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Review

Innovative Organic Fertilizers and Cover Crops: Perspectives for Sustainable Agriculture in the Era of Climate Change and Organic Agriculture

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Abstract: Anthropogenic activities have resulted in land desertification in various regions of the world, leading to the degradation of critical soil characteristics such as organic matter (OM) content, nutrient stock, and prevailing biodiversity. Restoring such degraded soils through organic matter amendments and diversified crop rotations is thus an intrinsic part of organic farming. This review discusses a wide range of organic farming impacts on soil health and crop productivity by focusing on organic fertilizers and crop diversification. Conventional fertilizers were considered vital for agricultural production to harvest high crop yields. Nevertheless, they are now deemed as environmentally hazardous and an obstacle to sustainable agroecosystems due to intensive chemical inputs that damage the soil over time and have long-lasting impacts. Conventional fertilization results in nutrient depletion, loss of microbial diversity, organic matter reduction, and deterioration of physical characteristics of the soil. Conversely, organic fertilization makes use of naturally existing resources to improve soil health. Organic amendments such as biochar, manure, and fermented grass improve soil's physical, chemical, and biological properties and promote the growth and diversity of beneficial soil microorganisms—important in nutrient cycling and soil stability. They facilitate the uptake of nutrients, hinder crop pathogen growth, mitigate heavy metals, and decompose xenobiotic organic substances. Moreover, growing cover crops is also a major strategy to improve soil health. Diversified crop rotation with combinatorial use of organic fertilizers may improve soil health and agricultural yields without any detrimental impacts on the environment and soil, ensuring sustainable food production, safety, and security. This integrated approach contributes to minimizing the use of chemical fertilizers and their effects on environmental health. It also contributes to reducing agricultural inputs along with enhancing OM, soil microbial diversity and biomass, nitrogen fixation, and carbon sequestration. Therefore, cover crops and organic fertilization may offer sustainable agroecosystems and climate change mitigation.

Keywords: organic fertilizers; cover crops; soil microbes; sustainable agriculture; organic agriculture

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1. Introduction

Soil health maintenance is a critical prerequisite of sustainable agricultural production. Unfortunately, excessive anthropogenic activities in recent years—including industrial agriculture, deforestation, and overgrazing—have resulted in soil deterioration in widespread areas of the world [1]. Hence, the restoration of degraded land is paramount to sustain ecosystems and agriculture, and combat climate change. This can be achieved by implementing organic amendments, growing a diverse variety of crops and cover crops, and beneficial microbiological applications. Healthy soils support environmentally healthy habitats for microbial communities and crops grown. Moreover, they provide balanced nutrient supplies for higher agricultural productivity [2].

Soil organic matter (SOM) is defined as decaying debris (mainly) of plant or animal origin. The plant debris may include dissolved or particulate plant materials, exudates, leaf and needle litter leachates, or dead root or shoot litter [3]. Organic matter (OM) is one of the most critical components that determines soil health. The role of SOM in crop production was recognized by agronomists at least two centuries ago. SOM represents the largest terrestrial C reservoir with higher C quantities even compared to vegetation and atmospheric C combined [4]. It improves physio-chemical and biological properties and processes within the soil. As such, it constitutes a key indicator of soil health [5]. Organic matter addition leads to enhanced soil productivity, physical parameters, nitrogen status, porosity, and water infiltration. Thus, organic matter amendments offer a balanced supply of nutrients improving crop productivity [6]. Soil organic amendments also facilitate microbial activity, diversity, and growth, and thus make unavailable nutrients in the soil more accessible to plants.

Soil microbial biomass (SMB) is also crucial to soil stability and nutrient cycling. The term SMB describes the living portion of OM, excluding plant roots and animals that reside within the soil. Although only 5% of SMB is present in SOM, it plays a crucial role in maintaining soil health through the turnover of carbon and other nutrients. The soil microbes may enhance plant nutrient uptake through symbiotic associations, suppress pathogens, and actively participate in heavy metals immobilization and degradation of xenobiotic organic compounds [7]. Even disturbed ecosystems with higher microbial diversity and SMB are more likely to maintain their ecological processes through microbiological buffering [8].

Kumar et al. [9] and Dual et al. [10] emphasized that conventional and nano-chemical fertilizers play crucial role in food production systems to fulfil the demand–supply gap. These conventional or synthetic fertilizers usually contain N, potassium (K), phosphorus (P), and other trace elements, whereas urea is also used as a conventional fertilizer. However, the traditional composite fertilizers, particularly those with a nitrogenous base, tend to increase the soil pH slowly during the vegetation growth of most crops [11]. Moreover, conventional fertilizers give rise to serious food safety issues. The use of these fertilizers for crop production leads to release of carbon dioxide (CO_2), ammonium ions (NH_4), and methane (CH_4) in the environment which may cause adverse human health effects [12]. Furthermore, human consumption of crops grown under conventional fertilizers may result in various health issues in the long run due to the use of hazardous chemicals in their production [13].

Apart from unsafe food production, plants typically only absorb 50% of the nitrogenous fertilizers. The remaining 10% of the 50% usually moves with irrigation or rainwater into freshwater supplies and, in this process, pollutes water bodies, affects water habitats, and eventually affects human populations using fresh water. For instance, drinking water with nitrates present in nitrogen fertilizers leads to gastric cancer in ruminants and blue baby syndrome in human infants [12]. The rest of the 50% applied chemical fertilizers either leaches to groundwater or is lost due to volatilization and denitrification. Thus, overapplication of chemical fertilizers leads to soil and air pollution, which causes soil acidification and destruction of physicochemical properties such as texture and structure through nutrient imbalance [14]. It also contributes harmful greenhouse gases, affecting the protective ozone layer [12,15]. Thus, chemical fertilizers impact soil and environment in dozens of multidimensional ways. It is a question to ponder whether the application of these fertilizers for higher crop yields actually benefits or worsens the agricultural systems and sustainable use of natural soil resources in the long run.

Organic fertilizers can primarily be described as by-products of animal and plant waste (Table 1). Organic fertilizers can deliver both macronutrients, such as nitrogen, potassium, phosphorus, and sulfur, and micronutrients, such as iron and zinc, among others, in a well-balanced manner. They stimulate a slow release of nutrients into the topsoil while improving microbial growth and activity, which helps improve the nutrient and water availability within the soil. These processes also improve the soil structure. All these processes promote plant root development accordingly [16]. Moreover, organic fertilizers decrease soil acidity and the availability of heavy metals [17], help avoid pest and disease infestation, and mitigate nutrient leaching. Organic fertilizers decompose slowly and thus provide a consistent supply of nutrients into the soil for longer duration [18]. Furthermore, organic fertilizers do not release harmful gases and chemicals into the environment, ensuring food safety.

Table 1. Properties of manure, composted grass, and biological origin compost as a source of OM.

Parameter	Manure	Composted Grass	Biological Origin Compost
Source	Cows, chickens, or horses	Composted green grass	Kitchen scraps, plant residues, agricultural waste, or animal manure
Primary Nutrient Focus	Nitrogen (N), Phosphorus (P), Potassium (K)	Nitrogen (N)	Balanced (N, P, K, micronutrients)
Nutrient Release Rate	Slow and consistent	Rapid decomposition	Moderate, balanced release
Soil Structure Improvement	Moderate (increases OM, but limited effects)	Significant improvement (boosts soil structure)	Significant improvement (promotes aggregation, tilth)
Microbial Impact	Moderate (supports microbial activity)	High (stimulates microbial activity)	High (promotes diverse microbial communities)
Long-term Soil Health Benefits	Moderate (improves cation exchange, gradual OM buildup)	Short to medium-term (quick nutrient and OM boost)	High (sustained improvement in OM, microbial health)
Stress Tolerance Enhancement	Low to Moderate (depends on nutrient balance)	Low (focuses on nutrient supply, limited stress resilience)	Moderate (balanced nutrients improve plant health)
Phosphorus Availability	High (direct source, but risk of over-application)	Low to moderate (less P, but improves availability)	High (organic acids enhance P availability)
References	[19–21]	[16,22]	[23–25]

For the aforementioned reasons, organic agriculture has become increasingly popular. Organic fertilization methods are therefore in demand to mitigate the environmental damage caused by conventional chemical fertilizers and pesticides. The development of advanced technologies for creating new types of organic fertilizers is invaluable to address the involved challenges [26]. Numerous readily available carbon sources have been explored and found to exhibit potential implications in this regard. For instance, biochar, prepared from several C-containing biomasses, such as wood chips, and waste originating from animals, food, industry, agriculture, and forest, is characterized by a wide range of beneficial physical and chemical properties. Biochar is mostly produced by pyrolysis [27]. Its combination with organic fertilizers coming from animal sources—manure, food waste [28]—or plant sources, for example, rice husk or straw compost biochar-coated urea [29], improves soil physical health and the availability of micronutrients. Even biochar coating of chemical fertilizers may also be utilized to improve C accumulation, nutrient absorption and to control soil acidity [26]. The addition of biochar to organic fertilizers improves the physical and chemical properties of soil, facilitating better root penetration and overall crop productivity [29,30].

Microbial population is another crucial component of the soil ecosystem. Soil microbes assist in sequestering carbon, nitrogen cycling, decomposition of organic matter, and improvement in soil structure. Thus, beneficial microbial species can also be used as a sustainable strategy of enhancing soil fertility. The combined application of organic fertilizers along with biofertilizers enriches the soil's organic carbon pool.

Specific advancements observed for modern organic farming were primarily skewed toward bridging the yield gap of organic farming with that of conventional farming. The objectives focused on improving nutrient access and plant utilization and mitigation of the negative impacts of chemical fertilizers [31]. Novel ideas associated with organic soil fertility involve unique organic amendments, cover crops, composting by earthworms, and growth of phytoaccumulators [26,31].

Crop rotation and cover crops offer another potential strategy for enhancing soil fertility without chemical amendments. This strategy can effectively substitute the use of costly fertilizers and pesticides. One of the most feasible approaches is to grow different species of plants rather than using monocultures because expensive farming inputs like pest control measures and pollinators can be significantly reduced by planting different plant species. It is now well proven that diversification of plant species in croplands has a number of advantages for raising crop and forage yields, controlling weeds and pests, increasing the level of soil carbon, and enhancing other soil nutrients.

Our previous studies have illustrated that soil fertility and health significantly depend on soil structure, compaction, and water retention. Moreover, we observed in prior investigations that low organic matter content is one of the most relevant issues hindering agricultural productivity in many regions [32]. Our prior research has also indicated that soil arable lands, which are under the higher influence of anthropogenic activities, exhibit lower SOC, N, MBC, and MBN compared to perennial grasslands and forests. The lower SMBC/SOC and SNBN/TN ratios for arable lands also stipulated lower ability to accumulate SOC and N, and sequester C [33]. We also noticed that intensive land utilization, such as in arable lands, deteriorates soil health in terms of microbial activity, water soluble organic carbon, humus formation, and acidity [34,35].

The long-term sustainability of agricultural systems depends on management practices. Our long-term investigation involving different crop residue management strategies, intercropping combinations, and tillage practices illustrated that utilization of chopped straw in combination with no-tillage improved SOC levels and reduced CO_2 emissions. We also noticed that cultivation of leguminous crops enhanced nutrient cycling and offered higher SOC stocks. Hence, organic fertilization, intercropping, and farm management practices play pivotal roles in soil health, CO_2 emissions, and are linked with climate change [36].

In similar investigations comparing organic versus conventional farming systems, we noted that conventional farming deteriorates the soil biological indicators, while these traits increase in the case of organic farming systems. We also noticed that organic systems offer higher K, P, and Ca than conventional systems [37]. We have also attempted to use different novel sources of organic fertilization and observed an increase in SOC, P, K, and Ca contents. The application of organic fertilizations also resulted in enhanced microbial abundance, MBC, and MBN in a direction relation [18]. Keeping this context in view, we aim to comprehensively review organic fertilization, the various options available in this regard, and mechanisms involved in this article. We also strive to put forward the value of organic fertilization as a sustainable agricultural practice to ensure stress resilience and climate change mitigation.

2. Impact of Anthropogenic Activities on Global Soil Deterioration

Excessive anthropogenic activities, such as intensive agriculture, deforestation, industrialization, and unsustainable use of limited resources have resulted in soil degradation in various regions of the world. Industrial agriculture is characterized by continuous production of the same lucrative crops over the years. This monoculture practice undermines the diversity of available SOM, detrimentally affecting the diversity of microbial communities thriving in the soil that further hampers the nutrient cycling [38]. These changes in soil make it prone to nutrient depletion, loss of biological diversity, and diminished resilience to environmental changes.

Unsustainable agricultural activities severely impact soil sustainability in dryland and semi-arid areas. The Aral Sea Basin and Mediterranean Basin are particular examples of such soil deteriorations. Intensive tillage and excessive use of synthetic fertilizers and pesticides are hallmarks of industrial agriculture. Tillage results in direct deterioration of soil structure by breaking soil aggregates, disturbing horizons, increasing erosion, and reducing water retention capacity. Soil tillage also causes breakdown of organic matter, resulting in reduced soil fertility [39]. The loss of soil structure from intensive tillage leads to increased runoff and erosion, especially in rainfall. Moreover, excessive use of synthetic nitrogen fertilizers and pesticides deteriorates soil quality through acidification and nutrient imbalance [40]. Acidification also releases toxic heavy metals into the soil. Likewise, the use of pesticides non-selectively damage microbial communities and soil thriving invertebrates which are both crucial to soil fertility. Pesticide residues can thrive in the soil for extended periods of time, resulting in damage to soil biodiversity. In addition, industrial development over time has also led to soil pollution with toxic contaminants. Industrial effluents often contain heavy metals such as Pb, Cd, and As which accumulate in soil and pose risks to plants, animals, and humans [41].

Forests play a critical role in reducing runoff and improving water infiltration. Thus, loss of vegetation covers to meet housing demands hampers groundwater recharge [42]. For instance, deforestation has significantly affected the Amazon rainforests in South America, where areas that were covered by dense forests have now become prone to erosion. Mato Grosso, Brazil, is a typical example demonstrating such ecosystem losses. The human activities in this region prioritizing cattle ranching and soybean production resulted in loss of forest covers and SOC stocks that led to leaching and erosion [43]. Likewise, cutting of palm and rubber plantations in Southeast Asian regions such as Indonesia and Malaysia has also resulted in soil deterioration [44].

The large-scale production of cattle to meet human needs results in overgrazing and loss of ground cover at a greater pace than natural recovery. Hence, overgrazing leads to soil exposure and compaction, making it prone to water and wind loss. Moreover, livestock trampling causes a reduction in soil porosity and increased bulk density that limits water availability, flow, infiltration and plant root growth penetration [45]. Overgrazing significantly impacts grasslands, savannas, and semi-arid rangelands. For instance, the Sahel region of Africa, the Mongolian Steppe in central Asia, and Nevada and Utah in the United States have been significantly impacted by overgrazing. The loss of grasslands brings about serious implications not only in the form of soil sustainability but also because of loss of biodiversity depending on such ecosystems [46].

The global decline in SOM because of anthropogenic activities has serious implications. The loss of topsoil and contamination of soil and water severely hinder rehabilitation efforts. The regions like Sahel, the Mediterranean Basin and the Amazon Basin demonstrate typical examples of consequences of mismanagement of limited resources available [47]. Therefore, coordinated and serious efforts to reverse losses to such ecosystems, restore SOM losses, and adoption of sustainable agricultural practices are urgently and direly required.

3. Soil Organic Matter: Dynamics and Importance

3.1. Components and Role of SOM in Soil Fertility and Nutrient Cycling

Soil organic matter is a chemically diverse and spatially variable biotic and abiotic aggregate of carbon-based compounds derived from the residues of plants and animals. SOM includes live microorganisms, wood roots, and leaves, barks and stems, all forms of dead plants, and animals [3]. SOM is primarily composed of humic substances and black C: humic substances are residues of biomass transformation of organic materials, including humic and fulvic acids [48]. The humic substances are essential components of soil fertility. Black C is made up of extra biogenic carbon by-products like soot, char, and charcoal originated from natural fires, burning of crop residues and fossil fuels [49]. The carbon component of SOM provides an energy substrate for microbial populations in the soil. It makes numerous biochemical transformations possible, such as soil C flux, the exchange of carbon between the soil and the atmosphere, and nitrogen fixation in the atmosphere into mineral forms. Similar to undecayed SOM, plant root tips and leaves are initially broken down by soil microbes during the early stages of soil organic carbon (SOC) formation into forms that facilitate plant growth [50].

3.2. Factors Influencing SOM Stability, Turnover, and Sequestration

The composition and source material of SOM determines its nutrient status, decomposition and chemical structure [51]. Other major factors that influence SOM dynamics include moisture content, temperature, and pH (Figure 1). Warmer environment promotes the growth of microorganisms and enzymatic activity. However, it reduces organic matter with the displacement of carbon, increasing the release of CO_2 [52–54].

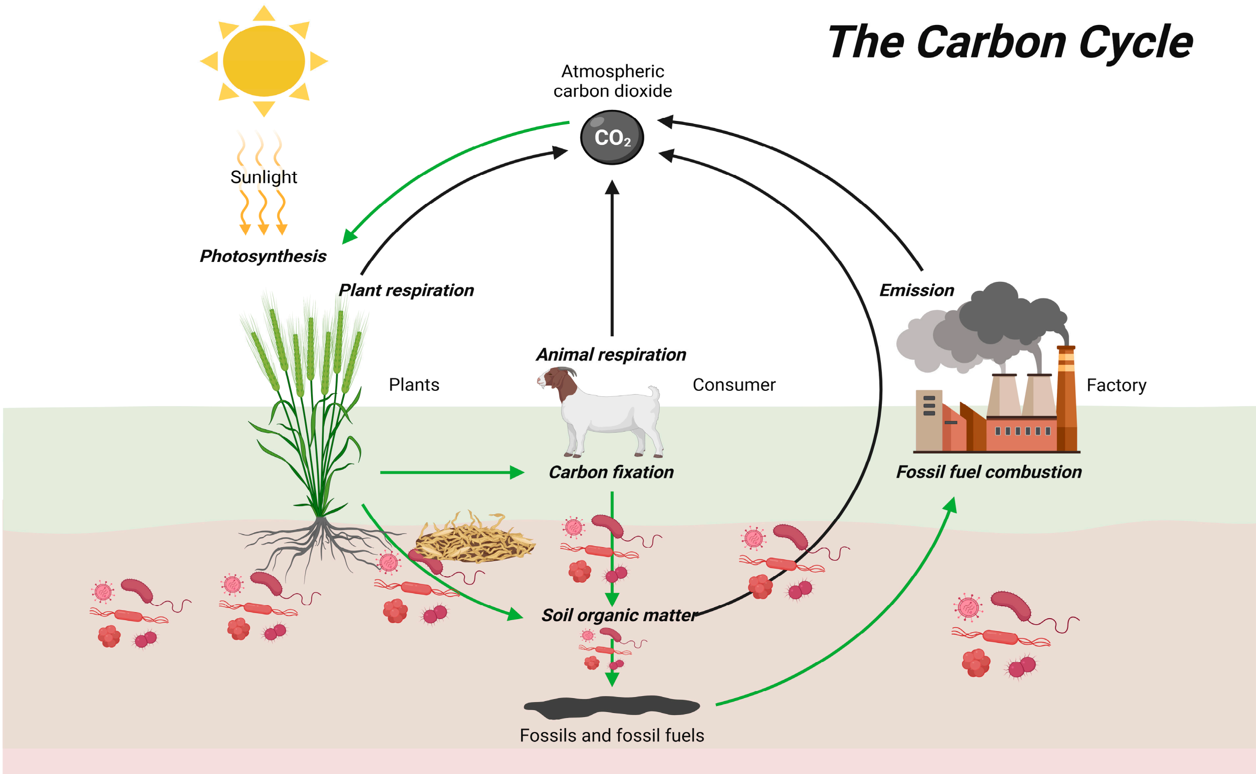

Figure 1. Carbon Dynamics in Soil. Plant or animal residues accumulation on soil leads to organic matter buildup. These organic materials are degraded by microbial decomposers that fix carbon in the soil and form humus. Soil organic carbon is used by other microbial communities to support metabolic activities in the soil living system. Created by author, in BioRender. Khan, M. (2024) https://BioRender.com/m23a751 (accessed on 28 November 2024).

Likewise, favorable water status increases microbial activities and enhances nutrient uptake and, hence, reduces oxygen limitations to organic matter decomposition compared to waterlogged or dried-up conditions. In addition, the pH of the soil is another important variable that controls SOM decomposition and carbon accumulation. It affects the interactions of microbial population dynamics; enzyme production and turnover; and the availability and distribution of the nutrients that determine the degradation and solidity of the soils' organic components [55].

4. Microbial Biomass Stabilization and Role in Soil Health

4.1. Soil Microbes: An Integral Part of Soil Ecosystem

Soil microbes form an essential, critical, and decisive factor in soil health determination. The microbial communities in the soil are fundamentally important to nutrient cycling, soil physical and chemical parameters, and carbon sequestration. For instance, *Clostridium* and *Azotobacter* spp. are typical examples that serve as free living nitrogen fixers and convert atmospheric nitrogen (N_2) to ammonia (NH_3). Ammonia is biologically available to plants and hence, the microbial species mentioned are important in making this crucial nutrient biologically available [56]. Moreover, *Rhizobium* and *Bradyrhizobium* also serve as nitrogen fixers. Furthermore, they form symbiotic relationships with plants, creating nodules which help plants absorb nitrogen. In addition, nitrifying bacteria (e.g., *Nitrosomonas* and *Nitrobacter*) transform ammonia into nitrate (NO_3^-). This conversion is carried out through intermediate production of nitrite (NO_2^-). These microbial activities are critically important in making nitrogen readily available for plant uptake. Other microbial communities in the soil, such as *Pseudomonas* and *Paracoccus* serve as denitrifying bacteria under anaerobic conditions and are involved in maintaining nitrogen balance in the soil [35].

Phosphorus is another important macronutrient essential for plant growth. It is often present in the soil in immobilized form as an insoluble mineral compound. In organic amendments, phosphorous is bound to organic compounds or mineral complexes. The interaction of SOM and microorganisms releases phosphorus for plant use [50]. Conversion of this unavailable phosphorus to biologically available forms is carried out through phosphate solubilizing bacteria (PSB) such as *Bacillus megaterium* and *Pseudomonas fluorescens*. These interactions result in the production of phosphate ions (PO_4^{3-}). Arbuscular mycorrhizal fungi (AMF) also play a crucial role in phosphorus absorption by plants by extending their roots far beyond into the soil to facilitate its uptake. In addition, *Penicillium* fungi secretes citric acid that lowers soil pH and dissolves mineral-bound phosphorous [57].

Carbon cycle is also carried out through microbial activities in the soil (Figure 2). Saprophytic fungi and bacteria, such as *Trichoderma* and *Bacillus subtilis*, are known for their role in decomposing organic molecules like cellulose and lignin. The resulting organic residues form the humus that plays a critical role in defining optimal soil structure and increasing its water retention as well as nutrient holding capacity [58]. Humic substances form the most stable fraction of soil organic matter. They work as a substrate and mediator in soil processes and support nutrient availability and plant growth. The humic substances are utilized by microbial communities as a carbon and energy source [59]. Extracellular enzymes such as ligninases, peroxidases, and cellulases, released by microbes degrade the recalcitrant aromatic and aliphatic structure of humus. Oxidoreductase enzymes of fungi *Trichoderma* and *Aspergillus* break down humic substances to release nutrients. Humic substances carry high cation and anion exchange capacity and thus serve as nutrient reservoirs and bind and release nutrients depending on microbial activities. Humic substances also bind metal ions like iron Fe^{2+}, Mg^{2+}, and Ca^{2+} and prevent their leaching off. For instance, *Pseudomonas* and *Bacillus* spp. release organic acids that interact with humic molecules enabling them to bind the mentioned ions [60].

Humus–phosphorous complexes also serve as a source of phosphorus. *Pseudomonas fluorescens* and *Bacillus megaterium* release phosphorous from humic substances by excreting citric and gluconic acids, that dissolve mineral-bound phosphorus. Microbial interaction with humic substances provides a steady supply of phosphorus. Additionally, humic substances provide nitrogen that is entrapped within their structure through ammonification and nitrification by interacting with *Nitrosomonas* and *Nitrobacter* spp. Humic substances also act as biostimulants and enhance plant growth [61]. Moreover, humic substances serve as signaling molecules for crosstalk between plants and microbial communities. Thus, humic substances are part of feedback interactions in the soil that are essentially manipulated by their interaction with microbial communities. Microorganisms also interact with humic substances for enhanced microbial resilience. Their hydrophilic nature and aggregate-forming capability provides microhabitats for microorganisms. Therefore, the presence of humic substances in the soil and its interaction with microbial communities play a critical role in determining soil health [62].

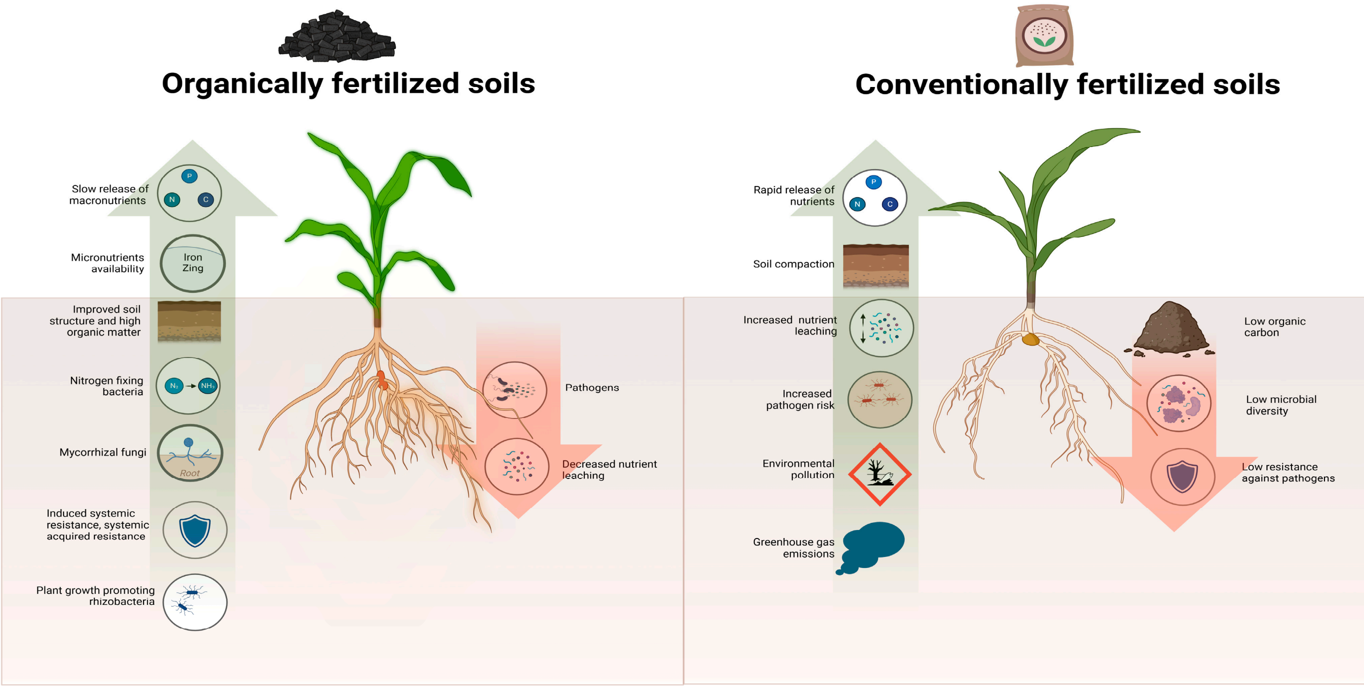

Figure 2. Comparison of organic and conventional fertilizers for soil fertilization. Organic fertilizers provide a sustainable and steady supply of nutrients. Moreover, they offer gradual but sustainable soil health improvement that exhibits resilience against extreme climatic events. Conventional fertilizers, on the other hand, result in nutrient leaching and degrade soil quality over time. Created by author, in BioRender. Khan, M. (2024) https://BioRender.com/m23a751 (accessed on 28 November 2024).

Pseudomonas fluorescens and *Bacillus subtilis* are recognized for the production of antimicrobial compounds, siderophores, and enzymes that hinder growth of pathogenic microorganisms and nematodes [63]. *Pseudomonas* spp. releases siderophores that trap iron, making it unavailable to pathogenic organisms. Likewise, *Trichoderma* fungi parasitize fungal pathogens by producing chitinase that can decompose fungal cell walls. Because of these characteristics, *Trichoderma* can act as a biocontrol agent against various fungal diseases. In addition to this, certain soil microorganisms also trigger induced systemic resistance in plants. Hence, soil microorganisms play a critical role in combating plant diseases and pathogens and SOM addition can improve these activities by supporting growth of such microbial communities [64].

4.2. Role of Microbial Biomass in Soil Health and Ecosystem Functioning

Soil microbial communities serve both as a reservoir and as the driver of nutrient cycling. Nitrogen-fixing bacteria such as *Rhizobium* species convert atmospheric nitrogen (N_2) into ammonia (NH_3), making it available to plants. Leguminous plants form symbiotic relationships with *Rhizobium* spp. for nitrogen uptake. Additionally, *Nitromonas* and *Nitrobacter* produce nitrate (NO_3^-) from ammonia [62]. Similarly, phosphorus (P) is unavailable to plants despite being present in the soil. The phosphate-solubilizing bacteria (PSB), such as *Pseudomonas* and *Bacillus*, solubilize insoluble inorganic phosphates or mineralize organic phosphate compounds into biologically accessible forms for plants. In addition, mycorrhizal fungi form symbiotic association with plants, increasing their penetration in the soil system to access nutrients and water. Mycorrhizal associations also increase crop resilience to environmental stresses [65]. Carbon cycling is also carried out by microbial communities in the soil. Microorganisms decompose dead plant and animal material, releasing CO_2, water, and other nutrients. For instance, cellulolytic fungi like *Trichoderma* play a major role in plant residue decomposition. Thus, microbial communities are crucial for carbon and nitrogen cycling and phosphorus availability to plants [66].

Microbial communities also thrive within plant tissues and assist in nutrient supply and disease resistance. *Azospirillum* spp. is a particular example in this regard that is involved in plant growth stimulation by improving nitrogen availability and producing plant hormones [64]. Moreover, soil microbial communities play an important part in disease suppression. The four most important mechanisms that such microorganisms use include competition with pathogens for nutrients and space, limiting the availability of such resources. Second, microbial species such as *Streptomyces* and *Actinomyces* produce antibiotics that target pathogenic microbes. Likewise, *Trichoderma* produces chitinases that decompose the cell wall of microbial pathogens. Finally, certain bacteria such as *Pseudomonas fluorescens* activate induced systemic resistance in plants to combat pathogens [67].

The total microbial composition in the soil is represented by SMB. It is considered a key indicator of soil health. The rate of nutrient transformation, nutrient availability, and the quantity and quality of soil organic input significantly influence SMB [68]. SMB also functions as both an accessible nutrient and a sink in relation to terrestrial bioresources. SMB comprises microbial biomass nitrogen (MBN), carbon (MBC) and phosphorus (MBP) [67].

MBN comprises potentially mineralizable nitrogen. Hence, it has a significant impact on nitrogen dynamics and bioavailability in plants [69]. The most labile soil carbon is MBC, which averages 1–4% of total organic carbon and rapidly alters in response to changes in C availability [70]. MBC determines the soil's capacity to store nutrients and energy. Consequently, MBP constitutes only 2–10% of TP in the soil, while it can be up to 50% in various P forms, in different soil horizons and its percentage can also depend on soil developmental stages [71].

Microbes can absorb inorganic phosphorus. They hinder inorganic phosphorus precipitation by physical and chemical attributes [72]. High SOM content is associated with an increase in SMB which presents a positive influence on the health of the soil ecosystem. Beyond nutrient cycling, SMB plays another essential role, viz., provision of extracellular polymeric substances (EPS) that bind soil particles, enhancing soil structure and aggregation [73] (Table 2).

Table 2. Functions of different EPS components.

EPS Component	Description	Function in Aggregate Formation	References
Polysaccharides	Sugars linked together into long chains	Form a gel-like matrix that encases soil particles and promotes adhesion	[73,74]
Proteins	Complex molecules containing amino acids	Act as bridges between soil particles and EPS polysaccharides	[75]
Humic-like substances	Similar to humic acids, but less decomposed	Contribute to binding and aggregation through electrostatic interactions	[76,77]

4.3. Microbial Amendments as Inoculants

The potential of different microbial species has also been explored as microbial inoculants. For instance, nitrogen-fixers (symbiotic *Rhizobium* and *Bradyrhizobium* or free-living *Azospirillum* and *Azotobacter*), phosphate solubilizers (*Bacillus megaterium* or *Penicillium*) can be used as microbial inoculants to enhance nitrogen and phosphate availability [78]. Other species of rhizobia, viz., *Azorhizobium*, *Mesorhizobium*, and *Sinorhizobium* form symbiotic relationships with different legumes [79]. These microbial species establish nodules in the plant roots and respond chemotactically to fix nitrogen for the plant.

Phosphate solubilizers increase phosphorus availability by solubilizing insoluble compounds. *Rhizobium*-based inoculants have particularly been used in recent studies to augment crop yields in legume crops [80]. The use of such inoculants can significantly reduce the requirements of synthetic fertilizers. Microbial inoculants can also be employed for their role in plant growth promotion. For instance, *Pseudomonas fluorescens* and *Bacillus subtilis* produce plant growth hormones, such as auxins, gibberellins, and cytokinins [81].

These hormones enhance plant growth, causing better root elongation, nutrient uptake and branching.

Microbial inoculants offer targeted solutions for certain specific nutrient deficiencies. Nevertheless, the effectiveness of microbial inoculants to achieve desired benefits varies widely depending on crop, soil conditions, climate, crop type, inoculant formulation, and carrier material [82]. On the other hand, organic fertilization offers a highly holistic, sustainable, cost-effective, readily available, and manageable approach to enhance soil health. These fertilizers enhance SOM content, provide a diverse array of nutrients, and support diverse microbial and faunal communities. These advantages make organic fertilization a unique and optimal option for long-term soil management and ecosystem resilience to harness a wide range of benefits for sustainable soil health improvement, agricultural productivity, and combat climate change on a larger scale.

4.4. Factors Influencing Microbial Biomass and Activity

Soil microbial biomass is significantly influenced by soil physical characteristics, climate, crop residues availability, organic and nutrient sources, and crops grown. SMB directly and positively relates with the amount of soil organic carbon and crop production in the area [83]. Moreover, moisture availability also influences SMB variations, making water availability an indirect factor determining plant productivity. However, these climatic effects are minimal at regional levels: properties such as SMB are more sensitive to the nature of the local soil or the specific plant community [57].

Other physical parameters such as soil depth, slope, textural class, and mineralogical groups also have predominant influence on microbial activities. Therefore, it becomes possible for some soils compared to others to support greater, more biodiverse, and more metabolically proactive SMB. A comprehensive investigation involving SMB analysis across 2150 sites identified that it is influenced by soil pH, texture, and SOM. In addition, SMB pools in the sites which received intensive agricultural activities such as horticulture, viticulture or arable cropping were significantly lower than those which did not [84]. Likewise, a French study with 278 sites elucidated that the microbial communities structure depends on the textural class of the soil [85].

Several soil physicochemical factors affect SMB and its activity. For example, a rise or decline in soil pH supports different microbial communities [86] and favors bacterial richness at various geographic scales [87]. Conversely, soils with acidic pH levels below 4.5 have been shown to negatively impact SMB while also affecting bacterial and fungal community composition. Notably, these effects are directly influenced by changes in pH and indirectly by other factors, such as the quantity and quality of organic matter inputs, crop productivity, nutrient availability, and the toxicity caused by high levels of aluminum (Al^{3+}) and other heavy metals [88].

5. Innovative Organic Fertilizers, Their Types, and Effects

5.1. Types of Innovative Organic Fertilizers

Biochar is an organic product of carbonation of various wastes like animal, food, industrial, and agricultural wastes, and forestry residues [26]. It is a stable carbon source with a high surface area and possesses promising physicochemical characteristics of absorbing nutrients like K, Ca, and NH_3 to enhance soil health. Further, biochar has excellent cation exchange capacity (CEC) that also facilitates nutrient retention [89]. Nutrient adsorption hinders their leaching and enhances soil fertility. Although biochar pH depends on the source material, it is often alkaline and can help increase soil pH serving as a valuable amendment in acidic soils. Its porous structure entraps waters and offers habitat for microbial populations that further assist in carbon sequestration and nutrient cycling [90]. Thus, it can play a vital role in increasing soil water retention and physical structure improvement.

Manure is one of the most popular organic materials that has been used for soil fertilization for decades. It is rich in organic matter, nutrients, and microbial content [20]. Manure promotes soil aggregate formation. This structural improvement in physical characteristics of soil is particularly important to hold soil particles together to reduce erosion under extreme climatic pressure [19]. Moreover, aggregation also enhances water retention. In addition, manure is a rich source of organic matter and nutrients such as N, P, and K that are vital for plant growth and development. Organic matter serves as a carbon source that increases growth of rhizobia in the soil, enhancing nitrogen fixation through their symbiotic relationship with legumes [91]. Also, manure helps balance soil pH, particularly in acidic soils [20].

Fermented grass, used as another popular source of organic fertilization, is produced through anaerobic fermentation and is a nutrient rich soil amendment [16]. It serves as a rapid source of nutrients as fermentation process already breaks down organic material present in it. Hence, the nutrients in fermented grass are readily available [22]. These nutrients can immediately support soil fertility and microbial growth. Fermented grass application also facilitates disease suppression in the soil and promotes a healthy soil environment. Moreover, it adds a good amount of organic material to the soil which improves its aggregation and reduces erosion and compaction.

Compost is also used as a promising strategy to enhance soil structure as an organic amendment. It is made from anaerobic decomposition of food waste, plant residues, agricultural waste, or animal manure [24]. Compost serves as a sponge-like material in the soil and absorbs and holds water, increasing moisture availability for longer times. It also provides a balanced amount of organic material to increase soil fertility. Moreover, it offers slow and steady release of macro and micronutrients for extended and sustainable fertilization. Biological origin compost enhances water-holding capacity of the soil and improves its texture [25]. Thus, the application of compost carries particular importance in water scarce areas. It is also rich in bacterial and fungal communities and actinomycetes, which are crucial to soil nutrient transformation [23].

In addition, vermicomposting employs earthworms to convert organic waste into nutrient-rich manure, enhancing microbial degradation processes [92]. The nutrient composition, particularly nitrogen (N), phosphorus (P), and potassium (K), is significantly higher in vermicompost compared to traditional compost, as noted by [93].

Likewise, cover crops cultivation leads to an increase in soil N levels by nitrogen fixation through symbiotic association with rhizobia, and carbon sequestration via photosynthesis, with organic carbon incorporated into the soil through plant biomass ultimately [94]. In addition, deep rooting cover crops also play a crucial role of accessing nutrients from the deeper layers of soil and then redistributing them to the upper layers [31]. They can either be cultivated as sole crops or be planted as intercrops within the cash crop fields. A study by Murphy [95] found that the soil connected to organic farming with winter cover crops had better pH, moisture, and dissolved C and N compared with conventional farming systems.

Biofertilization is another form of innovation in organic agriculture. It involves using beneficial microorganisms, for instance, mycorrhizal fungi and nitrogen fixers (Rhizobium). These microbes interact with crop plants and enhance nutrient uptake in soil either through solubilization of nutrients, increasing root area or enhancing nutrient cycling particularly N and P. In a comprehensive study conducted by Begum et al. [96], the authors found that crops grown with AMF were successful in withstanding adverse environmental factors including high salinity levels, low temperatures, nutrient unavailability, and abiotic stress conditions.

Additionally, mulching or conservation tillage facilitates crop residue retention on the soil surface. These residues have a high nutrient content and gradually decompose into the soil, releasing P, N, K, and other important macro and micronutrients that are readily available for plant use [31]. Hence, various sources of organic carbon can be used as fertilizers [28,29]. The challenge of balanced and sufficient supply of nutrients can be solved by using phytoextractors and phytoaccumulators. They can effectively close this gap as they can scavenge and store certain nutrients from the soil. Therefore, considering crop nutrient requirements, specific phytoaccumulators and phytoextractors can be utilized [97].

5.2. Benefits and Applications as a Sustainable Agricultural Practice

Organic fertilizers can play a paramount role in fostering sustainable agriculture. They enhance soil health and structure by increasing soil aggregation, water retention, and resilience to erosion and compaction [59]. Organic fertilizers bind soil particles together and form aggregates which are crucial for plant root penetration. Similarly, organic fertilizers increase the water retention capacity of the soil, which is critically important in water-scarce arid regions. Moreover, improvement in soil physical and structural parameters leads to better resilience to erosion and compaction [6]. In addition, organic amendments of soil increase biodiversity and microbial activity by promoting the growth of beneficial microorganisms by providing nutrients and a favorable environment. These improvements in microbial communities in the soil lead to the availability of mycorrhizal fungi and nitrogen-fixing bacteria, enhancing nutrient supply to plants and reducing the need for synthetic fertilizers. The increased presence of beneficial microbes in the soil also facilitates disease suppression [98].

Organic fertilizers reduce dependence of farming systems on synthetic fertilizers, which are a main source of water pollution and greenhouse gas (GHG) emissions. The use of organic fertilizers minimizes nutrient runoff, hazardous emissions, and soil acidification [6]. The slow and steady release from organic fertilizers offers sustainable nutrient supply. In addition, organic matter enhances the CEC of the soil which directly relates to the retention of essential nutrients and hinders their leaching and runoff [99]. Overall, organic fertilizers offer a healthier soil environment for plants and microorganisms [52].

Organic fertilizers also play a promising role in carbon sequestration. They are often derived from crop residues, food waste, and animal manure. Thus, they not only offer nutrient cycling but also reduce waste. In addition, organic fertilizers facilitate the growth of earthworms and nematodes, which form a vital component of soil health. These organisms improve soil structure by breaking down organic matter and improving aeration in the soil. Hence, organic fertilizers play a critical role in enhancing soil and environmental sustainability through multidimensional benefits and form a critical component of sustainable agriculture [100].

5.3. Mechanisms Underlying Effects of Organic Fertilizers on Soil

Compared to chemical fertilizers, numerous studies in the past have supported the benefits of organic fertilizers in enhancing the fertility of the soil and the growth of crops [6]. Three primary mechanisms of organic fertilization have been proposed to explain these improvements; namely, nutrient synchrony, the priming effects, and fertility enhancement. The nutrient synchrony mechanism indicates that organic fertilizers provide C energy for microbes. Moreover, slow decay leads to slow and consistent N fixation in the soil. As microbes decompose OM, this nitrogen becomes available to plants at the later stage of plant growth in a form that is usable by plants. This ensures that crops get the best value from the nutrients at optimal maturity, with almost negligible leaching losses [80]. Conversely, other authors have postulated that applying organic and mineral fertilizers simultaneously increases nutrient co-ordination, availability and plant utilization. The priming effect is an immediate alteration of the rates in nutrient cycling in the soil that arises from soil incorporation with labile OM. The nutrient content both in the soil and crops after the amendment period is higher than the initial soil nutrient content [101]. This additional nutrient content stems from the organic amendment through promoting the mineralization and dissolution of the hitherto 'fixed' nutrient content due to enhanced microbial biomass, variety, and activity. Furthermore, OM positively alters the physical characteristics of the soil. Thus, OM amendments enhance nutrient content as well as the physical structure of soils. As a result, crop nutrient uptake capacity, productivity and yield are improved [6].

Overall, organic fertilizers increase soil fertility and health and improve its structure by providing large amounts of C, increasing aggregation, improving water retention, and reducing bulk density [6]. Many of the organic fertilizers such as compost and manure exhibit sponge-like qualities that help in holding water in soil matrix. These properties enhance both water infiltration and retention. Likewise, biochar has a porous structure while manure exhibits a mix of fibers and organic compounds. These characteristics of organic fertilizers improve both soil physical and chemical properties [21]. Organic fertilizers are not only potential sources of macro and micronutrients, and promising physical characteristics but they are also rich in beneficial bacterial and fungal communities. These materials introduce promising microorganisms to the soil and support the growth of already prevailing beneficial communities. These microbial communities, particularly AMF, produce glomalin, a glycoprotein that acts as a glue to bind soil particles together, increasing soil porosity that reduces erosion. Organic fertilizers also increase the CEC of the soil and help retain K^+, Ca^{2+}, and Mg^{2+} ions. The CEC reduces leaching of nutrients, particularly in sandy soils where nutrient loss is a significant problem [100].

Organic amendments also bring about promising changes to the chemical properties of soils, such as pH. For instance, compost and manure have buffering capacity that can help stabilize soil pH and create an environment that facilitates microbial growth and nutrient availability. Finally, organic fertilizers contribute to carbon sequestration, serving as an effective resource for long-term carbon storage. Biochar, for instance, has a very stable structure and can resist microbial decomposition, serving as a slow-releasing carbon source. These chemical properties make organic fertilizers an excellent option for sustainable agriculture [59].

5.4. Comparative Analysis of Innovative Organic Fertilizers and Conventional Fertilization Methods

Agriculture in the last 50 years has become more dependent on non-renewable sources in the following ways: burning of fossil fuels in agriculture, the production and use of fertilizers and pesticides, mineral mining for K and P fertilizers, and the use of limited water resources. These costly inputs adversely affect environmental sustainability as well as crop production and food security [102]. Significant concerns have been raised about the impacts of these agriculture-related practices on the soils, microorganisms, diversity, crop yields, food quality, and resource efficiency, as indicated in Figure 2 [102,103].

Organic farming benefits the soil, biodiversity, and food quality as concluded from the various studies [102,103]. It has also been explicitly noticed that organic farming has lesser effects on global warming potential, terrestrial and aquatic toxicity, eutrophication, and acidification. This contrasts with conventional farming, where tremendous amounts of nitrogen and phosphorus are used unwisely. The conventional fertilizers are not only challenging resource efficiency but they also contribute food security issues and environmental toxicity [104].

6. Effects of Organic Fertilizers on Microbial Biomass, Diversity, and Activity

Various short-term and long-term experiments have been conducted to evaluate the soil function and health on SMB [36]. The concentration of C and N and C/N ratios are deemed important to determine SMB. Moreover, microbial growth and activity are increased under high C content. For instance, Li et al. [105] reported that MBC increased by about twofold under organic amendments compared to the control, in short-term experiments. Likewise, the C/N ratio of the SOM plays an important role in the rate of OM decay [106], because a substantial enhancement in the MBC and MBN was noted when the soil was supplemented with manure and crop residues. However, the crop residue with a high C/N ratio increased MBC and MBN more significantly compared to manure treatment in a short-term study [105]. High SOC content offers a higher SMB than soils with low SOC [105].

Studies indicate that long-term organic manure amendments are superior to short-term manure amendments in that they improve the exchangeable cations and, thus, the pH of the soil more than chemical fertilizers and treatments [50]. Organic manure amendments also enhance SOC and MBC. This enhancement can be explained by high organic C and MBC inputs and nutrient accumulation and high carbon addition by long-term organic manure treatment [107]. These studies also disclosed organic amendments to be more effective in increasing total soil N (TN), total soil P (TP), and total soil K (TK) than chemical fertilizers. In the same way, the inorganic fertilizer applied decreases the OM in the soil more than the organo-mineral amendment containing inorganic fertilizer with crop residues [108].

Furthermore, organic manure amendments have been observed to enhance the soil bacterial and fungal load, as highlighted by the shift in the microbial communities under long-term organic amendments [38]. Specific microbial operational taxonomic units reportedly associated with organic manure amendments include *Chytridiomycota, Aleuria aurantia, Cyanobacteria, Firmicutes*, and *Myxococcales* [109]. Such changes may affect the functionality of the soil, specifically with respect to certain types of microbes being favored, while others are reduced in number. Consequently, evidence suggests that organic amendments influence soil microbial number, biomass, and activity, including SMB, MBC, MBN, and dehydrogenase activity; by a greater extent than the conventional fertilizers [49].

Sabir et al. [50] analyzed the impact of conventional fertilization versus organic fertilization on microbial communities in soil and suggested that organic fertilization enhances the growth of heterotrophic microbes and increases organic carbon. On the contrary, inorganic fertilization causes soil acidity and changes soil osmolarity disturbing the taxonomic diversity of soil microbes. Azarbad [38] concluded that organic farming can be used to enhance soil microbial diversity, which can help attain improved soil resilience. In addition, the author also proposed that organic farming offers high organic matter and water holding capacity. Likewise, Dincă et al. [57] suggested that inorganic fertilizers cause changes in soil chemical properties that lead to OM losses and affect bacterial species abundance.

Wooliver et al. [49] investigated the association between crop diversification, microbial diversity, and SOC and observed that organic systems increase microbial diversity in contrast to conventional management that deteriorates it. They suggested that carbon storage and microbial diversity are positively associated with organic farming systems. Colautti et al. [40] compared soil microbiota between organically and conventionally fertilized soils. Armalytė et al. [110] studied microbial diversity using 16S rRNA gene sequencing under differently fertilized soils and reported shifts only in lower bacterial taxa between organic versus conventional farming systems.

Likewise, Peltoniemi et al. [98] investigated long term impact of organic and conventional fertilization on microbiota. They determined microbial abundance using bacterial 16S rRNA genes and the fungal ITS2 region using qPCR. Moreover, bacterial and AMF fungal community compositions were investigated using amplicon sequencing. The organic systems demonstrated higher microbial richness. The fungal abundance also implied microbial activity and C sequestration. The typical bacterial community representatives indicated lower diversity in conventionally fertilized soil. Furthermore, Amadou [52] reported that potential bacterial functions of both roots and above-ground plant tissues are influenced by organic or inorganic fertilization; and even type of fertilization in each category.

7. Diverse Plant Varieties and Their Implications for Soil Health

7.1. Importance of Crop Diversity for Soil Health, Ecosystem Resilience, and Nutrient Cycling

Soil health is related to the environmental viability of the farming system over time. Soil stability, in turn, concerns five distinct soil attributes: biodiversity, nutrient cycling, physical structure, water regulating capacity, and the filtration and buffering capacity against environmental challenges [111]. Implementing crop diversification can serve as a potential strategy to increase soil fertility and mitigate other agricultural challenges such as insect/pest and weed control. Their implementation with organic farming or cover cropping may result in more profitable and resilient farming systems [112].

Crop rotation increases yields and productivity while enhancing water and nutrient use efficiency. This, in turn, enhances the ability of the agroecosystem to resist agricultural threats, such as weed invasions, pests, and diseases, and helps the system recover quickly once these pressures are alleviated [113]. Furthermore, crop diversification contributes to increased carbon sequestration by enhancing the process of converting atmospheric CO_2 into carbon stored in plant biomass and soil [94].

It is worth noting that legume-based crop diversification also spears the use of external N fertilizers because legume crops are able to fix N_2 from the atmosphere and thrive in microbial communities that promote nutrient cycling, soil bioremediation, and health, and lessen anthropogenic impacts [94,114]. Baldwin-Kordick et al. [113] observed potential C and nutrients cycle improvement, better conservation, and their accessibility to plants in a 4-year study with composted cattle manure applied under a diversified cropping system ((maize–soybean–oat (*Avena sativa* L.) + alfalfa (*Medicago sativa* L.)–alfalfa). Studies using meta-analysis have also corroborated the role of soil macro and microflora in the soil nutrient availability [115]. Hence, these studies indicate attributes of crop diversification in the restoration of soil quality and sustainable environmental management.

7.2. Effects of Crop Diversification on SMB and SOM

Crop diversification improves SMB, microbial diversity, and community composition [116], which contribute to the better functional resilience of soil [117]. Hence, it serves as a protective and corrective measure in crop management to benefit soil fertility. Adding forages, pulses, oilseeds, multipurpose trees, and balanced organic and residue amendments increases and maintains the net accrual of SOC content. Pulses are an excellent source of biological nitrogen fixation. They also offer a deep rooting system enhancing the physical parameters of soil. Moreover, pulses can be grown as intercrops with cereals [118]. For example, a long-term investigation found a 6% enhancement of SOC and 85% of MBC over a cropping system of the rice–wheat–mung bean compared with the conventional rice-wheat cropping system [119].

In addition, intercropping of cowpea–berseem enhanced the amount of SOC and its rate of accumulation significantly than that observed with the conventional Guinea grass-based cropping system [118]. However, these strategies should be adopted with caution as crop diversification does not eliminate the impacts of potential diseases such as soil-borne diseases or pulse-specific pathogens which may elevate given the application of pulse crops in the cropping system [120]. Overall, the diversified crop rotation is useful to support the maintenance of agroecosystem species richness and prevent diseases and pest attacks (when used appropriately), improve soil quality and health, and enhance the production of crops [121].

The crop rotation strategy should be decided based on factors such as type of crops, the possible pattern of rotation series [59], the number of crops grown per year [122], and the characteristics of agricultural land [123]. For instance, some rotations can promote beneficial bacteria in soil populations, while decreasing pathogenic outbreaks by breaking the cycles of soil pathogens related to specific crops or crop cultivars. Baldwin-Kordick et al. [113], in a four-year experiment, observed 62% higher MBC and 80% higher MBN under the (maize–soybean–oat (*Avena sativa* L.) + alfalfa (*Medicago sativa* L.)–alfalfa) crop rotation system with livestock manure compared to two-year investigation under maize soybean rotation with synthetic N fertilizer.

Lastly, it has also been shown that cropping systems, by virtue of rotation, can control pests, weeds, and disease pathogens, by breaking the disease cycle [124]. Therefore, diverse crops with unique characteristics should be part of crop rotation to improve SOM, SOC, SMB, and crop productivity, while reducing crop diseases to improve overall soil quality and health [94].

7.3. Relationship Between Crop Rotation, Cover Crops, and Soil Health

Crop rotation in fallow times increases plant litter amount and diversity on the soil top [117]. This significantly changes SOM quantity and quality and helps raise and sustain SOC levels over the years. Several long-term studies found higher SOC and total N in complex crop rotation systems [125] due to better cycling of plant leftovers.

Using diverse plant types in crop rotation is deemed to release different root exudates and other substances into the rhizosphere, which changes soil nutrient content and availability for microbes [49]. The different root exudates facilitate the growth and development of variable microbial communities giving rise to diverse microbial environments in the soil. Microbial diversity, such as the presence of nitrogen fixing bacteria, mycorrhiza fungi, and efficient decomposers enhance fertility, nutrient cycling, and resilience against extreme climatic events. The microbial diversity also enhances soil aggregation by production of glycoproteins [58]. Crop rotation also facilitates growth of mycorrhizal fungi in the soil, which enhances porosity and density of soil and supports plant growth by providing them with a better, longer rooting system.

Legumes and brassicas efficiently and significantly enhance microbial diversity in the rhizosphere to create a microbial network that improves soil health [126]. Under these principles, rotation of a deep-rooted crop (e.g., alfalfa) with a shallow-rooted crop (e.g., wheat) can form a system in which the deep roots break up compacted soil forming macropores while shallow roots stabilize the surface soil. This rotation system can offer efficient aggregation and prevent compaction, especially in clay soils. Prior studies have strongly advocated for increasing crop diversity in rotation, as it enhances microbial diversity and, in turn, improves soil health. Growing cover crops helps to stabilize the structure of the soil, its water-holding capacity, ability to retain N and C, and the infiltration rate more than the cultivation of bare soils [127]. Furthermore, cover crops exudates aid in managing biotic crop stress factors such as pests, weeds, and other diseases from the soil [128].

Cover crops also significantly influence other soil characteristics. For instance, grass covers reduce soil nutrient content through nutrient uptake, while using legume covers provides the soil with nitrogen that they first capture from the atmosphere, meaning that the requirement of synthetic nitrogen can be reduced [124]. Likewise, brassica residues contribute to production of glucosinolates that exert anti-parasitic nematodes activity, serve as a buffer for the soil, and alter the physicochemical properties supporting better root penetration of the subsequent planted cash crops [129].

Crop diversification also enhances soil's ability to infiltrate and retain water. A combination of shallow and deep-rooted system crops can provide micropose with better water infiltration and reduced runoff. In this regard, maize cultivation with a deep-rooted crop like pigeon pea can offer a dual root system. The shallow roots of maize offer better surface oil porosity, while the deep roots of pigeon pea increase water infiltration across the soil profile [130]. Moreover, diversification with cover crops can offer a protective canopy that decreases soil erosion. The dense root systems of cover crops can hold the soil particles together preventing erosion by wind and water. In addition, cover crops cultivation can help in maintaining soil health indicators as well [131].

Graminaceous cover crops have also been shown to increase the subsequent cash crop production [132]. Legumes form efficient symbiotic relationships with rhizobia and AMF. This symbiotic association with fungi offers deep-rooted system to absorb water and nutrients for C and N cycling [133]. Hence, soybean, an excellent nitrogen fixer, can reduce the need for synthetic nitrogen fertilization for the subsequent growth of high nitrogen demand crops such as maize [134]. Similarly, deep-rooted crops such as sunflowers can mine phosphorus from lower layers of soil and make it available for shallow-rooted crops [135] to be grown in the next cycle (for instance, lettuce).

Crop rotation also interrupts pest and disease cycles by the unavailability of their plant hosts. For instance, Paudel et al. [136] reported that sorghum/sorghum–sudangrass cover crops cultivation not only increased soil moisture, microbial biomass, and other fertility parameters but also suppressed the infestation of plant-parasitic nematodes in the cropping system. Moreover, Mushtaq et al. [137] also proposed that parasitic nematodes can be managed using antagonistic plant diversity.

Hence, crop diversification and rotation bring about various promising changes to soil health that increase nutrient availability, fertility, soil chemical and physical parameters, and disease mitigation. Overall, appropriate cover cropping systems can improve soil health to mitigate the impact of climate change and can assist in controlling soil-borne diseases [138].

8. Synergistic Effects and Field Applications of Organic Fertilizers and Crop Diversification

8.1. Impact of Interactions Between Organic Fertilizers and Plant Diversification on Soil Health

The disastrous and permanent outcomes of synthetic fertilizers on soil health are alarming and demand sustainable agricultural development [139] in a way that can fulfill the needs of the growing human population without degrading the quality and fertility of the soil for next generations [140,141]. Studies have demonstrated that organic farming can mitigate the negative consequences caused by chemical fertilizers [142,143]. Organic farming, which is hailed as a sustainable agricultural practice, can increase income from cash crops without adversely affecting soil fertility [122,144].

Organic fertilizers offer multifaceted benefits to agroecosystems by providing macro and micronutrients, controlling soil erosion and affecting the composition and diversity of soil microbial communities [145]. Crop rotation and cover cropping practices are strongly related to organic fertilization [146,147]. Organic fertilizers, such as green manure, for example, have been proven to contribute primarily to an increase in SOM [148]; thus, cover cropping or intercropping can improve soil fertility and biodiversity. The application of leguminous cover crops and organic N sources together allows greater conversion of atmospheric N and CO_2 into plant-available N and C through nitrogen fixation performed by the soil microbes associated with these crops. Diversity in plant use in crop rotation also helps curb the growth of harmful pests, pathogens, and weed species, protects cash crop yields and productivity, increases soil nutrient content availability [79], and improves soil health characteristics as well as fertility [149–151].

8.2. Field and Case Studies Demonstrating the Impact of Organic Fertilizers and Crop Diversification

Environmental conservation and sustainability are equally vital to food production and high yield. It is critical to shift current monocultural cropping and chemical fertilization methods to diversified crop rotations and organic fertilization approaches for agricultural and environmental conservation. This improvement is especially noted when more than three years of crop rotations are accompanied by slurry and manure fertilizer applications [152]. De Roest et al. [153] pointed out that apart from sustainability and food security, crop diversification also enhances the economic benefits. Similar observations were recorded by Scherer et al. [154] as well.

Francaviglia et al. [152] explored the effect of both crop diversification and the use of organic fertilization on arable crops and noticed that unlike chemical fertilization that involved tilling in conventional farming, either diverse crop rotation of autumn–winter cereals/fodder grains or spring–summer cereals/fodder grains led to a 12% increased production compared to synthetic farming. Likewise, using organic fertilizers like slurries, crop residues, or mulch increased crop yields by 40%, 39%, and 74%, respectively [152]. Another study established that a maize–soybean–oats rotation scheme with alfalfa for four years and cattle manure as an organic amendment decreased the soil root growth resistance by 8%, enhanced the CEC by 16%, increased the microbial biomass by 62%, and enhanced the value of salt-extractable soil carbon by 157%. With better soil health, farming became less dependent on inputs, grew higher-yielding crops, incurred lesser environmental impacts, and became more profitable [113].

Nascimento et al. [155] investigated the crop performance of wheat under a three-year crop diversity program of canola–pea–wheat and a cereal crops rotation program of barley–triticale–wheat with either organic nutrition from anaerobic digestate or inorganic fertilizer. The outcome of the study revealed that diversification of crop rotation enhanced the yield of wheat by 1.79 t ha^{-1}, improved N uptake through better availability of high N content preceding the growth of pea and enhanced the water use efficiency. Similarly, the fields with crop rotation and digestate also had relatively higher nitrogen content in the form of nitrate compared to the fields that applied mineral fertilizers [155].

These field-level studies indicate the need to employ crop rotations, particularly for long-term, and the use of organic amendments, to improve the yield and productivity of crops. This approach can contribute to the decrease in the use of mineral fertilizers, the reduction in the negative impact on the environment, as well as the increase in SOC, SOM, SMB, and the overall quality of soil [113].

9. Significance of Soil Health: A Larger Perspective Beyond Agriculture

Soil is an integral part of ecosystem resilience against climatic extremes including drought, temperature fluctuations, and floods. Healthy soils with high organic matter content, diverse microbial communities, and promising physical parameters can buffer against such environmental extremes [156]. Soil is one of the largest carbon reservoirs on earth. The organic matter of the soil contains carbon derived from plant residues, microbial biomass, and root exudates. This carbon is stored within the soil for centuries after the decomposition of organic matter. The carbon stored in the soil reduces the amount of CO_2 in the atmosphere. Soil organic carbon serves as an energy source for microbial communities, improves soil structure, and regulates the availability of nutrients [49].

The microorganisms in the soil in turn enhance nutrient availability and carbon sequestration from the environment into the soil. Thus, healthy soils improve the environmental sustainability and help in climate change mitigation [157]. All these roles of soil as an integral part of agroecosystems are also essential for hosting biodiversity in terms of microbial populations, plants, fungi, and earthworms. Biodiversity is critical to maintain soil and ecosystem health and food chain. The biodiversity of life forms in the soil enhances resilience to pests and diseases and offers sustainable resource utilization by providing promising physical properties to the soil [158]. Healthy soil also offers balanced nutrient availability through natural activities, without the application of synthetic contaminants.

Healthy soils containing high amounts of organic matter exhibit good water holding capacity which is an important parameter in water scarce regions. They have good infiltration capacity and thus serve as a source of moisture preventing runoff. Healthy soils also serve as natural filters to remove contaminants, pesticides, and other hazardous chemicals from excess water. Soil particles and organic matter entrap these chemicals from the surface runoff and hinder their movement to groundwater and other water bodies [159]. Furthermore, microbes thriving in the soil detoxify hazardous industrial effluents through their metabolic activities.

10. Environmental Trade-Offs of Organic Versus Conventional Fertilizers

Soil fertilization is a prime component of modern agriculture. Nevertheless, fertilization practices come at the cost of environmental impacts, particularly GHG emissions. The environmental footprints of fertilization practices vary significantly [160]. Exploring these trade-offs is critical for evaluating available fertilization options.

Organic fertilization makes use of natural resources to enhance soil fertility and therefore is of utmost importance for sustainable agriculture with limited environmental outcomes [52]. Contrarily, conventional fertilizers are synthesized chemically. They immediately release nutrients and may result in leaching and runoff. For instance, nitrogen fertilizers synthesis is carried out through the Haber–Bosch process; a highly energy-intensive method that relies on fossil fuels [161]. Hence, production of these fertilizers results in a significant amount of CO_2 emissions. Around 5% of the global GHG emissions is attributed to the production and use of these fertilizers [162]. In addition, synthetic nitrogen fertilizers release nitrogen at a higher rate, resulting in higher N_2O emissions because of leaching and volatilization as the release exceeds plant uptake. The use of conventional fertilizers is also often associated with frequent tillage, which enhances SOM decomposition and releases stored carbon [38].

Organic fertilizers, on the other hand, generally release nitrogen slowly on decomposition and thus, the risk of oversaturation and emission is lower. Still, proper application and management is required in the case of organic fertilizers as well [21]. The processing and transporting of organic materials causes emissions, if not managed locally. Moreover, manure application in waterlogged soils may result in N_2O emissions; but even in such cases, this release is generally localized and small. Compositing before application of these fertilizers can further help reduce the chances of such outcomes [163].

Conventional fertilizers do not directly result in methane emissions; however, their application in monocropping systems may cause indirect release of CH_4, especially in rice paddies [11]. Organic fertilizers need to be produced under regulated and well-managed conditions to ensure proper composting. However, organic fertilization has a promising advantage of carbon sequestration. This benefit gives organic fertilizers a unique edge as a sustainable and feasible agricultural practice [101].

Conventional fertilizers also generally offer higher yields per unit area. Therefore, emissions per unit of crop output need to be compared between organic versus inorganic fertilizers. Nevertheless, organic systems enhance soil health by augmenting microbial activity and diversity, SOM content, and carbon sequestration and result in long-term soil health improvement and sustainable climate resilience [39]. Conventional systems, on the contrary, often deteriorate soil organic matter, fertility, and biological diversity, resulting in lower resilience to climate stresses.

11. Challenges and Limitations

Organic fertilization also faces several challenges and limitations. Improving microbial biomass through organic fertilization is critical to ensure optimal nutrient cycling [164]. However, efficiency of organic interventions substantially varies among different ecosystems. For instance, high temperatures and low moisture in arid and semi-arid aeras offers a challenge to microbial activity and biomass stabilization [165]. Under such conditions, OM decomposition slows down, and it becomes challenging to achieve a robust soil microbial population. Moreover, sandy soils also offer such limitations because of low water retention and nutrient-holding capacity. Such environments hinder microbial growth and may necessitate frequent re-application of the amendments [166]. In addition, acidic soils deteriorate microbial growth because of low pH, while saline soils introduce such challenges because of osmotic stress on microbial cells. Hence, profiling of the target environmental conditions is important, and organic amendments need to be applied accordingly. Climate-specific management practices and localized strategies may be required to attain better efficiency of such applications [167].

From farmers' perspectives, they are generally reluctant to adopt organic measures due to the possibility of a decline in the yield and productivity of crops and the cost of machinery necessary for organic farming and crop diversification [152]. The lack of capital investments, human resources, machinery, and R&D are also major challenges in this regard [168,169]. Including other crops in crop rotation also presents economic challenges and risks to farmers. Another reason contributing to the low adoptability of crop rotation and organic fertilization is the fact that most farmers are tenant farmers; they do not actually own the farmlands they cultivate and hence cannot invest in long-term soil health and fertility improvement [170]. The inability of farmers to implement these practices successfully and the deficit of technological support from policymakers and other stakeholders are also significant challenges [171].

Hence, poor knowledge, lack of funds, low interest in long-term soil improvement, and inadequate human resources are perceived as major challenges that hinder farmers from practicing sustainable agricultural techniques [172]. Likewise, lenders are also mostly unaware of the potential of sustainable and long-term cropping systems economically and are often reluctant to expend funds for such purposes. Moreover, the absence of market opportunities in a diverse range of agricultural produce and high dependence on government policies supporting major crops dampens the farmers' confidence and hinders them from embracing crop diversification initiatives [169,173].

In addition, organic fertilization is particularly challenging in areas with limited access to organic inputs and knowledge about diversified cropping systems and their benefits. Unavailability of infrastructure and limited access to organic fertilizers and economic resources makes their adoption difficult in such regions [174]. For instance, livestock densities in arid and semi-arid regions are often low. In such regions, the availability of manure in enough quantities may be too low for such applications [175]. Additionally, farmers in resource-scarce regions, such as Sub-Saharan Africa or South Asia may have limited access to high-quality compost or biochar. Moreover, organic fertilizers require higher transportation costs as they are less dense in nature, making them less fit for use by small farmers. Finally, the production of organic fertilizers is labor- and time-intensive and requires basic knowledge of operations [176].

Organic fertilizers also provide an inconsistent supply of nutrients. Furthermore, nutrient release in arid and semi-arid regions may be very slow and thus the efficacy of organic fertilizers falls off. Organic fertilization may be less effective in saline or acidic soils. Additionally, it also requires technical knowledge which may not always be available to farmers in under-privileged regions [177]. Establishing biochar kilns, cover cropping systems, or composting facilities require investments, which may be unavailable to small farmers. Organic fertilization also needs to be managed properly, or it can result in GHG emissions, particularly under anaerobic conditions [174].

In addition to the mentioned obstacles, geographical impediments like limited marketing infrastructure for different crops, unfavorable climate, technological transitional problems, institutional and socioeconomic factors such as non-consolidation of land ownership and group farming models are the main issues which hinder crop diversification on larger scales [169,178,179]. To summarize, the main challenges to adopting organic farming in agricultural lands include slow production and low crop yield concerns, shortages of certified organic inputs, and technical limitations [180,181]. Hence, appropriate capacity building, policy support, and technology development are necessary for making use of organic fertilization on large scales.

12. Future Directions for Research and Practical Implications

There are considerable gaps in the current knowledge on the practical implications of organic farming. Extensive socioeconomic analyses are required to evaluate the effect of crop diversification and organic farming on the income of rural communities for poverty alleviation. Comprehensive data on economic outcomes are critical to incline policymakers and average farmers towards organic fertilizers and crop diversification [182,183]. Additionally, the impacts of inter- and intra-season crop rotations on soil fertility, nutrients, and moisture need to be explored considering the multifaceted aspects involved.

There is also a need to explore the relationships between organic practices and their impact on increasing SOC, SMB, and promoting agroecosystem health and sustainability. Particularly, the interaction of diversified crops and various types of organic amendments needs to be investigated under different climatic conditions. It is also critical to explore organic fertilization in relation to nutrient leaching, pest or weed establishment, and soil-borne pathogens inhibition [184].

In addition, the social implications of crop diversification and organic farming should also be investigated in detail [185]. Moreover, composting processes for optimal production of organic fertilizers need to be established. Methods of converting organic sources to high-quality fertilizers need to be optimized, while new organic materials need to be explored for wider availability of organic fertilization. Also, organic fertilizers' fortification with nutrient-dense additives needs dire attention. There is also a need to develop precision and predictive models for optimal in-field analysis of organic fertilizers [26]. Finally, the environmental impact of organic fertilization should be established under different climatic conditions and region-specific fertilization strategies should be developed.

13. Conclusions

This comprehensive review underscores the critical role of organic agricultural strategies in improving soil health, sustainable nutrient cycling, and mitigation of climate change. Organic systems make use of natural interactions between soil, plant, and microorganisms to ensure ecosystem resilience for sustainable agricultural development and productivity. The use of organic fertilizers and crop diversification are potential organic agricultural practices that can enhance crop productivity and carbon sequestration, while limiting the use of chemical inputs in the farming systems at the same time. Thus, organic farming can help reduce GHG emissions and decrease the use of synthetic fertilizers, diminishing the energy footprint of farming operations. Organic fertilizers provide a slow, steady, and long-term supply of macro- and micronutrients for recycling natural resources. Hence, organic fertilization helps increase SOM, SOC, and SMB content in the soil and thrives beneficial microbes that fix N, solubilize P, and mobilize nutrients. It provides multifaceted benefits to soil fertility and crop development by acting not only as a source of micro- and macronutrients but also improving chemical and physical characteristics of the soil, reducing runoff. Moreover, incorporating cover crops and crop diversification in an agriculture system may help enhance atmospheric nitrogen fixation, carbon sequestration, and phosphate solubilization by interacting with soil microbes. In addition to this, crop diversification breaks disease cycles and enhances soil porosity, aggregate formation, and water infiltration and retention. It also helps preserve biodiversity by creating diverse habitats for beneficial organisms and reducing the need for chemical pesticides. Hence, combinatorial use of organic fertilizers, crop rotation, and crop diversification can serve as an excellent strategy for sustainable agriculture, organic farming, reduction in methane and nitrous oxide emissions, mitigation of climate change, and even reversal of soil degradation. These broad and long-term environmental advantages highlight the transformative potential of organic agricultural practices. Therefore, organic fertilization and crop diversification have serious implications for agricultural and environmental policies to combat soil deterioration, food security, and climate change. Nevertheless, widespread adoption of these sustainable strategies in the field is met by several challenges such as socioeconomic aspects and farmers' cost and benefit ratio in the short versus the long term. There is also a lack of comprehensive data on interaction of SOM and different microbial populations under varying environments such as arid versus tropic regions. Future studies should focus on establishing long-term, field-scale experiments under varying climatic conditions to evaluate the influence of organic inputs. A knowledge gap also exists in certain conditions under which high-nitrogen organic fertilizers may exacerbate nitrous oxide when mismanaged. Determining rotational strategies, region-specific crop combinations, and amendments that diminish environmental trade-offs are crucial for large-scale applications. Furthermore, new sources of organic materials such as algae-based fertilizers warrant detailed exploration. More research and technological developments can help address these limitations and assist in environmental safety, food security, and sustainable use of land resources for the generations to come.

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References

1. Tahat, M.M.; Alananbeh, K.M.; Othman, Y.A.; Leskovar, D.I. Soil Health and Sustainable Agriculture. *Sustainability* **2020**, *12*, 4859. [CrossRef]
2. Lehmann, J.; Bossio, D.A.; Kögel-Knabner, I.; Rillig, M.C. The concept and future prospects of soil health. *Nat. Rev. Earth Environ.* **2020**, *1*, 544–553. [CrossRef] [PubMed]
3. Sokol, N.W.; Kuebbing, S.E.; Karlsen-Ayala, E.; Bradford, M.A. Evidence for the primacy of living root inputs, not root or shoot litter, in forming soil organic carbon. *New Phytol.* **2019**, *221*, 233–246. [CrossRef]
4. Carvalho, M.L.; Maciel, V.F.; Bordonal, R.D.; Carvalho, J.L.; Ferreira, T.O.; Cerri, C.E.; Cherubin, M.R. Stabilization of organic matter in soils: Drivers, mechanisms, and analytical tools—A literature review. *Rev. Bras. Ciência Solo* **2023**, *47*, e0230130. [CrossRef]
5. Lal, R. Soil organic matter content and crop yield. *J. Soil. Water Conserv.* **2020**, *75*, 27A–32A. [CrossRef]
6. Brempong, M.B.; Addo-Danso, A. Improving Soil Fertility with Organic Fertilizers. In *New Generation of Organic Fertilizers*; Turan, M., Yildirim, E., Eds.; BoD—Books on Demand: London, UK, 2022; pp. 1–11, ISBN 978-1-83969-212-3.
7. Gayan, A.; Borah, P.; Nath, D.; Kataki, R. Soil microbial diversity, soil health and agricultural sustainability. In *Sustainable Agriculture and the Environment*; Farooq, M., Gogoi, N., Pisante, M., Eds.; Academic Press: Cambridge, MA, USA, 2023; Chapter 4; pp. 107–126, ISBN 978-0-323-90500-8.
8. Gondal, A.H.; Hussain, I.; Ijaz, A.B.; Zafar, A.; Ch, B.I.; Zafar, H.; Sohail, M.D.; Niazi, H.; Touseef, M.; Khan, A.A. Influence of soil pH and microbes on mineral solubility and plant nutrition: A review. *Int. J. Agric. Biol. Sci.* **2021**, *5*, 71–81.
9. Kumar, A.; Ram, H.; Kumar, S.; Kumar, R.; Yadav, A.; Gairola, A.; Kumar, V.; Sharma, T. A comprehensive review of nano-urea vs. conventional urea. *Int. J. Plant Soil. Sci.* **2023**, *35*, 32–40. [CrossRef]
10. Duan, Q.; Jiang, S.; Chen, F.; Li, Z.; Ma, L.; Song, Y.; Yu, X.; Chen, Y.; Liu, H.; Yu, L. Fabrication, evaluation methodologies and models of slow-release fertilizers: A review. *Ind. Crops Prod.* **2023**, *192*, 116075. [CrossRef]
11. Ashitha, A.; Rakhimol, K.; Mathew, J. Fate of the conventional fertilizers in environment. In *Controlled Release Fertilizers for Sustainable Agriculture*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 25–39.
12. Chandini; Kumar, R.; Kumar, R.; Prakash, O. The Impact of Chemical Fertilizers on our Environment and Ecosystem. In *Research Trends in Environmental Sciences*; AkiNik Publications: New Delhi, India, 2019; Chapter 5; pp. 69–86, ISBN 978-93-5335-062-8.
13. Jote, C.A. The impacts of using inorganic chemical fertilizers on the environment and human health. *Org. Med. Chem. Int. J.* **2023**, *13*, 555864.
14. Pahalvi, H.N.; Rafiya, L.; Rashid, S.; Nisar, B.; Kamili, A.N. Chemical fertilizers and their impact on soil health. In *Microbiota and Biofertilizers*; Ecofriendly Tools for Reclamation of Degraded Soil Environs; Springer: Cham, Switzerland, 2021; Volume 2, pp. 1–20.
15. Assefa, S.; Tadesse, S. The Principal Role of Organic Fertilizer on Soil Properties and Agricultural Productivity—A Review. *Agric. Res. Technol. Open Access J.* **2019**, *22*, 1–5. [CrossRef]
16. Wang, D.; Li, S.; Sun, X.; Hao, D.; Li, Y.; Wang, H. Effects of Compost Application of Green Waste on Soil Properties: A Meta-Analysis. *Sustainability* **2024**, *16*, 8877. [CrossRef]
17. Lin, W.; Lin, M.; Zhou, H.; Wu, H.; Li, Z.; Lin, W. The effects of chemical and organic fertilizer usage on rhizosphere soil in tea orchards. *PLoS ONE* **2019**, *14*, e0217018. [CrossRef] [PubMed]
18. Šiaudinis, G.; Karčauskienė, D.; Aleinikovienė, J.; Repšienė, R.; Skuodienė, R. The effect of mineral and organic fertilization on common osier (*Salix viminalis* L.) productivity and qualitative parameters of naturally acidic Retisol. *Agriculture* **2021**, *11*, 42. [CrossRef]
19. Liu, S.; Wang, J.; Pu, S.; Blagodatskaya, E.; Kuzyakov, Y.; Razavi, B.S. Impact of manure on soil biochemical properties: A global synthesis. *Sci. Total Environ.* **2020**, *745*, 141003. [CrossRef]
20. Rayne, N.; Aula, L. Livestock manure and the impacts on soil health: A review. *Soil Syst.* **2020**, *4*, 64. [CrossRef]
21. Verma, S.; Pradhan, S.S.; Singh, A.; Kushuwaha, M. Effect of Organic Manure on Different Soil Properties: A Review. *Int. J. Plant Soil Sci.* **2024**, *36*, 182–187. [CrossRef]
22. Sharma, A.; Soni, R.; Soni, S.K. From waste to wealth: Exploring modern composting innovations and compost valorization. *J. Mater. Cycles Waste Manag.* **2024**, *26*, 20–48. [CrossRef]
23. Jakubus, M. A comparative study of composts prepared from various organic wastes based on biological and chemical parameters. *Agronomy* **2020**, *10*, 869. [CrossRef]
24. Policastro, G.; Cesaro, A. Composting of organic solid waste of municipal origin: The role of research in enhancing its sustainability. *Int. J. Environ. Res. Public Health* **2022**, *20*, 312. [CrossRef]
25. Wong, C.T.; Falcone, M.; Rich, G.; Stubler, C.; Malama, B.; Lazcano, C.; Decock, C. Short-term effects of increasing compost application rates on soil C and greenhouse gas (N2O and CO2) emissions in a California central coast vineyard. *Front. Environ. Sci.* **2023**, *11*, 1123510. [CrossRef]
26. Gamage, A.; Gangahagedara, R.; Gamage, J.; Jayasinghe, N.; Kodikara, N.; Suraweera, P.; Merah, O. Role of organic farming for achieving sustainability in agriculture. *Farming Syst.* **2023**, *1*, 100005. [CrossRef]
27. Kukreti, A.; Kurmanchali, N.; Rawat, L. Organic Farming and Biochar. In *Trends in Agriculture: Traditional and Modern Approaches*; Agrobios Research: Jodhpur, India, 2021; pp. 141–153, ISBN 978-81-949237-9-4.

28. Zhang, Z.; Dong, X.; Wang, S.; Pu, X. Benefits of organic manure combined with biochar amendments to cotton root growth and yield under continuous cropping systems in Xinjiang, China. *Sci. Rep.* **2020**, *10*, 4718. [CrossRef] [PubMed]
29. Gamage, A.; Basnayake, B.; De Costa, J.; Merah, O. Effects of Rice Husk Biochar Coated Urea and Anaerobically Digested Rice Straw Compost on the Soil Fertility, and Cyclic Effect of Phosphorus. *Plants* **2021**, *11*, 75. [CrossRef] [PubMed]
30. Agu, O.S.; Tabil, L.G.; Mupondwa, E.; Emadi, B.; Dumonceaux, T. Impact of Biochar Addition in Microwave Torrefaction of Camelina Straw and Switchgrass for Biofuel Production. *Fuels* **2022**, *3*, 588–606. [CrossRef]
31. Parida, P.K.; Sahoo, C.; Jakkampudi, S.; Deb, A. Innovations in Organic Farming System. In *Recent Trends in Agriculture*; Chhangani, G., Yadav, T., Sahoo, S., Sharma, S., Sannidi, S., Eds.; Integrated Publications: Delhi, India, 2023; Volume 8, pp. 109–130, ISBN 978-93-5834-009-9.
32. Feiza, V.; Šlepetienė, A.; Feizienė, D.; Liaudanskienė, I.; Deveikytė, I.; Pranaitienė, S.; Gaurilčikaitė, R.; Amalevičiūtė-Volungė, K.; Veršulienė, A.; Bunevičiūtė, L. Fertility and Sustainability of Morainic Soils: Now Days Challenge. 2022. Available online: https://hdl.handle.net/20.500.12259/241181 (accessed on 15 October 2024).
33. Muraškienė, M.; Armolaitis, K.; Varnagirytė-Kabašinskienė, I.; Baliuckas, V.; Aleinikovienė, J. Evaluation of soil organic carbon stability in different land uses in Lithuania. *Sustainability* **2023**, *15*, 16042. [CrossRef]
34. Aleinikovienė, J.; Butkevičienė, L.M.; Jakutis, A.; Bogužas, V. Complex of soil tillage, organic and biological fertilization for improving soil microbial activity and nitrogen transformation efficiency in intensive cropping on calcaric luvisols. In Proceedings of the AgroEco 2020: 3rd International Scientific Virtual Conference: Agroecosystem Sustainability: Links Between Carbon Sequestration in Soils, Food Security and Climate Change, Kaunas, Lithuania, 2–3 December 2020; [Akademija]. Vytautas Magnus University, Agriculture Academy: Kaunas, Lithuania, 2020.
35. Muraškienė, M.; Aleinikovienė, J.; Skuodienė, R.; Tomchuk, D. Soil respiration and microbial biomass peculiarities as influenced by different land use intensity. *Zemdirb. Agric.* **2020**, *107*, 3–10. [CrossRef]
36. Giedrius, Ž.; Vaida, S.; Jūratė, A.; Vaclovas, B. Long-term effects of tillage, crop residues, and intercropping combination on soil health. In Proceedings of the Agroecosystem Sustainability: Links Between Carbon Sequestration in Soils, Food Security and Climate Change: 5th International Scientific Conference AgroEco2024: Programme and Abstracts, Kaunas, Lithuania, 16–18 October 2024; Volume 5, p. 33.
37. Vaitkevičienė, N.; Jarienė, E.; Kulaitienė, J.; Danillčenko, H.; Černiauskienė, J.; Aleinikovienė, J.; Średnicka-Tober, D.; Rembiałkowska, E. Influence of agricultural management practices on the soil properties and mineral composition of potato tubers with different colored flesh. *Sustainability* **2020**, *12*, 9103. [CrossRef]
38. Azarbad, H. Conventional vs. organic agriculture–which one promotes better yields and microbial resilience in rapidly changing climates? *Front. Microbiol.* **2022**, *13*, 903500. [CrossRef] [PubMed]
39. Chenu, C.; Angers, D.A.; Barré, P.; Derrien, D.; Arrouays, D.; Balesdent, J. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil. Tillage Res.* **2019**, *188*, 41–52. [CrossRef]
40. Colautti, A.; Civilini, M.; Contin, M.; Celotti, E.; Iacumin, L. Organic vs. conventional: Impact of cultivation treatments on the soil microbiota in the vineyard. *Front. Microbiol.* **2023**, *14*, 1242267. [CrossRef] [PubMed]
41. Okereafor, U.; Makhatha, M.; Mekuto, L.; Uche-Okereafor, N.; Sebola, T.; Mavumengwana, V. Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2204. [CrossRef] [PubMed]
42. Volungevičius, J.; Feiza, V.; Amalevičiūtė-Volungė, K.; Liaudanskienė, I.; Šlepetienė, A.; Kuncevičius, A.; Vengalis, R.; Vėlius, G.; Prapiestienė, R.; Poškienė, J. Transformations of different soils under natural and anthropogenized land management. *Zemdirb. Agric.* **2019**, *106*, 3–14. [CrossRef]
43. Kuschnig, N.; Cuaresma, J.C.; Krisztin, T.; Giljum, S. Spatial spillover effects from agriculture drive deforestation in Mato Grosso, Brazil. *Sci. Rep.* **2021**, *11*, 21804. [CrossRef] [PubMed]
44. Omran, A.; Schwarz-Herion, O. Deforestation in Malaysia: The current practice and the way forward. *Sustain. Our Environ. Better. Future Chall. Oppor.* **2020**, 175–193.
45. Wang, L.; Delgado-Baquerizo, M.; Zhao, X.; Zhang, M.; Song, Y.; Cai, J.; Chang, Q.; Li, Z.; Chen, Y.; Liu, J. Livestock overgrazing disrupts the positive associations between soil biodiversity and nitrogen availability. *Funct. Ecol.* **2020**, *34*, 1713–1720. [CrossRef]
46. Fischer, S.; Henderson, D.C.; Koper, N. A resilient system: North American mixed-grass prairie responds rapidly to livestock exclusion. *Biol. Conserv.* **2020**, *243*, 108453. [CrossRef]
47. Bennour, A.; Jia, L.; Menenti, M.; Zheng, C.; Zeng, Y.; Barnieh, B.A.; Jiang, M. Assessing impacts of climate variability and land use/land cover change on the water balance components in the Sahel using Earth observations and hydrological modelling. *J. Hydrol. Reg. Stud.* **2023**, *47*, 101370. [CrossRef]
48. Ukalska-Jaruga, A.; Bejger, R.; Debaene, G.; Smreczak, B. Characterization of soil organic matter individual fractions (fulvic acids, humic acids, and humins) by spectroscopic and electrochemical techniques in agricultural soils. *Agronomy* **2021**, *11*, 1067. [CrossRef]
49. Wooliver, R.; Kivlin, S.N.; Jagadamma, S. Links among crop diversification, microbial diversity, and soil organic carbon: Mini review and case studies. *Front. Microbiol.* **2022**, *13*, 854247. [CrossRef]
50. Sabir, M.S.; Shahzadi, F.; Ali, F.; Shakeela, Q.; Niaz, Z.; Ahmed, S. Comparative effect of fertilization practices on soil microbial diversity and activity: An overview. *Curr. Microbiol.* **2021**, *78*, 3644–3655. [CrossRef]

51. Wang, Y.; Hu, H.; Zhou, Y.; Zhang, B.; Li, S.; Liu, J.; Tong, X. Evolving characteristics of dissolved organic matter in soil profiles during 56 years of revegetation in Mu Us Sandy Land. *Plant Soil* **2024**, *497*, 567–584. [CrossRef]
52. Amadou, A.; Song, A.; Tang, Z.-X.; Li, Y.; Wang, E.-Z.; Lu, Y.-Q.; Liu, X.-D.; Yi, K.; Zhang, B.; Fan, F. The effects of organic and mineral fertilization on soil enzyme activities and bacterial community in the below-and above-ground parts of wheat. *Agronomy* **2020**, *10*, 1452. [CrossRef]
53. Dijkstra, F.A.; Cheng, W. Moisture modulates rhizosphere effects on C decomposition in two different soil types. *Soil Biol. Biochem.* **2007**, *39*, 2264–2274. [CrossRef]
54. Wong, V.N.L.; Greene, R.S.B.; Dalal, R.C.; Murphy, B.W. Soil carbon dynamics in saline and sodic soils: A review: Soil carbon dynamics in saline and sodic soils. *Soil Use Manag.* **2010**, *26*, 2–11. [CrossRef]
55. Chowdhury, S.; Bolan, N.; Farrell, M.; Sarkar, B.; Sarker, J.R.; Kirkham, M.B.; Hossain, M.Z.; Kim, G.-H. Role of cultural and nutrient management practices in carbon sequestration in agricultural soil. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 166, pp. 131–196, ISBN 978-0-12-824587-3.
56. Basu, S.; Kumar, G.; Chhabra, S.; Prasad, R. Role of soil microbes in biogeochemical cycle for enhancing soil fertility. In *New and future developments in microbial biotechnology and bioengineering*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 149–157.
57. Dincă, L.C.; Grenni, P.; Onet, C.; Onet, A. Fertilization and soil microbial community: A review. *Appl. Sci.* **2022**, *12*, 1198. [CrossRef]
58. Javed, A.; Ali, E.; Afzal, K.B.; Osman, A.; Riaz, S. Soil fertility: Factors affecting soil fertility, and biodiversity responsible for soil fertility. *Int. J. Plant Anim. Environ. Sci.* **2022**, *12*, 21–33. [CrossRef]
59. Masilionytė, L.; Kriaučiūnienė, Z.; Šarauskis, E.; Arlauskienė, A.; Krikštolaitis, R.; Šlepetienė, A.; Jablonskytė-Raščė, D.; van Lier, Q. de J. Effect of long-term crop rotation and fertilisation management on soil humus dynamics in organic and sustainable agricultural management systems. *Soil Res.* **2021**, *59*, 573–585. [CrossRef]
60. Muhamedyarova, L.; Derkho, M.; Meshcheriakova, G.; Gumenyuk, O.; Shakirova, S. Influence of bio-humus on soil fertility, productivity and environmental safety of spring wheat grain. *Agron. Res.* **2020**, *18*, 483–493. [CrossRef]
61. Gurbanov, R.; Kalkanci, B.; Karadag, H.; Samgane, G. Phosphorus solubilizing microorganisms. *Biofertil. Study Impact* **2021**, 151–182.
62. Zhang, M.; Wu, Y.; Qu, C.; Huang, Q.; Cai, P. Microbial extracellular polymeric substances (EPS) in soil: From interfacial behaviour to ecological multifunctionality. *Geo-Bio Interfaces* **2024**, *1*, e4. [CrossRef]
63. Dukare, A.; Paul, S.; Mhatre, P.; Divekar, P. Biological disease control agents in organic crop production system. In *Pesticide Contamination in Freshwater and Soil Environs*; Apple Academic Press: Palm Bay, FL, USA, 2021; pp. 255–282.
64. Hamdi, R.F.; Alzawi, K.S. Using fungi and bacteria as biological control agents of fungal plant diseases an article. *J. Univ. Anbar Pure Sci.* **2023**, *17*, 50–61. [CrossRef]
65. Tedersoo, L.; Bahram, M.; Zobel, M. How mycorrhizal associations drive plant population and community biology. *Science* **2020**, *367*, eaba1223. [CrossRef] [PubMed]
66. Bai, B.; Liu, C.; Zhang, C.; He, X.; Wang, H.; Peng, W.; Zheng, C. Trichoderma species from plant and soil: An excellent resource for biosynthesis of terpenoids with versatile bioactivities. *J. Adv. Res.* **2023**, *49*, 81–102. [CrossRef] [PubMed]
67. De Simeis, D.; Serra, S. Actinomycetes: A never-ending source of bioactive compounds—An overview on antibiotics production. *Antibiotics* **2021**, *10*, 483. [CrossRef] [PubMed]
68. Jacoby, R.; Peukert, M.; Succurro, A.; Koprivova, A.; Kopriva, S. The Role of Soil Microorganisms in Plant Mineral Nutrition—Current Knowledge and Future Directions. *Front. Plant Sci.* **2017**, *8*, 1617. [CrossRef]
69. Li, J.; Lusher, A.L.; Rotchell, J.M.; Deudero, S.; Turra, A.; Bråte, I.L.N.; Sun, C.; Shahadat Hossain, M.; Li, Q.; Kolandhasamy, P.; et al. Using mussel as a global bioindicator of coastal microplastic pollution. *Environ. Pollut.* **2019**, *244*, 522–533. [CrossRef]
70. Yang, X.; Wang, D.; Lan, Y.; Meng, J.; Jiang, L.; Sun, Q.; Cao, D.; Sun, Y.; Chen, W. Labile organic carbon fractions and carbon pool management index in a 3-year field study with biochar amendment. *J. Soils Sediments* **2018**, *18*, 1569–1578. [CrossRef]
71. Peng, Y.; Duan, Y.; Huo, W.; Xu, M.; Yang, X.; Wang, X.; Wang, B.; Blackwell, M.S.; Feng, G. Soil microbial biomass phosphorus can serve as an index to reflect soil phosphorus fertility. *Biol. Fertil. Soils* **2021**, *57*, 657–669. [CrossRef]
72. Bhaduri, D.; Sihi, D.; Bhowmik, A.; Verma, B.C.; Munda, S.; Dari, B. A review on effective soil health bio-indicators for ecosystem restoration and sustainability. *Front. Microbiol.* **2022**, *13*, 938481. [CrossRef]
73. Csitári, G.; Tóth, Z.; Kökény, M. Effects of Organic Amendments on Soil Aggregate Stability and Microbial Biomass in a Long-Term Fertilization Experiment (IOSDV). *Sustainability* **2021**, *13*, 9769. [CrossRef]
74. Bhagat, N.; Raghav, M.; Dubey, S.; Bedi, N. Bacterial exopolysaccharides: Insight into their role in plant abiotic stress tolerance. *J. Microbiol. Biotechnol.* **2021**, *31*, 1045. [CrossRef] [PubMed]
75. Ali, N.; Abbas, S.A.A.A.; Sharif, L.; Shafiq, M.; Kamran, Z.; Haseeb, M.; Shahid, M.A. Microbial extracellular polymeric substance and impacts on soil aggregation. In *Bacterial Secondary Metabolites*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 221–237.
76. Yoon, H.Y.; Jeong, H.J.; Cha, J.-Y.; Choi, M.; Jang, K.-S.; Kim, W.-Y.; Kim, M.G.; Jeon, J.-R. Structural variation of humic-like substances and its impact on plant stimulation: Implication for structure-function relationship of soil organic matters. *Sci. Total Environ.* **2020**, *725*, 138409. [CrossRef] [PubMed]
77. Zavarzina, A.; Danchenko, N.; Demin, V.; Artemyeva, Z.; Kogut, B. Humic substances: Hypotheses and reality (a review). *Eurasian Soil Sci.* **2021**, *54*, 1826–1854. [CrossRef]

78. Abadi, V.; Sepehri, M.; Rahmani, H.; Dolatabad, H.; Shamshiripour, M.; Khatabi, B. Diversity and abundance of culturable nitrogen-fixing bacteria in the phyllosphere of maize. *J. Appl. Microbiol.* **2021**, *131*, 898–912. [CrossRef] [PubMed]
79. Barbieri, P.; Starck, T.; Voisin, A.-S.; Nesme, T. Biological nitrogen fixation of legumes crops under organic farming as driven by cropping management: A review. *Agric. Syst.* **2023**, *205*, 103579. [CrossRef]
80. Kumar, P.S.; Rangasamy, G.; Gayathri, K.V.; Parthasarathy, V. Rhizobium mayense sp. Nov., an efficient plant growth-promoting nitrogen-fixing bacteria isolated from rhizosphere soil. *Environ. Res.* **2023**, *220*, 115200.
81. Angelina, E.; Papatheodorou, E.M.; Demirtzoglou, T.; Monokrousos, N. Effects of Bacillus subtilis and Pseudomonas fluorescens inoculation on attributes of the lettuce (*Lactuca sativa* L.) soil rhizosphere microbial community: The role of the management system. *Agronomy* **2020**, *10*, 1428. [CrossRef]
82. Rai, P.K.; Rai, A.; Sharma, N.K.; Singh, T.; Kumar, Y. Limitations of biofertilizers and their revitalization through nanotechnology. *J. Clean. Prod.* **2023**, 138194. [CrossRef]
83. Siedt, M.; Schäffer, A.; Smith, K.E.; Nabel, M.; Roß-Nickoll, M.; Van Dongen, J.T. 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. *Sci. Total Environ.* **2021**, *751*, 141607. [CrossRef]
84. Dequiedt, S.; Saby, N.P.A.; Lelievre, M.; Jolivet, C.; Thioulouse, J.; Toutain, B.; Arrouays, D.; Bispo, A.; Lemanceau, P.; Ranjard, L. Biogeographical patterns of soil molecular microbial biomass as influenced by soil characteristics and management: Biogeography of soil microbial biomass. *Glob. Ecol. Biogeogr.* **2011**, *20*, 641–652. [CrossRef]
85. Constancias, F.; Terrat, S.; Saby, N.P.A.; Horrigue, W.; Villerd, J.; Guillemin, J.; Biju-Duval, L.; Nowak, V.; Dequiedt, S.; Ranjard, L.; et al. Mapping and determinism of soil microbial community distribution across an agricultural landscape. *MicrobiologyOpen* **2015**, *4*, 505–517. [CrossRef] [PubMed]
86. Naz, M.; Dai, Z.; Hussain, S.; Tariq, M.; Danish, S.; Khan, I.U.; Qi, S.; Du, D. The soil pH and heavy metals revealed their impact on soil microbial community. *J. Environ. Manag.* **2022**, *321*, 115770. [CrossRef] [PubMed]
87. Liu, L.; Zhu, K.; Wurzburger, N.; Zhang, J. Relationships between plant diversity and soil microbial diversity vary across taxonomic groups and spatial scales. *Ecosphere* **2020**, *11*, e02999. [CrossRef]
88. Stockdale, E.A.; Murphy, D.V. Chapter-3 Managing Soil Microbial Biomass for Sustainable Agro-Ecosystems. In *Microbial Biomass: A Paradigm Shift In Terrestrial Biogeochemistry*; World Scientific: Singapore, 2017; pp. 67–100, ISBN 978-1-78634-132-7.
89. Ullah, M.S.; Malekian, R.; Randhawa, G.S.; Gill, Y.S.; Singh, S.; Esau, T.J.; Zaman, Q.U.; Afzaal, H.; Du, D.L.; Farooque, A.A. The potential of biochar incorporation into agricultural soils to promote sustainable agriculture: Insights from soil health, crop productivity, greenhouse gas emission mitigation and feasibility perspectives—A critical review. *Rev. Environ. Sci. Bio/Technol.* **2024**, *23*, 1105–1130. [CrossRef]
90. Kumar, A.; Bhattacharya, T. Biochar: A sustainable solution. *Environ. Dev. Sustain.* **2021**, *23*, 6642–6680. [CrossRef]
91. Ulzen, J.; Abaidoo, R.C.; Ewusi-Mensah, N.; Osei, O.; Masso, C.; Opoku, A. Organic manure improves soybean response to rhizobia inoculant and P-fertilizer in northern Ghana. *Front. Agron.* **2020**, *2*, 9. [CrossRef]
92. Zhou, Y.; Liu, H.; Chen, H.; Awasthi, S.K.; Sindhu, R.; Binod, P.; Pandey, A.; Awasthi, M.K. Introduction: Trends in composting and vermicomposting technologies. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 1–28, ISBN 978-0-323-91874-9.
93. Parihar, P.; Choudhary, R. Evaluation of the effect of Organic Waste on Nutrient Quality of Compost. *J. Xi'an Shiyou Univ. Nat. Sci. Ed.* **2022**, *18*, 712–715.
94. Liu, C.; Plaza-Bonilla, D.; Coulter, J.A.; Kutcher, H.R.; Beckie, H.J.; Wang, L.; Floc'h, J.-B.; Hamel, C.; Siddique, K.H.M.; Li, L.; et al. Diversifying crop rotations enhances agroecosystem services and resilience. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2022; Volume 173, pp. 299–335, ISBN 978-0-323-98955-8.
95. Murphy, E.M. Nutrient Cycling in Organic and Conventional Agricultural Systems with Winter Cover Crops. Available online: https://nature.berkeley.edu/classes/es196/projects/2019final/MurphyE_2019.pdf (accessed on 15 October 2024).
96. Begum, N.; Qin, C.; Ahanger, M.A.; Raza, S.; Khan, M.I.; Ashraf, M.; Ahmed, N.; Zhang, L. Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. *Front. Plant Sci.* **2019**, *10*, 1068. [CrossRef]
97. Adarsh, A.; Mathew, S.; Thomas, G.; Roshni, A.S.; Gopika, K.T.; Nirosha, V.; Arya, A.P. Phyto-accumulators to mitigate micronutrient deficiency in organic farming. *Int. J. Agric. Sci.* **2022**, *13*, 1–14. [CrossRef]
98. Peltoniemi, K.; Velmala, S.; Fritze, H.; Lemola, R.; Pennanen, T. Long-term impacts of organic and conventional farming on the soil microbiome in boreal arable soil. *Eur. J. Soil Biol.* **2021**, *104*, 103314. [CrossRef]
99. Ćirić, V.; Prekop, N.; Šeremešić, S.; Vojnov, B.; Pejić, B.; Radovanović, D.; Marinković, D. The implication of exchange capacity (CEC) assessment for soil quality management and improvement. *Agric. For.* **2023**, *69*, 113–133.
100. Wei, Z.; Hoffland, E.; Zhuang, M.; Hellegers, P.; Cui, Z. Organic inputs to reduce nitrogen export via leaching and runoff: A global meta-analysis. *Environ. Pollut.* **2021**, *291*, 118176. [CrossRef] [PubMed]
101. Apaeva, N.N.; Manishkin, S.G.; Kudryashova, L.V.; Yamalieva, A.M. An innovative approach to the use of the granulated organic fertilizers based on bird droppings on crops of spring wheat. In *Proceedings of the IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2020; Volume 421, p. 022062.
102. Rempelos, L.; Baranski, M.; Wang, J.; Adams, T.N.; Adebusuyi, K.; Beckman, J.J.; Brockbank, C.J.; Douglas, B.S.; Feng, T.; Greenway, J.D.; et al. Integrated Soil and Crop Management in Organic Agriculture: A Logical Framework to Ensure Food Quality and Human Health? *Agronomy* **2021**, *11*, 2494. [CrossRef]

103. Ozlu, E.; Arriaga, F.J.; Bilen, S.; Gozukara, G.; Babur, E. Carbon Footprint Management by Agricultural Practices. *Biology* **2022**, *11*, 1453. [CrossRef] [PubMed]
104. Verdi, L.; Marta, A.D.; Falconi, F.; Orlandini, S.; Mancini, M. Comparison between organic and conventional farming systems using Life Cycle Assessment (LCA): A case study with an ancient wheat variety. *Eur. J. Agron.* **2022**, *141*, 126638. [CrossRef]
105. Li, L.; Xu, M.; Eyakub Ali, M.; Zhang, W.; Duan, Y.; Li, D. Factors affecting soil microbial biomass and functional diversity with the application of organic amendments in three contrasting cropland soils during a field experiment. *PLoS ONE* **2018**, *13*, e0203812. [CrossRef]
106. Sauvadet, M.; Chauvat, M.; Brunet, N.; Bertrand, I. Can changes in litter quality drive soil fauna structure and functions? *Soil. Biol. Biochem.* **2017**, *107*, 94–103. [CrossRef]
107. Yu, Q.; Hu, X.; Ma, J.; Ye, J.; Sun, W.; Wang, Q.; Lin, H. Effects of long-term organic material applications on soil carbon and nitrogen fractions in paddy fields. *Soil. Tillage Res.* **2020**, *196*, 104483. [CrossRef]
108. Jia, S.; Yuan, D.; Li, W.; He, W.; Raza, S.; Kuzyakov, Y.; Zamanian, K.; Zhao, X. Soil chemical properties depending on fertilization and management in China: A meta-analysis. *Agronomy* **2022**, *12*, 2501. [CrossRef]
109. Wu, Z.; Li, Y.; Chen, H.; Rao, J.; Sun, Q. Effects of straw mulching on predatory myxobacterial communities in different soil aggregates under wheat-corn rotation. *Environ. Sci. Pollut. Res.* **2022**, *29*, 29062–29074. [CrossRef] [PubMed]
110. Armalytė, J.; Skerniškytė, J.; Bakienė, E.; Krasauskas, R.; Šiugždinienė, R.; Kareivienė, V.; Kerzienė, S.; Klimienė, I.; Sužiedėlienė, E.; Ružauskas, M. Microbial diversity and antimicrobial resistance profile in microbiota from soils of conventional and organic farming systems. *Front. Microbiol.* **2019**, *10*, 892. [CrossRef] [PubMed]
111. Hatfield, J.L.; Sauer, T.J.; Cruse, R.M. Soil: The Forgotten Piece of the Water, Food, Energy Nexus. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2017; Volume 143, Chapter 1; pp. 1–46.
112. Francaviglia, R.; Almagro, M.; Lehtonen, H.; Hüppi, R.; Rodrigo-Comino, J. Editorial: Agricultural diversification: Benefits and barriers for sustainable soil management. *Front. Environ. Sci.* **2022**, *10*, 1046354. [CrossRef]
113. Baldwin-Kordick, R.; De, M.; Lopez, M.D.; Liebman, M.; Lauter, N.; Marino, J.; McDaniel, M.D. Comprehensive impacts of diversified cropping on soil health and sustainability. *Agroecol. Sustain. Food Syst.* **2022**, *46*, 331–363. [CrossRef]
114. Sanford, G.R.; Jackson, R.D.; Booth, E.G.; Hedtcke, J.L.; Picasso, V. Perenniality and diversity drive output stability and resilience in a 26-year cropping systems experiment. *Field Crops Res.* **2021**, *263*, 108071. [CrossRef]
115. Li, Z.; Zeng, Z.; Tian, D.; Wang, J.; Fu, Z.; Wang, B.; Tang, Z.; Chen, W.; Chen, H.Y.H.; Wang, C.; et al. The stoichiometry of soil microbial biomass determines metabolic quotient of nitrogen mineralization. *Environ. Res. Lett.* **2020**, *15*, 034005. [CrossRef]
116. Wang, L.; Gan, Y.; Bainard, L.D.; Hamel, C.; St-Arnaud, M.; Hijri, M. Expression of N-cycling genes of root microbiomes provides insights for sustaining oilseed crop production. *Environ. Microbiol.* **2020**, *22*, 4545–4556. [CrossRef]
117. Venter, Z.S.; Jacobs, K.; Hawkins, H.-J. The impact of crop rotation on soil microbial diversity: A meta-analysis. *Pedobiologia* **2016**, *59*, 215–223. [CrossRef]
118. Ghosh, P.K.; Palsaniya, D.R. Sustainable intensification and diversification: Means for maintaining soil health. *Fourth Int. Agron. Congr. Ext. Summ.* **2016**, *4*, 101–102.
119. Ghosh, P.K.; Venkatesh, M.S.; Hazra, K.K.; Kumar, N. Long-term effect of pulses and nutrient management on soil organic carbon dynamics and sustainability on an inceptisol of Indo-Gangetic plains of India. *Ex. Agric.* **2012**, *48*, 473–487. [CrossRef]
120. Bainard, L.D.; Navarro-Borrell, A.; Hamel, C.; Braun, K.; Hanson, K.; Gan, Y. Increasing the frequency of pulses in crop rotations reduces soil fungal diversity and increases the proportion of fungal pathotrophs in a semiarid agroecosystem. *Agric. Ecosyst. Environ.* **2017**, *240*, 206–214. [CrossRef]
121. Barbieri, P.; Pellerin, S.; Seufert, V.; Nesme, T. Changes in crop rotations would impact food production in an organically farmed world. *Nat. Sustain.* **2019**, *2*, 378–385. [CrossRef]
122. Busby, P.E.; Soman, C.; Wagner, M.R.; Friesen, M.L.; Kremer, J.; Bennett, A.; Morsy, M.; Eisen, J.A.; Leach, J.E.; Dangl, J.L. Research priorities for harnessing plant microbiomes in sustainable agriculture. *PLoS Biol.* **2017**, *15*, e2001793. [CrossRef] [PubMed]
123. Li, X.; Jousset, A.; De Boer, W.; Carrión, V.J.; Zhang, T.; Wang, X.; Kuramae, E.E. Legacy of land use history determines reprogramming of plant physiology by soil microbiome. *ISME J.* **2019**, *13*, 738–751. [CrossRef]
124. Hanrahan, B.R.; King, K.W.; Duncan, E.W.; Shedekar, V.S. Cover crops differentially influenced nitrogen and phosphorus loss in tile drainage and surface runoff from agricultural fields in Ohio, USA. *J. Environ. Manag.* **2021**, *293*, 112910. [CrossRef] [PubMed]
125. Maiga, A.; Alhameid, A.; Singh, S.; Polat, A.; Singh, J.; Kumar, S.; Osborne, S. Responses of soil organic carbon, aggregate stability, carbon and nitrogen fractions to 15 and 24 years of no-till diversified crop rotations. *Soil Res.* **2019**, *57*, 149. [CrossRef]
126. Bainard, L.D.; Evans, B.; Malis, E.; Yang, T.; Bainard, J.D. Influence of annual plant diversity on forage productivity and nutrition, soil chemistry, and soil microbial communities. *Front. Sustain. Food Syst.* **2020**, *4*, 560479. [CrossRef]
127. García-González, I.; Hontoria, C.; Gabriel, J.L.; Alonso-Ayuso, M.; Quemada, M. Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land. *Geoderma* **2018**, *322*, 81–88. [CrossRef]
128. Sturm, D.J.; Peteinatos, G.; Gerhards, R. Contribution of allelopathic effects to the overall weed suppression by different cover crops. *Weed Res.* **2018**, *58*, 331–337. [CrossRef]
129. Jabro, J.D.; Allen, B.L.; Rand, T.; Dangi, S.R.; Campbell, J.W. Effect of Previous Crop Roots on Soil Compaction in 2 Yr Rotations under a No-Tillage System. *Land* **2021**, *10*, 202. [CrossRef]
130. Phiri, M.; Mulder, J.; Chishala, B.H.; Chabala, L.M.; Martinsen, V. Phosphorus Availability and Uptake following a Maize-Pigeon Pea Rotation under Conservation Agriculture. *Agronomy* **2024**, *14*, 169. [CrossRef]

131. Kumar, P.; Kumar, M.; Kumar, A.; Gharsiram, B.S.; Kumar, S. Effect of conservation tillage and nutrient management on maize in maize-pigeon pea intercropping system. *Pharma Innov. J.* **2022**, *11*, 1005–1010.
132. Jensen, J.L.; Thomsen, I.K.; Eriksen, J.; Christensen, B.T. Spring barley grown for decades with straw incorporation and cover crops: Effects on crop yields and N uptake. *Field Crops Res.* **2021**, *270*, 108228. [CrossRef]
133. Liu, A.; Ku, Y.-S.; Contador, C.A.; Lam, H.-M. The impacts of domestication and agricultural practices on legume nutrient acquisition through symbiosis with rhizobia and arbuscular mycorrhizal fungi. *Front. Genet.* **2020**, *11*, 583954. [CrossRef] [PubMed]
134. Costantini, M.; Bacenetti, J. Soybean and maize cultivation in South America: Environmental comparison of different cropping systems. *Clean. Environ. Syst.* **2021**, *2*, 100017. [CrossRef]
135. Babec, B.; Šeremešić, S.; Hladni, N.; Terzić, S.; Vojnov, B.; Ćuk, N.; Gvozdenac, S. Effect of intercrop-ping sunflower with legumes on some sunflower morphological traits. *Ratar. Povrt. /Field Veg. Crops Res.* **2020**, *57*, 61–67.
136. Paudel, R.; Waisen, P.; Wang, K.-H. Exploiting the innate potential of sorghum/sorghum–sudangrass cover crops to improve soil microbial profile that can lead to suppression of plant-parasitic nematodes. *Microorganisms* **2021**, *9*, 1831. [CrossRef] [PubMed]
137. Mushtaq, S.; Tak, H.; Sheikh, J.H.; Malik, I.M.; -un-Nisa, U. Plant parasitic nematode management using antagonistic plants as a potential substitute to hazardous chemical control—A review. *Int. J. Pest Manag.* **2024**, 1–11. [CrossRef]
138. Quintarelli, V.; Radicetti, E.; Allevato, E.; Stazi, S.R.; Haider, G.; Abideen, Z.; Bibi, S.; Jamal, A.; Mancinelli, R. Cover Crops for Sustainable Cropping Systems: A Review. *Agriculture* **2022**, *12*, 2076. [CrossRef]
139. Broman, G.I.; Robèrt, K.-H. A framework for strategic sustainable development. *J. Clean. Prod.* **2017**, *140*, 17–31. [CrossRef]
140. Nosrati, K.; Collins, A.L. A soil quality index for evaluation of degradation under land use and soil erosion categories in a small mountainous catchment, Iran. *J. Mt. Sci.* **2019**, *16*, 2577–2590. [CrossRef]
141. Zeraatpisheh, M.; Bakhshandeh, E.; Hosseini, M.; Alavi, S.M. Assessing the effects of deforestation and intensive agriculture on the soil quality through digital soil mapping. *Geoderma* **2020**, *363*, 114139. [CrossRef]
142. Guo, S.; Tao, C.; Jousset, A.; Xiong, W.; Wang, Z.; Shen, Z.; Wang, B.; Xu, Z.; Gao, Z.; Liu, S.; et al. Trophic interactions between predatory protists and pathogen-suppressive bacteria impact plant health. *ISME J.* **2022**, *16*, 1932–1943. [CrossRef] [PubMed]
143. Paul Chowdhury, S.; Babin, D.; Sandmann, M.; Jacquiod, S.; Sommermann, L.; Sørensen, S.J.; Fliessbach, A.; Mäder, P.; Geistlinger, J.; Smalla, K.; et al. Effect of long-term organic and mineral fertilization strategies on rhizosphere microbiota assemblage and performance of lettuce. *Environ. Microbiol.* **2019**, *21*, 2426–2439. [CrossRef] [PubMed]
144. Saleem, M.F.; Ghaffar, A.; Rahman, M.H.U.; Imran, M.; Iqbal, R.; Soufan, W.; Danish, S.; Datta, R.; Rajendran, K.; El Sabagh, A. Effect of Short-Term Zero Tillage and Legume Intercrops on Soil Quality, Agronomic and Physiological Aspects of Cotton under Arid Climate. *Land* **2022**, *11*, 289. [CrossRef]
145. Jousset, A. Application of Protists to Improve Plant Growth in Sustainable Agriculture. In *Rhizotrophs: Plant Growth Promotion to Bioremediation*; Mehnaz, S., Ed.; Springer Singapore: Singapore, 2017; pp. 263–273, ISBN 978-981-10-4861-6.
146. Martin-Guay, M.-O.; Paquette, A.; Dupras, J.; Rivest, D. The new Green Revolution: Sustainable intensification of agriculture by intercropping. *Sci. Total Environ.* **2018**, *615*, 767–772. [CrossRef] [PubMed]
147. Sharma, P.; Singh, A.; Kahlon, C.S.; Brar, A.S.; Grover, K.K.; Dia, M.; Steiner, R.L. The Role of Cover Crops towards Sustainable Soil Health and Agriculture—A Review Paper. *Am. J. Plant Sci.* **2018**, *09*, 1935–1951. [CrossRef]
148. Koishi, A.; Bragazza, L.; Maltas, A.; Guillaume, T.; Sinaj, S. Long-Term Effects of Organic Amendments on Soil Organic Matter Quantity and Quality in Conventional Cropping Systems in Switzerland. *Agronomy* **2020**, *10*, 1977. [CrossRef]
149. Baritz, R.; Wiese, L.; Verbeke, I.; Vargas, R. Voluntary Guidelines for Sustainable Soil Management: Global Action for Healthy Soils. In *International Yearbook of Soil Law and Policy 2017*; Ginzky, H., Dooley, E., Heuser, I.L., Kasimbazi, E., Markus, T., Qin, T., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 17–36, ISBN 978-3-319-68885-5.
150. Majid, M.; Ali, M.; Shahzad, K.; Ahmad, F.; Ikram, R.M.; Ishtiaq, M.; Alaraidh, I.A.; Al-hashimi, A.; Ali, H.M.; Zarei, T.; et al. Mitigation of Osmotic Stress in Cotton for the Improvement in Growth and Yield through Inoculation of Rhizobacteria and Phosphate Solubilizing Bacteria Coated Diammonium Phosphate. *Sustainability* **2020**, *12*, 10456. [CrossRef]
151. Manzoor, S.; Habib-ur-Rahman, M.; Haider, G.; Ghafoor, I.; Ahmad, S.; Afzal, M.; Nawaz, F.; Iqbal, R.; Yasin, M.; Danish, S.; et al. Biochar and slow-releasing nitrogen fertilizers improved growth, nitrogen use, yield, and fiber quality of cotton under arid climatic conditions. *Environ. Sci. Pollut. Res.* **2022**, *29*, 13742–13755. [CrossRef]
152. Francaviglia, R.; Álvaro-Fuentes, J.; Di Bene, C.; Gai, L.; Regina, K.; Turtola, E. Diversification and Management Practices in Selected European Regions. A Data Analysis of Arable Crops Production. *Agronomy* **2020**, *10*, 297. [CrossRef]
153. De Roest, K.; Ferrari, P.; Knickel, K. Specialisation and economies of scale or diversification and economies of scope? Assessing different agricultural development pathways. *J. Rural Stud.* **2018**, *59*, 222–231. [CrossRef]
154. Scherer, L.A.; Verburg, P.H.; Schulp, C.J.E. Opportunities for sustainable intensification in European agriculture. *Glob. Environ. Change* **2018**, *48*, 43–55. [CrossRef]
155. Nascimento, G.; Villegas, D.; Cantero-Martínez, C. Crop diversification and digestate application effect on the productivity and efficiency of irrigated winter crop systems. *Eur. J. Agron.* **2023**, *148*, 126873. [CrossRef]
156. Timmis, K.; Ramos, J.L. The soil crisis: The need to treat as a global health problem and the pivotal role of microbes in prophylaxis and therapy. *Microb. Biotechnol.* **2021**, *14*, 769–797. [CrossRef]
157. Hector, A. The importance of biodiverse plant communities for healthy soils. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2119953118. [CrossRef] [PubMed]

158. Rastogi, M.; Verma, S.; Kumar, S.; Bharti, S.; Kumar, G.; Azam, K.; Singh, V. Soil health and sustainability in the age of organic amendments: A review. *Int. J. Environ. Clim. Change* **2023**, *13*, 2088–2102. [CrossRef]
159. Zewide, I. Review paper on effect of natural condition on soil infiltration. *Chemistry* **2021**, *7*, 34–41.
160. Kyttä, V.; Helenius, J.; Tuomisto, H.L. Carbon footprint and energy use of recycled fertilizers in arable farming. *J. Clean. Prod.* **2021**, *287*, 125063. [CrossRef]
161. Humphreys, J.; Lan, R.; Tao, S. Development and recent progress on ammonia synthesis catalysts for Haber–Bosch process. *Adv. Energy Sustain. Res.* **2021**, *2*, 2000043. [CrossRef]
162. Gao, Y.; Cabrera Serrenho, A. Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. *Nat. Food* **2023**, *4*, 170–178. [CrossRef]
163. Yang, W.; Zhang, L. Biochar and cow manure organic fertilizer amendments improve the quality of composted green waste as a growth medium for the ornamental plant *Centaurea cyanus* L. *Environ. Sci. Pollut. Res.* **2022**, *29*, 45474–45486. [CrossRef] [PubMed]
164. Bergstrand, K.-J. Organic fertilizers in greenhouse production systems–a review. *Sci. Hortic.* **2022**, *295*, 110855. [CrossRef]
165. O'Callaghan, M.; Ballard, R.A.; Wright, D. Soil microbial inoculants for sustainable agriculture: Limitations and opportunities. *Soil Use Manag.* **2022**, *38*, 1340–1369. [CrossRef]
166. Canfora, L.; Costa, C.; Pallottino, F.; Mocali, S. Trends in soil microbial inoculants research: A science mapping approach to unravel strengths and weaknesses of their application. *Agriculture* **2021**, *11*, 158. [CrossRef]
167. Shahwar, D.; Mushtaq, Z.; Mushtaq, H.; Alqarawi, A.A.; Park, Y.; Alshahrani, T.S.; Faizan, S. Role of microbial inoculants as bio fertilizers for improving crop productivity: A review. *Heliyon* **2023**, *9*, e16134. [CrossRef]
168. Meynard, J.-M.; Charrier, F.; Fares, M.; Le Bail, M.; Magrini, M.-B.; Charlier, A.; Messéan, A. Socio-technical lock-in hinders crop diversification in France. *Agron. Sustain. Dev.* **2018**, *38*, 54. [CrossRef]
169. Roesch-McNally, G.E.; Arbuckle, J.G.; Tyndall, J.C. Barriers to implementing climate resilient agricultural strategies: The case of crop diversification in the U.S. Corn Belt. *Glob. Environ. Change* **2018**, *48*, 206–215. [CrossRef]
170. Roesch-McNally, G.; Garrett, A.; Fery, M. Assessing perceptions of climate risk and adaptation among small farmers in Oregon's Willamette Valley. *Renew. Agric. Food Syst.* **2020**, *35*, 626–630. [CrossRef]
171. Autio, A.; Johansson, T.; Motaroki, L.; Minoia, P.; Pellikka, P. Constraints for adopting climate-smart agricultural practices among smallholder farmers in Southeast Kenya. *Agric. Syst.* **2021**, *194*, 103284. [CrossRef]
172. Roesch-McNally, G.E.; Basche, A.D.; Arbuckle, J.G.; Tyndall, J.C.; Miguez, F.E.; Bowman, T.; Clay, R. The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renew. Agric. Food Syst.* **2018**, *33*, 322–333. [CrossRef]
173. Weisberger, D.A.; McDaniel, M.D.; Arbuckle, J.G.; Liebman, M. Farmer perspectives on benefits of and barriers to extended crop rotations in Iowa, USA. *Agric. Amp; Environ. Lett.* **2021**, *6*, e20049. [CrossRef]
174. Verma, B.; Pramanik, P.; Bhaduri, D. Organic fertilizers for sustainable soil and environmental management. In *Nutrient Dynamics for Sustainable Crop Production*; Springer: Singapore, 2020; pp. 289–313.
175. Ferdous, Z.; Zulfiqar, F.; Datta, A.; Hasan, A.K.; Sarker, A. Potential and challenges of organic agriculture in Bangladesh: A review. *J. Crop Improv.* **2021**, *35*, 403–426. [CrossRef]
176. Srivastava, A.K.; Kumar, A. Exploring organic farming: Advantages, challenges, and future directions. *Plant Sci. Arch.* **2022**, *9*, 13. [CrossRef]
177. Chen, M.; Zhang, S.; Liu, L.; Liu, J.; Ding, X. Organic fertilization increased soil organic carbon stability and sequestration by improving aggregate stability and iron oxide transformation in saline-alkaline soil. *Plant Soil* **2022**, *474*, 233–249. [CrossRef]
178. Barman, A.; Saha, P.; Patel, S.; Bera, A. Crop Diversification an Effective Strategy for Sustainable Agriculture Development. In *Sustainable Crop Production—Recent Advances*; Singh Meena, V., Choudhary, M., Prakash Yadav, R., Kumari Meena, S., Eds.; IntechOpen: London, UK, 2022; ISBN 978-1-80355-696-3.
179. Ijaz, M.; Nawaz, A.; Ul-Allah, S.; Rizwan, M.S.; Ullah, A.; Hussain, M.; Sher, A.; Ahmad, S. Crop Diversification and Food Security. In *Agronomic Crops*; Hasanuzzaman, M., Ed.; Springer Singapore: Singapore, 2019; pp. 607–621, ISBN 978-981-329-150-8.
180. Babajani, A.; Muehlberger, S.; Feuerbacher, A.; Wieck, C. Drivers and challenges of large-scale conversion policies to organic and agro-chemical free agriculture in South Asia. *Int. J. Agric. Sustain.* **2023**, *21*, 2262372. [CrossRef]
181. Han, G.; Grudens-Schuck, N. Motivations and Challenges for Adoption of Organic Grain Production: A Qualitative Study of Iowa Organic Farmers. *Foods* **2022**, *11*, 3512. [CrossRef]
182. Das, S.; Patra, S.; N P, D. *Agricultural Diversification: Necessity, Drivers, and Future Prospects*; 2023; ISBN 978-93-5915-683-5. Available online: https://www.researchgate.net/publication/373419942_Agricultural_Diversification_Necessity_Drivers_and_Future_Prospects (accessed on 15 October 2024).
183. Reardon, T.; Timmer, C.P.; Berdegue, J. The rapid rise of supermarkets in developing countries: Induced organizational, institutional and technological change in agri-food systems. In *The Transformation of Agri-Food Systems*; Routledge: Oxfordshire, UK, 2012; pp. 47–65.

184. Pervaiz, Z.H.; Iqbal, J.; Zhang, Q.; Chen, D.; Wei, H.; Saleem, M. Continuous Cropping Alters Multiple Biotic and Abiotic Indicators of Soil Health. *Soil Syst.* **2020**, *4*, 59. [CrossRef]
185. Hufnagel, J.; Reckling, M.; Ewert, F. Diverse approaches to crop diversification in agricultural research. A review. *Agron. Sustain. Dev.* **2020**, *40*, 14. [CrossRef]