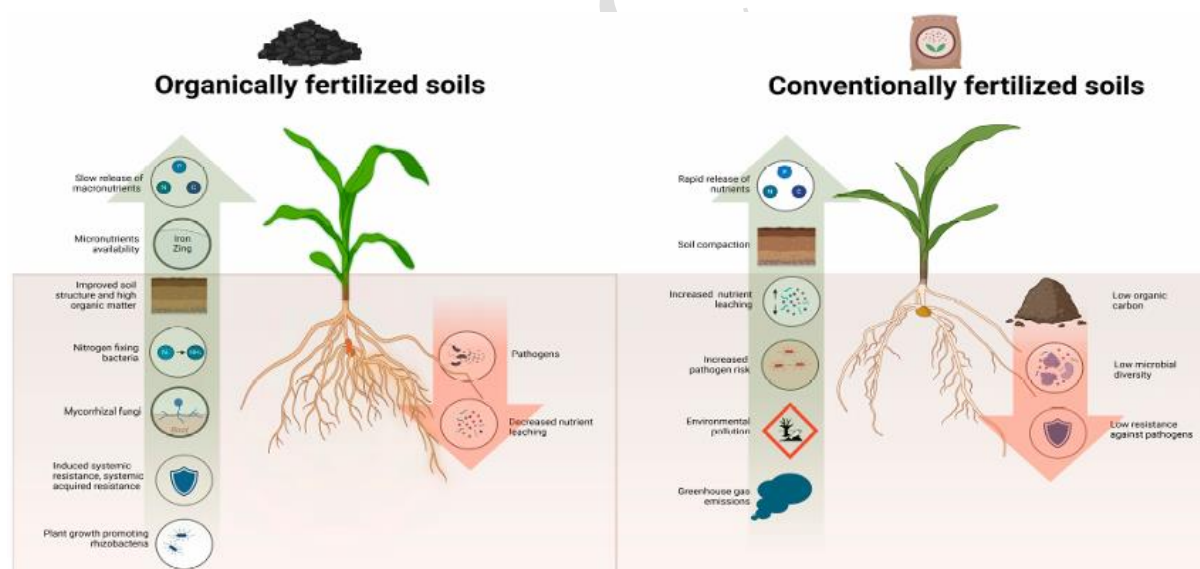


Figure 3: Comparism of organic and conventional fertilized soil

4.2 Organic Farming

Organic yields can achieve levels comparable to those of conventional systems following several years of cultivation [70]. In summary, organic agriculture represents the optimal approach for enhancing both soil and produce quality. As such, any disparity in output between organic and conventional methods

might simply be temporary, prolonged organic practices will potentially foster greater resilience in soil microbial populations and related activities [70].

In organic farming setups, rotating crops with legumes typically serves as the primary method for supplying nitrogen [71]. That is, delivering sufficient nitrogen to plants in organic systems can prove difficult due to the relatively gradual release of this nutrient when compared to synthetic fertilizers [72]. For this reason, farmers rely on fertilizers derived from plants and animals to meet basic crop needs. A variety of commercially accessible options exist for organic producers, including plant-derived ones (such as meals from leguminous crops and maize) and animal-derived ones (like blood and fishmeals, feathers, bones, and manure-based compost) [73].

Lately, the farming industry has promoted replacing synthetic inputs with biologically active organic alternatives through methods like biological or biodynamic cultivation. The usage of synthetic chemicals in farming is connected to elevated greenhouse gas emissions, thereby exacerbating climate change concerns [74]. Consequently, farming techniques should be reassessed and modified to promote environmental sustainability.

4.3. Climate Change Adaptation and Resilience

Land-use changes can substantially modify soil properties and thereby shift the balance between soils acting as sources or sinks of greenhouse gases. Vegetation composition, root depth and the spatial arrangement of plants can also exert strong control over soil carbon fluxes and related emissions.

4.4. Advantages of Sustainable Organic Agricultural Methods

Organic fertilizers are a cornerstone of sustainable agriculture. They improve the structure of soil and health by enhancing aggregate formation, enhancing water-holding capacity, and increasing resistance to erosion and compaction [35]. Organic fertilizer, which results in improved root penetration, and greater moisture retention enhance soil aggregation, which is particularly valuable in arid and water-limited regions. Organic amendments also stimulate soil biodiversity and microbial activity by supplying nutrients and creating favorable habitats for beneficial microorganisms; this enhanced biological activity can help suppress soil-borne diseases [23]. By reducing reliance on synthetic chemicals—which contaminate water and release greenhouse gas emissions. Organic fertilizers lower nutrient runoff, harmful emissions, and soil acidification [29]. Their gradual, steady nutrient addition provides a sustained supply that reduces leaching and runoff of essential elements [75]. Additionally, organic inputs support carbon sequestration and foster healthy soil fauna such as earthworms and nematodes, which break down organic matter, improve aeration, and further strengthen soil structure. Collectively, these effects create a healthier soil environment for plants and microbes and contribute to the resilience and sustainability of agricultural systems.

Organic fertilizers therefore contribute substantially to soil and environmental sustainability through multiple pathways, making agricultural system sustainable. [51]. Organic system of fertilizer enhances soil structure, moisture retention, and biological activity. It also strengthens agroecosystem resilience to climate stresses such as temperature extremes, prolonged dryness, and erosion. Beyond improving

productivity, organic farming encourages environmentally responsible management and conservation measures that protect ecosystem over the long term.

Contemporary agriculture is notably facing declining soil fertility and falling crop productivity. Over dependence on synthetic chemicals undermines soil's efficiency and harms the environment by polluting water and the broader environment [10]. To protect soil function and secure productive landscapes for future generations, a timely transition to organic practices is needed to restore and sustain soil fertility through ecologically based management [76].

Eradicating hunger, achieving food security, and promoting sustainable agriculture are central objectives of the Sustainable Development Goals (SDGs). These aims are met when food systems deliver adequate, safe, and nutritious food for everyone while reducing environmental harm and enabling producers to earn a fair livelihood [77]. Viewed collectively, agriculture contributes—directly or indirectly—to all 17 SDGs [9]. For example, eliminating poverty is impossible without ensuring food security; attaining SDG 2 requires accessible, safe, and affordable food for all, and good health and effective learning depend fundamentally on adequate nutrition. [77] [9]

Food security, ending world hunger and promoting sustainable agriculture are central aims of SDGs. These objectives are attainable only when food systems deliver adequate, safe, and qualitative food for all while mitigating environmental harm and enabling fair livelihoods for farmers [77]. Agriculture strengthens many aspects of development; it contributes directly or indirectly to all 17 SDGs [9]. For example, eliminating poverty depends on secure food supplies; achieving SDG-2 requires access to abundant, low cost and qualitative food for everyone; and sound health and effective learning are founded on adequate nutrition, which in turn supports quality education.

4.5. Challenges and Constraints in Achieving Sustainability through Organic Farming

Organic farming has expanded globally, however various constraints continue to limit organic practice [78]. Organic producers face a different cost profile than conventional farmers. While organic operations typically spend less on purchased inputs, they incur substantially higher labor and feed expenses [79]. Products free of synthetic chemicals are often appreciated for their environmental benefits compared with those from conventional farming. Organic agriculture is surrounded by many challenges (Srivastava *et al.*, 2022). Producing organic food requires considerable effort and expertise because management depends on systematic, knowledge-intensive approaches to maintain fertility and control weeds and pests rather than relying on chemical application.

Products free of synthetic chemicals also tend to be more perishable and usually must be eaten as soon as possible to ensure safety of food, as they generally have a shorter shelf life (Shennan *et al.*, 2017). Pest infestations remain a significant concern. Many synthetic chemicals are prohibited in organic systems because they are not organic and can harm the soil, so crops may be severely damaged if pests are not effectively managed.

4.6. Environmental impacts of current practices

The widespread and unregulated application of pesticides, including insecticides, herbicides, and fungicides, poses significant obstacles to achieving sustainable development. The heavy reliance on these chemicals endangers ecosystems, compromises safety of food, and jeopardizes health safety. Pesticides are commonly added directly to soils and crops, and their persistent use results in ongoing environmental contamination.

Intensive tillage also oxidizes SOC and releases CO₂, whereas reduced tillage or no-till helps retain carbon in the soil. Ozlu *et al.*, (2022) highlight that carbon-rich soils act as sinks and thus mitigate net emission. Minimizing tillage frequency and depth, ensuring adequate soil moisture, diversifying crops, and limiting heavy machinery to prevent compaction are recommended (Ozlu *et al.*, 2022). Importantly, building of SOC in its most stable forms (e.g. as humus within aggregates) is considered as the most optimizing method for sustainable crop production with maximum efficiency reducing the carbon footprint.

6.4. Adjusting to changing climate and resilience-building measures.

Agroecological practice very essential for adapting to changing climate, enabling farmers to handle the unpredictability states of weather associated with global warming. Such adaptation strategies could be connected to improved soil carbon content known for greater resilience especially in regions prone adverse weather occurrences like droughts and floods.

5. Conclusion

This review highlights numerous advantages that healthy soils offers to the broader public and particularly to farmers. Ecological soil management can reconcile productive agriculture with environmental sustainability. Practices that build soil OM (organic matter) such as bio-fertilizers, crop rotations with cover crops, and reduced tillage – consistently improve soil health. Carbon-rich soils also act as sinks and thus mitigate net emission. Organic farming principles reduce dependence on synthetic inputs and maintain natural nutrient cycle. Healthier soils are more stable and resilient, providing ecosystem services that benefit farmers and society. Crop diversification enhances soil health compare to monoculture practices. Limiting machinery operations helps maintain soil structure. Enhancing soil organic carbon storage is key to sustainable farming practices.

Recommendations

Based on the study findings, here are some recommendations for scaling up the adoption of integrated agroecological practices are proposed.

1. Government should make policy that will incorporate agroecological principles into national agricultural and climate strategies, with clear recognition of the interlinkages between soil carbon, biodiversity, and climate change.

2. Improve Knowledge Transfer and Capacity Building by Establish farmer-led extension services to provide ongoing technical support for adopting agroecological practices. These services should focus on building local knowledge and peer-to-peer learning, helping farmers share best practices and adapt strategies to their specific conditions.
3. Economic benefits such as subsidies or grants for the start-up costs of conversion to organic practices should be implemented. Support mechanisms like micro-loans or insurance programs to support the scaling of agroecological methods, which could also help to mitigate risks, associated with the transition period, which may include temporary yield reductions.
4. Nationally Determined incentive and recognition should be provided for farmers who perform organic practices that preserve soil health and biodiversity.
5. Engage indigenous population in deliberation processes, ensuring that land-use and conservation policies are included, socially equitable, and accommodating the necessities of vulnerable populations.

References

- [1] Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global change biology*, 25(8), 2530-2543.
- [2] Agu, O. S., Tabil, L. G., Mupondwa, E., Emadi, B., & Dumonceaux, T. (2022). Impact of biochar addition in microwave torrefaction of camelina straw and switchgrass for biofuel production. *Fuels*, 3(4), 588-606.
- [3] Aitkazina, M. A., Nurmaganbet, E., Syrlybekkyzy, S., Koibakova, S., Zhidebayeva, A. E., & Aubakirov, M. Z. (2019). THREATS TO SUSTAINABLE DEVELOPMENT DUE TO INCREASE OF GREENHOUSE GAS EMISSIONS IN A KEY SECTOR. *Journal of Security & Sustainability Issues*, 9(1).
- [4] Ananyeva, N. D., Ivashchenko, K. V., & Sushko, S. V. (2021). Microbial indicators of urban soils and their role in the assessment of ecosystem services: a review. *Eurasian Soil Science*, 54, 1517-1531.
- [5] Araya, S. N., Mitchell, J. P., Hopmans, J. W., & Ghezzehei, T. A. (2022). Long-term impact of cover crop and reduced disturbance tillage on soil pore size distribution and soil water storage. *Soil*, 8(1), 177-198.
- [6] Babaniyi, G. G., Akor, U. J., & Odeseye, A. A. (2025). Pesticide Contributions to Greenhouse Gas Emissions. In *The Interplay of Pesticides and Climate Change: Environmental Dynamics and Challenges* (pp. 173-230). Cham: Springer Nature Switzerland.
- [7] Bailey, V. L., Pries, C. H., & Lajtha, K. (2019). What do we know about soil carbon destabilization? *Environmental Research Letters*, 14(8), 083004.
- [8] Bamboriya, S. D., Bana, R. S., Kuri, B. R., Kumar, V., Bamboriya, S. D., & Meena, R. P. (2022). Achieving higher production from low inputs using synergistic crop interactions under maize-based polyculture systems. *Environmental Sustainability*, 5(2), 145-159.
- [9] Bi, H., & Neethirajan, S. (2024). Mapping Methane—The Impact of Dairy Farm Practices on Emissions Through Satellite Data and Machine Learning. *Climate* 2024, 12, 223.

- [10] Bilen, C., El Chami, D., Mereu, V., Trabucco, A., Marras, S., & Spano, D. (2022). A systematic review on the impacts of climate change on coffee agrosystems. *Plants*, 12(1), 102.
- [11] Biswas, S., & Pakhira, R. (2023). Natural Farming in India: Concept and Current Scenario. *Vigyan Varta*, 4(9), 76-79.
- [12] Bouhia, Y., Hafidi, M., Ouhdouch, Y., Boukhari, M. E. M. E., Mphatso, C., Zeroual, Y., & Lyamlouli, K. (2022). Conversion of waste into organo-mineral fertilizers: current technological trends and prospects. *Reviews in Environmental Science and Bio/Technology*, 21(2), 425-446.
- [13] Byrnes, B. H., & Bumb, B. L. (2017). Population growth, food production and nutrient requirements. In *Nutrient use in crop production* (pp. 1-27). CRC Press.
- [14] Canwat, V., & Onakuse, S. (2022). Organic agriculture: A fountain of alternative innovations for social, economic, and environmental challenges of conventional agriculture in a developing country context. *Cleaner and Circular Bioeconomy*, 3, 100025.
- [15] Carvalho, P. C., da Silveira Pontes, L., Barro, R. S., Simões, V. J. L. P., Dominschek, R., dos Santos Cargnelutti, C., ... & Bremm, C. (2024). Integrated crop-livestock-forestry systems as a nature-based solution for sustainable agriculture. *Agroforestry Systems*, 98(7), 2309-2323.
- [16] Cech, R., Leisch, F., & Zaller, J. G. (2022). Pesticide use and associated greenhouse gas emissions in sugar beet, apples, and viticulture in Austria from 2000 to 2019. *Agriculture*, 12(6), 879.
- [17] Chang, Y., Hou, K., Li, X., Zhang, Y., & Chen, P. (2018, February). Review of land use and land cover change research progress. In *IOP Conference Series: Earth and Environmental Science* (Vol. 113, p. 012087). IOP Publishing.
- [18] Crusciol, C. A., Mateus, G. P., Momesso, L., Pariz, C. M., Castilhos, A. M., Calonego, J. C., ... & Cantarella, H. (2020). Nitrogen-fertilized systems of maize intercropped with tropical grasses for enhanced yields and estimated land use and meat production. *Frontiers in Sustainable Food Systems*, 4, 544853.
- [19] Deng, X., Huang, Y., Yuan, W., Zhang, W., Ciais, P., Dong, W., & Qin, Z. (2023). Building soil to reduce climate change impacts on global crop yield. *Science of The Total Environment*, 903, 166711.
- [20] Devi, N. M., Devi, S. B., Longkumer, L. T., & Nengparmoi, T. (2024). Organic Farming: Promoting Soil Health and Environmental Sustainability. *Revolutionizing Agriculture: Innovations in Agronomy for Sustainable Food Production*, 69.
- [21] Gamage, A., Gangahagedara, R., Gamage, J., Jayasinghe, N., Kodikara, N., Suraweera, P., & Merah, O. (2023). Role of organic farming for achieving sustainability in agriculture. *Farming System*, 1(1), 100005.
- [22] Geissen, V., Silva, V., Lwanga, E. H., Beriot, N., Oostindie, K., Bin, Z., & Ritsema, C. J. (2021). Cocktails of pesticide residues in conventional and organic farming systems in Europe—Legacy of the past and turning point for the future. *Environmental Pollution*, 278.
- [23] Gołasa, P., Wysokiński, M., Bieńkowska-Gołasa, W., Gradziuk, P., Golonko, M., Gradziuk, B., & Gromada, A. (2021). Sources of greenhouse gas emissions in agriculture, with particular emphasis on emissions from energy used. *Energies*, 14(13), 3784.
- [24] Halder, A., Mandal, S. N., Deb, S., Roy, R., & Laishram, M. (2022). Application of information and electronic technology for best practice management in livestock production system. In *Agriculture, Livestock Production and Aquaculture: Advances for Smallholder Farming Systems Volume 2* (pp. 173-218). Cham: Springer International Publishing.

- [25] Jakubus, M., & Bakinowska, E. (2020). Quantitative changes in various nutrient ratios in cultivated plants in relation to fertilisation. *Journal of Elementology*, 25(3), 1155-1174.
- [26] Kan, Z. R., Liu, W. X., Liu, W. S., Lal, R., Dang, Y. P., Zhao, X., & Zhang, H. L. (2022). Mechanisms of soil organic carbon stability and its response to no-till: A global synthesis and perspective. *Global Change Biology*, 28(3), 693-710.
- [27] Kirchmann, H., Börjesson, G., Kätterer, T., & Cohen, Y. (2017). From agricultural use of sewage sludge to nutrient extraction: A soil science outlook. *Ambio*, 46, 143-154.
- [28] Kukreti, N., & Singh, V. K. (2024). Performance of Organic manure with Rhizobium inoculation on growth and yield of Mungbean (*Vigna radiata* L.). *Ecology, Environment & Conservation (0971765X)*, 30.
- [29] Kumar, V., Gathala, M. K., Saharawat, Y. S., Parihar, C. M., Kumar, R., Kumar, R., & Kuri, B. R. (2019). Impact of tillage and crop establishment methods on crop yields, profitability and soil physical properties in rice–wheat system of Indo-Gangetic Plains of India. *Soil Use and Management*, 35(2), 303-313.
- [30] Lee, T., Jang, W. S., Chun, B., Ahmad, M. J., Jung, Y., Kim, J., & Shin, Y. (2023). Development of irrigation schedule and management model for sustaining optimal crop production under agricultural drought. *Paddy and Water Environment*, 21(1), 31-45.
- [31] Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, 1(10), 544-553.
- [32] Liebig, M. A., Abendroth, L. J., Robertson, G. P., Augustine, D., Boughton, E. H., Bagley, G., ... & Yost, J. (2024). The LTAR Common Experiment: Facilitating improved agricultural sustainability through coordinated cross-site research. *Journal of Environmental Quality*, 53(6), 787-801.
- [33] Lovarelli, D., & Bacenetti, J. (2019). Exhaust gases emissions from agricultural tractors: State of the art and future perspectives for machinery operators. *Biosystems engineering*, 186, 204-213.
- [34] Ma, X., Li, H., Xu, Y., & Liu, C. (2021). Effects of organic fertilizers via quick artificial decomposition on crop growth. *Scientific reports*, 11(1), 3900.
- [35] Mangalassery, S., Kalaivanan, D., & Philip, P. S. (2019). Effect of inorganic fertilisers and organic amendments on soil aggregation and biochemical characteristics in a weathered tropical soil. *Soil and Tillage Research*, 187, 144-151.
- [36] Mateo-Marín, N., Bosch-Serra, À. D., Molina, M. G., & Poch, R. M. (2022). Impacts of tillage and nutrient management on soil porosity trends in dryland agriculture. *European Journal of Soil Science*, 73(1), e13139.
- [37] Mazurek-Kusiak, A., Sawicki, B., & Kobylka, A. (2021). Contemporary challenges to the organic farming: a Polish and Hungarian case study. *Sustainability*, 13(14), 8005.
- [38] Melman, D. A., Kelly, C., Schneekloth, J., Calderon, F., & Fonte, S. J. (2019). Tillage and residue management drive rapid changes in soil macrofauna communities and soil properties in a semiarid cropping system of Eastern Colorado. *Applied soil ecology*, 143, 98-106.
- [39] Mockeviciene, I., Repsiene, R., Amaleviciute-Volunge, K., Karcauskiene, D., Slepeticene, A., & Lepane, V. (2022). Effect of long-term application of organic fertilizers on improving organic matter quality in acid soil. *Archives of Agronomy and Soil Science*, 68(9), 1192-1204.
- [40] Mushi, G. E., Serugendo, G. D. M., & Burgi, P. Y. (2023). Data management system for sustainable agriculture among smallholder farmers in Tanzania: research-in progress. *Information Technology for Development*, 29(4), 558-581.

- [41] Mushtaq, Z., Faizan, S., & Hussain, A. (2021). Role of microorganisms as biofertilizers. *Microbiota and Biofertilizers: A Sustainable Continuum for Plant and Soil Health*, 83-98.
- [42] Naab, J. B., Mahama, G. Y., Yahaya, I., & Prasad, P. V. V. (2017). Conservation agriculture improves soil quality, crop yield, and incomes of smallholder farmers in North Western Ghana. *Frontiers in plant science*, 8, 996.
- [43] Nijs, E. A., & Cammeraat, E. L. (2020). The stability and fate of soil organic carbon during the transport phase of soil erosion. *Earth-Science Reviews*, 201, 103067.
- [44] Ozlu, E., Arriaga, F. J., Bilen, S., Gozukara, G., & Babur, E. (2022). Carbon footprint management by agricultural practices. *Biology*, 11(10), 1453.environment, 256, 123-130.
- [45] Parven, A., Meftaul, I. M., Venkateswarlu, K., & Megharaj, M. (2025). Herbicides in modern sustainable agriculture: environmental fate, ecological implications, and human health concerns. *International Journal of Environmental Science and Technology*, 22(2), 1181-1202.
- [46] Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, 532(7597), 49-57.
- [47] Pires, L. F., Borges, J. A., Rosa, J. A., Cooper, M., Heck, R. J., Passoni, S., & Roque, W. L. (2017). Soil structure changes induced by tillage systems. *Soil and Tillage Research*, 165, 66-79.
- [48] Policastro, G., Cesaro, A., Fabbicino, M., & Pirozzi, F. (2022). Opportunities and challenges from symbiosis of agro-industrial residue anaerobic digestion with microalgae cultivation. *Sustainability*, 14(23), 15607.
- [49] Quintarelli, V., Radicetti, E., Allevato, E., Stazi, S. R., Haider, G., Abideen, Z., & Mancinelli, R. (2022). Cover crops for sustainable cropping systems: a review. *Agriculture*, 12(12), 2076.
- [50] Sabir, K., Rose, T., Wittkop, B., Stahl, A., Snowdon, R. J., Ballvora, A., & Chen, T. W. (2023). Stage-specific genotype-by-environment interactions determine yield components in wheat. *Nature Plants*, 9(10), 1688-1696.
- [51] Saccá, M. L., Barra Caracciolo, A., Di Lenola, M., & Grenni, P. (2017). Ecosystem services provided by soil microorganisms. In *Soil biological communities and ecosystem resilience* (pp. 9-24). Cham: Springer International Publishing.
- [52] Sahu, H., Kumar, U., Mariappan, S., Mishra, A. P., & Kumar, S. (2024). Impact of organic and inorganic farming on soil quality and crop productivity for agricultural fields: A comparative assessment. *Environmental Challenges*, 15, 100903.
- [53] Sarkar, S., Kumar, R., Kumar, A., Kumar, U., Singh, D. K., Mondal, S., & Yadav, S. K. (2022). Role of soil microbes to assess soil health. In *Structure and Functions of Pedosphere* (pp. 339-363). Singapore: Springer Nature Singapore.
- [54] 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(5), 93.
- [55] Schrama, M., De Haan, J. J., Kroonen, M., Verstegen, H., & Van der Putten, W. H. (2018). Crop yield gap and stability in organic and conventional farming systems. *Agriculture, ecosystems &*
- [56] Schütz, L., Gattinger, A., Meier, M., Müller, A., Boller, T., Mäder, P., & Mathimaran, N. (2018). Improving crop yield and nutrient use efficiency via biofertilization—A global meta-analysis. *Frontiers in plant science*, 8, 2204.
- [57] Shaji, H., Chandran, V., & Mathew, L. (2021). Organic fertilizers as a route to controlled release of nutrients. In *Controlled release fertilizers for sustainable agriculture* (pp. 231-245). Academic Press.

- [58] Sharma, K., & Garg, V. K. (2019). Vermicomposting of waste: a zero-waste approach for waste management. In *Sustainable resource recovery and zero waste approaches* (pp. 133-164). Elsevier.
- [59] Sharma, R., Sindhu, S. S., & Glick, B. R. (2024). Potassium solubilizing microorganisms as potential biofertilizer: a sustainable climate-resilient approach to improve soil fertility and crop production in agriculture. *Journal of Plant Growth Regulation*, 43(8), 2503-2535.
- [60] Shennan, C., Krupnik, T. J., Baird, G., Cohen, H., Forbush, K., Lovell, R. J., & Olimpi, E. M. (2017). Organic and conventional agriculture: a useful framing? *Annual Review of Environment and Resources*, 42(1), 317-346.
- [61] Khan, Z., Zhang, K., Khan, M. N., Zhu, K., & Hu, L. (2024). Effects of biochar persistence on soil physiochemical properties, enzymatic activities, nutrient utilization, and crop yield in a three-year rice-rapeseed crop rotation. *European Journal of Agronomy*, 154, 127096.
- [62] Shivay, Y. S. (2023). Digital Tools for Organic Farming. *Souvenir*, 7.
- [63] Singh, A. K., Sisodia, A., Sisodia, V., & Padhi, M. (2019). Role of microbes in restoration ecology and ecosystem services. In *New and future developments in microbial biotechnology and bioengineering* (pp. 57-68). Elsevier.
- [64] Singh, S. K., Krishna, H., Sharma, S., Singh, R. K., Tripathi, A. N., & Behera, T. K. (2024). Organic farming in vegetable crops: Challenges and opportunities. *Vegetable Science*, 51, 1-10.
- [65] Sokol, N. W., Sohng, J., Moreland, K., Slessarev, E., Goertzen, H., Schmidt, R., & Scow, K. (2024). Reduced accrual of mineral-associated organic matter after two years of enhanced rock weathering in cropland soils, though no net losses of soil organic carbon. *Biogeochemistry*, 167(8), 989-1005.
- [66] Srivastava, A. K., Kumar, A., Vigyan, K., & Bokaro, K. (2022). Exploring organic farming: Advantages, challenges, and future directions. *Plant Science Archives*, 9, 13.
- [67] Tahat, M., M. Alananbeh, K., A. Othman, Y., & I. Leskovar, D. (2020). Soil health and sustainable agriculture. *Sustainability*, 12(12), 4859.
- [68] Tanveer, A., Ikram, R. M., & Ali, H. H. (2019). Crop rotation: Principles and practices. *Agronomic Crops: Volume 2: Management Practices*, 1-12.
- [69] Thomas, L., & Singh, I. (2019). Microbial biofertilizers: types and applications. *Biofertilizers for sustainable agriculture and environment*, 1-19.
- [70] Timsina, J. (2018). Can organically sources of nutrients increase crop yields to meet global food demand? *Agronomy*, 8(10), 214.
- [71] Tyagi, J., Ahmad, S., & Malik, M. (2022). Nitrogenous fertilizers: Impact on environment sustainability, mitigation strategies, and challenges. *International Journal of Environmental Science and Technology*, 19(11), 11649-11672.
- [72] Uddain, J. (2024). Enhancing food safety and security through organic agriculture and innovative fertilizer management. *Asian-Australasian Journal of Food Safety and Security*, 8(2), 27-31.
- [73] Ukalska-Jaruga, A., Beijer, R., Debaene, G., & Smreczak, B. (2021). Characterization of soil organic matter individual fractions (fulvic acids, humic acids, and humins) by spectroscopic and electrochemical techniques in agricultural soils. *Agronomy*, 11(6), 1067.
- [74] Wang, B., Wang, G., van Dam, J., Yang, X., Ritsema, C., Siddique, K. H., ... & Kang, S. (2024). Diversified crop rotations improve crop water use and subsequent cereal crop yield through soil moisture compensation. *Agricultural Water Management*, 294, 108721.
- [75] Wenda-Piesik, A., & Synowiec, A. (2021). Productive and ecological aspects of mixed cropping system. *Agriculture*, 11(5), 395.

- [76] Wooliver, R., & Jagadamma, S. (2023). Response of soil organic carbon fractions to cover cropping: A meta-analysis of agroecosystems. *Agriculture, Ecosystems & Environment*, 351, 108497.
- [77] Wu, H., Zhang, J., Zhang, Z., Han, J., Cao, J., Zhang, L., & Tao, F. (2022). AsiaRiceYield4km: seasonal rice yield in Asia from 1995 to 2015. *Earth System Science Data Discussions*, 2022, 1-30.
- [78] Yang, S., Wang, Y., Liu, R., Xing, L., & Yang, Z. (2018). Improved crop yield and reduced nitrate nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district. *Scientific reports*, 8(1), 9458.
- [79] Yu, W., Yue, Y., & Wang, F. (2022). The spatial-temporal coupling pattern of grain yield and fertilization in the North China plain. *Agricultural Systems*, 196, 103330.
- [80] Zhou, J., Zhu, P., Kluger, D. M., Lobell, D. B., & Jin, Z. (2024). Changes in the Yield Effect of the Preceding Crop in the US Corn Belt Under a Warming Climate. *Global change biology*, 30(11), e17556.
- [81] Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A., & Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: Advantages and limitations. *Plant science*, 289, 110270.