



Enhance the productivity of field crops through bio- and organic fertilization as a sustainable alternative to chemical fertilizers: A Comprehensive review

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Abstract:

Sustainable agriculture has become a global priority in response to the challenges of climate change, soil degradation, and overreliance on environmentally harmful synthetic chemical fertilizers. Field crop productivity depends heavily on soil fertility and nutrient management, making the search for environmentally friendly alternatives critically important. Biofertilizers and organic fertilization methods have gained considerable attention as viable solutions for promoting crop growth and increasing yields while maintaining ecological balance. Biofertilizers, which include nitrogen-fixing bacteria such as *Rhizobium* and *Azotobacter*, phosphate-solubilizing microorganisms, and mycorrhizal fungi, improve nutrient availability and stimulate plant metabolic activities through biological processes. They not only provide essential macro- and micronutrients but also promote root growth, stress tolerance, and overall plant vigor. On the other hand, organic fertilizers derived from compost, animal manure, crop residues, and green manure enrich the soil with organic matter, improve its physical structure, and promote water retention and microbial diversity. When used together, biofertilizers and organic fertilizers create synergistic effects that enhance nutrient cycling, reduce nutrient loss, and support long-term soil fertility.

Recent studies have shown that integrated organic biofertilization systems can significantly increase field crop yields, reduce their dependence on chemical inputs, and minimize negative environmental impacts such as greenhouse gas emissions and groundwater pollution. Furthermore, these systems contribute to climate-resilient agriculture by improving soil carbon sequestration and enhancing biodiversity within the soil ecosystem. This review highlights the mechanisms, benefits, and applications of biofertilization and organic fertilization in field crop production, emphasizing their role in sustainable agriculture. Evidence suggests that the adoption of integrated nutrient management strategies combining biofertilizers and organic amendments represents a promising path toward higher productivity, environmental sustainability, and food security in diverse agricultural ecosystems.

Keywords: Field crops, Crop productivity, Sustainable agriculture, Organic fertilization, Biofertilizers, Soil fertility.

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1. Introduction

Arable crops, including cereals, pulses, oilseeds, and fiber crops, provide the global staple foods and raw materials for many commodity industries, and each year, the direct and indirect economic losses of crop diseases account for more than 10% of the harvest on average worldwide. The world population is predicted to increase by about 30% in the next 27 years, which means global agriculture will have to rise to the unprecedented challenge of feeding this rapid growth of the human population (1). Increasing acreage alone will not suffice, since fertilizers supply over 40% of the yield-enhancing nutrients in most intensive agricultural cropping systems worldwide, so new ways for formulating and using these materials efficiently have to be developed to prevent the loss of total arable land to building and infrastructure, ending up with very uncertain and menacing consequences to be faced in the future (2). Microbial resources can improve fertilizer efficiency and constitute important components of sustainable agriculture (3). Microbial-based biofertilizers, including nitrogen-fixing bacteria, phosphorus-solubilizing and potassium-solubilizing micro-organisms, composting and degrading micro-organisms, and biopesticides, embody nutrient supply, plant nutrition, protection, and growth improvement, and many other aspects of plant health are concerned (4). Biofertilizers contribute to enhanced nutrient use efficiency when combined with organic or chemical fertilizers or both, through microbial activities in the release of plant-available nutrients from organic and inorganic substances and also in maintaining nutrient balance in the rhizosphere by fixing, solubilizing, or mobilizing major nutrients in soil (5). Well-documented cases of the impact of biofertilizers on different field crops highlight the opportunities in developing biofertilizer technologies (6). Microbial inoculants have been widely tested on cereals, pulses, oilseeds, fibers, and commercial crops, with mixed effects on productivity. Nevertheless, examples abound that show impressive increases, and the use of this cost-

effective, eco-friendly technology can be extended to cover other untested crops, especially in conjunction with organic manures and chemical fertilizers (7).

2. Overview of Fertilization Practices

Significant agricultural activities include reseedling, crop protection, and biomass fertilization. These agricultural practices provide raw materials and food, which ultimately shape human lifestyles (8). As water and minerals are essential nutrients for plant growth, residual elements from the previous crop are important. Furthermore, the nutrients in the living organisms present in the soil contribute to soil enrichment, especially when the residues are present on the surface. Moreover, culminating mineral reserves contribute to biomass production (9). For instance, nitrogen is an element that must be supplied externally because it is susceptible to being leached into the subsoil because of its high solubility (10). The production chain comprises the acquisition of inputs, which include water and minerals, followed by plant protection techniques, the implementation of agricultural practices, the harvest period, and post-harvest processing (11).

The cultivation techniques vary according to crop types and soil characteristics. The processes involved in the cultivation of various crops, such as cereals and vegetables, differ (12). Cereal cultivation activities include plowing, turning, seeding, and surface maintenance using mechanical equipment, such as hoes or other agricultural tools. Plowing and turning, harvesting, threshing, transport, storage, packaging, and processing are considered discrete processes of the cereal production chain (13). Biological fixation serves as an alternative method of nitrogen uptake for biomass production by certain plants. In this context, the production chain continues with seeding, followed by biological fixation, harvest, harvesting, and post-harvesting activities. Without biological agents, biomass production substantially decreases, resulting in a significant decrease in yields (14). Cultivation techniques, apart from biological fixation, serve as

the main factors limiting biomass production. Consequently, biological fixation is widely adopted owing to environmental concerns and the increasing economic costs of inputs from other nitrogen sources. Despite these advantages, its adoption remains limited (15).

2.1. Chemical Fertilizers

Chemical fertilizers contain primary nutrients (N, P, K) and secondary nutrients. Their application rates depend on crop requirements for growth, development, and productivity, and on soil nutrient status (16). While chemical fertilizers efficiently supply nutrients to replenish soil N, P, and K for successful cropping, excessive use leads to environmental disruption through contamination of water, soil, and air. High accumulation of phosphate and nitrogen compounds in water causes eutrophication, altering aquatic ecosystems and affecting flora and fauna. Repeated use of chemical fertilizers decreases rice productivity and degrades soil quality in the long term due to acidification, heavy metal accumulation, nitrate leaching, and greenhouse gas emissions (17). Imbalanced fertilizer use harms soil microbial communities, reduces beneficial microbes, and favors pathogens. Heavy reliance on chemical fertilizers increases production costs, decreases market competitiveness, and diminishes product quality (18).

2.2. Bio Fertilizers

Biofertilizers play a pivotal role in enhancing field crop and horticultural productivity by stimulating plant growth via atmospheric nitrogen fixation, phosphorus solubilization, and plant hormone synthesis (19). Essentially, a biofertilizer is a concoction of microorganisms that mobilizes essential elements from chemically fixed nutrient stocks, rendering them accessible to crop plants through a vital symbiotic interplay with the rhizosphere (20). These microbial inoculants augment crop yield and biomass synthesis by mobilizing important macro-elements such as nitrogen, phosphorus, and potassium. Moreover, the

application of biofertilizers to crop plants over an extended period improves the amount of organic carbon and total nitrogen, thereby maintaining soil fertility (21). Biofertilizers are recognized as economical and eco-friendly alternatives to chemical fertilizers and pesticides; due to their cheapness and availability, they are extensively utilized in India by farmers who cannot afford chemical inputs; their use also reduces soil and environmental pollution (22).

In a recent large-scale meta-analysis, the effect of microbial inoculants on the yield of cereal, vegetable, and legume crops was examined using yield data from 171 studies and 6,348 paired observations globally (23). Symbiotic microorganisms, predominantly arbuscular mycorrhizal fungi and rhizobia, were assessed separately from free-living microorganisms such as *Azospirillum*, *Bacillus*, and *Pseudomonas*. Overall, microbial inoculants led to a significant median yield increase of +16.1% relative to uninoculated controls, with variation between recorded crop species and microbial inoculants (24). Low phosphorus availability was identified as a prime limiting factor for nitrogen fixation through the legume-rhizobia symbiosis in agricultural soils, a situation that is largely remediated by biofertilization (21). In arid and semiarid ecosystems, the use of biofertilizers based on nitrogen-fixing bacteria and other beneficial microorganisms is regarded as a viable option to support biogeochemical cycles and increase productivity efficiently (25).

2.3. Organic Fertilizers

Organic fertilizers, derived from materials of plant, animal, or microbial origin, enrich the soil with both nutrients and organic matter. The constituent nutrients must first undergo mineralization by soil microbes, converting them into forms readily absorbed by plants (26).

Common types of organic fertilizers include manure, slurry, compost, sewage sludge, crop residues, and green manure. Manure and slurry are excreta from herbivores such as cattle, sheep, and horses. Compost comprises decomposed organic materials

such as plant waste from kitchen scraps or garden refuse. Crop residues like straw and stalks remain in the field after harvest. Green manure involves the incorporation of fresh plant material into the soil to augment nutrient content (27). Compost application enhances soil fertility by supplying organic carbon, which serves as an energy source for soil microorganisms and stabilizes soil structure (28). The carbon-to-nitrogen (C: N) ratio of compost is a critical parameter; values exceeding 15 indicate nitrogen immobilization and limited nitrogen availability to crops. Optimizing the C: N ratio often requires balancing the proportions of green and dry materials, with supplementary mineral nitrogen sometimes necessary to reach desirable levels (29). Incorporating organic inputs positively affects soil aggregate stability, nutrient content, and microbial biomass, thereby increasing soil fertility and crop yields (30). The decomposition of organic matter releases essential nutrients, such as nitrogen, which support plant development. Additionally, the use of organic amendments promotes sustainable soil management practices that improve long-term crop productivity (31).

3. Importance of Sustainable Agriculture

Sustainable agriculture maintains productivity and usefulness to society indefinitely. Nutrient availability is vital for crop productivity; excessive chemical fertilizer use, coupled with insufficient organic manure application, threatens sustainability. Bio and organic fertilizers augment nutrient balance and are fundamental for sustainability. Comprehensive biofertilizer adoption is necessary for sustainability (32).

4. Mechanisms of Biofertilizers

Bio-fertilization is a promising, cost-effective, efficient, and eco-friendly innovation providing sustainable alternatives to enhance plant development and productivity. Biofertilizers are typically formulations containing an inoculum of living or latent cells of efficient strains of nitrogen-fixing, phosphate-solubilizing, or cellulolytic

microorganisms. When added to soil or crop rhizospheres, these live microorganisms mobilize nutrients from non-useable to usable forms, thereby increasing mineral nutrient supply (18). The success of biofertilization depends on the beneficial interaction between plant roots and microbes, with the living inoculated microorganisms persistently multiplying and colonizing the roots to promote growth (2). Biofertilizers regulate crop growth and productivity through mechanisms such as nitrogen fixation, phosphorus solubilization, zinc solubilization, potassium solubilization, phytohormone production, antibiotic production, and siderophore production (20).

The biofertilizer concept originated with the use of *Rhizobium* as a source of nitrogen for legumes but now covers a wider spectrum of fertility agents, including a range of bacteria, filamentous fungi, and algae (22). The increase in plant growth observed with biofertilization is attributed to improved nitrogen supply, production of growth-promoting substances, and beneficial effects of symbiotic fungi. Common biofertilizers encompass nitrogen fixers such as *Rhizobium*, *Azospirillum*, *Azotobacter*, and cyanobacteria; phosphate solubilizers like *Bacillus*, *Pseudomonas*, and *Penicillium*; zinc solubilizers, including *Pseudomonas* and *Bacillus*; potassium solubilizers such as *Frateriella aurantia*; phosphate-mobilizing fungi; and vesicular arbuscular mycorrhiza (VAM) (6). Recently, the term “biofertilizers” has been redefined as formulations containing specific beneficial microorganisms that enhance the availability of nutrients from non-usable to usable forms through biological cycling, subsequently promoting plant growth (33).

4.1. Microbial Activity

Fertilizers significantly improve plant growth, productivity, and food quality, with the widespread use of chemical forms impacting soil fertility, human health, and the ecosystem. Environmentally sustainable alternatives are thus essential to reduce chemical-fertilizer application (34). Bio and organic fertilization offer such solutions, motivating

numerous field-crop researchers to study their effects on productivity and yield (35).

Biofertilizers are preparations containing living or latent cells of efficient strains of nitrogen-fixing, phosphate-solubilizing, or cellulose-decomposing microorganisms. Applying these enriches the rhizosphere or soil with beneficial microbes that mobilize nutrients from virtually unavailable sources, connecting nutrients to existing supplies and enhancing plant availability (22). Biofertilizers function either by providing an essential nutrient through microbial activity (e.g., *Rhizobium*, *Azotobacter*, *Azospirillum*, blue-green algae, or *Azolla*) or by stimulating plant growth via the synthesis of growth-promoting substances (e.g., *Bacillus megaterium*, *Bacillus circulans*, and phosphate-solubilizing bacteria) (2). They also regulate soil microbial communities, stimulate beneficial microbes, replenish nutrient status, and significantly increase yields (36).

Microorganisms thrive in organic-fertilizer-enriched environments due to readily available organic material, fostering higher populations and, consequently, increased mobilization of unavailable nutrients. A closer soil microorganism–nutrition relationship exists when organic fertilizer is applied. Enhancing soil nutrients consequently boosts microbial counts (37). The naturally elevated microbial population in organic-fertilizer soils, coupled with the nutrients it provides, leads to maximum nutrient availability. The prevalent microbial population also reinforces the soil's available nutrient content (38). Extensive literature supports organic fertilization for sustainable agriculture, further confirming its benefits on the ecosystem and humans beyond productivity improvements (28).

4.2. Nutrient Cycling

The efficient cycling of nutrients through the soil-plant atmosphere continuum in agroecosystems underpins plant nutrition and productivity. However, anthropogenic pressures challenge the maintenance of cycling pathways and soil ecosystem services on

a sustainable trajectory (39). Within the plant-soil rhizosphere complex, nutrient and energy fluxes undergo continuous, intense recycling. Biofertilizers stimulate these processes by activating the nutrient cycle, thereby increasing the photosynthetic capacity of plants and releasing hormones conducive to growth via the action of natural microflora on soils and vegetal detritus (40).

The use of biofertilizers represents a strategy aimed at recycling the soil's nitrogen, phosphorus, potassium, and micronutrients. The efficiency of nutrient use is thereby increased, leading to improved production and a reduction in the need for chemical fertilizers (41). Phosphorus fertilization, in particular, is challenging because a significant fraction added to soil becomes insoluble and consequently unavailable to plants. Biofertilizers for phosphorus fixation, solubilization, and mobilization are employed to circumvent this limitation (42).

Accordingly, the use of biofertilizers facilitates the recycling of major and trace elements necessary for field crop growth and production (2,7,43).

5. Types of Organic Fertilizers

Compost, manure, and green manure are different types of organic fertilizers (29). Compost consists of decomposed organic waste generated from crop residues, animal manure, and animal wastes (44). This material is stabilized readily by microbial activity. Application of organic fertilizers is basically a need to recycle a large quantity of crop residues and organic materials. About 11-25% of farmers applied compost by the mid-2000s using crop residues, farmyard manures, and household refuse. The organic carbon content of compost is generally in the range of 12-20%, responsible for its function as an energy source for soil organisms and a supply of nutrients for plants. The C/N ratio of compost is also an important factor that determines the quality of compost. A higher C: N ratio (>15) indicates a limited nitrogen availability, and compost produced through higher carbon materials should be supplemented with nitrogen to optimize the system

(45). Green materials generally have a low C/N ratio (10-15), making them better as a composting feedstock than dry woody materials with high C/N ratios of 40-70. Manure consists of organic wastes generated from domestic animal excreta, with a different composition depending on the type of animals and their rearing condition. Fertilizer applied at the rate of 15–25 t ha⁻¹ increased the plant dry weight compared to that of a lower dose. The highest yield was obtained at a rate of 20–25 t ha⁻¹. Soybeans responded better to the dry field rice residues than the maize residues as a source of organic fertilizers. Application of 15–25 t ha⁻¹ organic fertilizer increased the growth and yield of soybean after rice cultivation (7). These results imply that different residues from previous crops can be used to enhance the productivity of soybean through organic fertilization. Application of organic fertilizers via quick artificial decomposition enhances the crop growth (26). The produced fertilizer can increase the crop yield and quality compared with mineral and conventional organic fertilizers. Further studies on the fertilizer production and the function of organic nutrients provide a direction to improve organic fertilizers (46). Applying organic fertilizers such as compost, farm yard manure, biogas manure, and biofertilizers results in a considerable increase in grain yield and yield components. Application of organic fertilizers via quick artificial decomposition enhances growth, yield, and quality of cabbage (47).

5.1. Compost

Compost is the process of recovering potentially recyclable waste by means of a controlled aerobic biological process, which converts the organic fraction of waste into a stable product that can be used as a soil conditioner or as a fertilizer (29). Compost as a common organic fertilizer in many developing countries, results from the fermentation of plant remains and animal excrement, leaving a dark, crumbly material (48). When high-quality compost is added to the soil, it improves soil physical, chemical, and biological properties such as

soil water content, cation exchange capacity, nutrient retention, and microbial activity. Furthermore, because the amount of organic fertilizer used by farmers in developing countries is small, the addition of well-decomposed compost at 10 to 30 t ha⁻¹ is enough to reduce challenges such as low field crop productivity and frequent extension calls from farmers (49).

5.2. Manure

Manure is one of the oldest and most utilized forms of organic fertilizer. The major sources of manure include farm yard manure, poultry manure, green manure, and composts. Manure plays an important role in improving plant growth, seed germination, and crop yield (50). Combined application of N and P fertilizers with manure increased maize yield and nutrient uptake by stimulating root growth in a long-term experiment. Organic amendments enhance soil structure and water retention, thereby increasing fertilizer use efficiency (51).

5.3. Green Manure

Green manure—consisting of a crop specifically grown to be incorporated into the soil before reaching maturity—commonly comprises leguminous plants like *Sesbania rostrata* or *Crotalaria juncea* that embody one of the oldest bio-fertilization forms (52). The agronomic benefits ensuing from green manure application resemble those of bio-fertilizer amendments. It can increase the content of available nitrogen, phosphorus, and potassium in soil. Additionally, it enhances soil microbial activity, which in turn activates soil nutrients and promotes productivity; consequently, a reduction in chemical fertilizer application often does not significantly affect soil nutrient levels (53). The advantageous effects of green manure arise from nitrogen fixation and its capacity to mobilize phosphorus and trace elements from the subsoil. For example, its integration into a cereal legume crop rotation system leads to a maize grain yield increase averaging 600 kg ha⁻¹ compared to unfertilized control plots, while a similar arrangement with

Sesbania as green manure in Senegal has been reported to double the yield relative to control, with an overall increase of 50% (54).

Despite these benefits, adoption of green manure has generally been low. Its main disadvantages include the lack of immediate benefits, the typically short-lived effect in tropical soils, nonalignment with traditional farming practices, and significant labor requirements. However, cultivating fodder legumes in crop sequences and intercropping can help mitigate these constraints (55).

6. Comparative Analysis of Fertilizer Types

Sustainable intensification of agricultural production requires the maintenance and improvement of the soil resource base. To meet of an accelerating world climate and environmental changes, environmental impacts mitigation and prosperity goals, sustainable agriculture is therefore fundamental. Such a requirement has a great influence on the inputs used in agricultural production (56). Fertilizers for long times have an important role not only in modulating plant growth but also in soil sustainability. Besides the traditional chemical fertilization, new alternatives are reaching increasing attention, such as bio and organic fertilization (57). Chemical fertilizers include inorganic compounds supplying macronutrients nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur, as well as micronutrients. Bio fertilizers consist of beneficial living microorganisms belonging to diverse taxa and providing different services to field crops, e.g., nitrogen fixation, phosphate solubilisation, pest and disease mitigation. Organic fertilizers are organic matter predominantly made of plants, but can also be animal wastes (58). The blossom of papers addressing the contribution of bio and organic fertilizers to sustainable crop productivity has led to the need for a comprehensive review of their importance in the context of cereal and vegetable crop production, alongside a necessity to stress their significance as alternatives to chemical fertilizers. Chemical fertilizer encourages the rapid development curve of the plant, which leads to the

improvement of fruit yield, quality, and shelf-life (59). Under micro-irrigation in Southwest Nigeria, inorganic fertilizers gave the best fruit yield and economic advantage. This corroborates the importance of chemical fertilizer in providing an appreciable increase in crop yield (60), but it comes with drawbacks. The continuous use of chemical fertilizers upsets the availability of soil nutrients, which affects sustainable production. With the precision agriculture concept recently receiving wide attention, the use of applying chemical fertilizers and pesticides in high quantities has been declining, while bio and organic fertilizers have witnessed a wider spread (16). Bio and organic fertilizers continue to receive increased attention across the globe as they address the environmental challenges associated with chemical fertilizer use.

6.1. Effectiveness on Crop Yield

Linked to the high cost of synthetic fertilizers and concerns about their environmental impact, there is a renewed interest in enhancing crop productivity through bio- and organic fertilization. While the effect of organic fertilizers on growth, yield, and quality has long been recognized, biofertilizers are emerging as a viable alternative to synthetic inputs. With the dual aim of maximizing fertility in a cost-effective and environmentally friendly manner, much research has explored how biofertilizers influence productivity (28).

Globally, synthetic fertilizers continue to dominate crop management, with an expected market increase of more than 35% between 2016 and 2023. Their excessive use, along with improper management of organic wastes, has disrupted soil ecosystems, reduced biodiversity, and caused severe environmental pollution. Consequently, there is a growing interest in bio- and organic fertilization, particularly within sustainable agriculture, whereby soil fertility and crop performance can be improved naturally and economically (61).

Biofertilizers consist of living microbes that enhance the availability, supply, and uptake of primary nutrients for plants through biological activity in the

rhizosphere. Such input positively affects various physiological processes related to plant growth, including nitrogen fixation, nutrient uptake, and solubilization of insoluble nutrients, with significant effects on crop productivity. Compared to biofertilizers, organic fertilizers act more slowly in releasing nutrients, but their content and microbial populations help induce long-term beneficial effects in the agricultural ecosystem. As forms of sustainable fertilization, bio- and organic fertilizers preserve soil fertility, optimize nutrient use efficiency, and reduce negative externalities (62).

Shedding light on the specific effectiveness of bio- and organic fertilizers, many studies have reported positive impacts on crop yield. For instance, the use of dried rice residues (DPR) after 30 days of decomposition to fertilize soybean promoted better growth and seed yield compared to maize residues or no organic amendment, with 15–25 t/ha of organic fertilizer also producing higher biomass (7). Similarly, in vertisols, inoculation with *Azospirillum* and phosphate-solubilizing bacteria, combined with vermicompost, *Trichoderma viride*, 100% inorganic nitrogen, and farmyard manure, significantly improved rainfed coriander performance, increasing the number of secondary branches and umbels per plant, and contributing to nitrogen fixation and soil enrichment (19). These findings corroborate earlier reports that legumes can alter chemical properties in the rhizosphere, influencing pH and nutrient uptake, while organic manures such as farmyard manure often elicit yield increases across crop types and soil conditions when applied at 3–6 t/ha (54).

6.2. Soil Health Impacts

Bio and organic fertilization are considered important approaches for sustainable yield intensification because they effectively enhance crop yields, either alone or in combination with chemical fertilizers. These fertilization methods also improve soil fertility by establishing balanced biogeochemical cycles and supporting key soil biological functions (7,63). During the early stages of crop growth, bio fertilizers promote rapid plant

development—with taller plants, more foliage, and larger leaf areas—compared to plants receiving only chemical fertilizers (64).

7. Case Studies on Biofertilization

Biofertilization contributes significantly to the productivity of both cereal and vegetable crops. The practice is based on the application of microorganisms such as plant growth-promoting rhizobacteria, mycorrhiza, and nitrogen-fixing bacteria. These biofertilizers can produce and excrete regulatory substances that stimulate plant growth, an activity that mimics the natural soil microbial activity responsible for nutrient cycling and plant productivity. They can also improve the availability of mineral nutrients such as phosphorus and iron, and establish symbiotic relationships that supply leguminous plants with nitrogen (60). Various studies have documented the positive effects of microbial fertilizers. In cereal crops, the use of *Rhizobium* with nitrogen, phosphorus, and potassium fertilizer improves both cereal and legume yields. *Azotobacter* application to field crops enhances productivity; *Rhizobium*, *Bacillus*, and *Azospirillum* increase grain yield; and *Azolla* incorporation can replace up to 40 % of nitrogen fertilizer requirements for rice. In vegetable production, combining *Azotobacter* and *Phosphobacterium* with half the recommended dose of chemical fertilizer yields better results than either alone (7). Bio fertilizers, therefore, hold promise as sustainable and environmentally safe tools to improve field crop productivity.

7.1. Cereal Crops

Cereal crops are among the most important for human nutrition worldwide. Salinity stress is a major challenge in agriculture, especially in arid and semiarid regions, affecting plant water relations and causing physiological drought and cell dehydration. Heavy metal bioavailability in soil can be minimized through biological immobilization using organic fertilizers like cattle manure and poultry manure, which improve crop growth and yield without

environmental harm. Poultry manure is particularly valued for its high nitrogen content (65). Integrated application of bio-, organic, and inorganic nitrogen fertilizers, such as combining ammonium nitrate, bio-fertilizer, and cattle manure, can enhance wheat growth, yield, and minimize heavy metal uptake, especially in saline soils (66).

7.2. Vegetable Crops

Application of bio-fertilizers comprising beneficial microbes such as nitrogen fixers, mycorrhizal fungi, PGPR, and plant growth regulators has been widely adopted in field crops. Benefits include targeted nutrient supply through symbiotic interactions, improved nutrient uptake, enhanced photosynthesis, and strengthened stress resistance (67). Significant yield increases have been demonstrated in cereal and vegetable crops and a range of industrial crops at moderate costs. The practices contribute to nutrient cycling and organic matter buildup, especially when integrated with recent innovations; wider adoption will reduce yield losses and pollution compared to exclusive reliance on chemical fertilizers (68).

Co-application of reduced chemical fertilizer amounts and bio-organic fertilizer significantly improves the yield and quality of cauliflower, with concomitant enhancements in soil biochemical properties, microbial communities, and environment (69). Supply of bio-organic fertilizer raises the contents of soil organic matter and available nutrients, and maintains relatively stable pH and electrical conductivity. These improvements may prevent the harmful effects of high levels of soluble salts on plant growth during continuous cropping. Activities of sucrose, urease, alkaline phosphatase, and β -glucosidase are effectively enhanced by bio-organic fertilizer application (70). Microbial richness, diversity, and evenness are also much greater under combined fertilization with reduced chemical fertilizer and bio-organic fertilizer. The results indicate that the combined application restrains the reduction in soil quality caused by the overuse of chemical fertilizers and is an effective

strategy for sustainable and high cauliflower yield production (16).

9. Challenges in the Adoption of Organic Practices

Despite the documented benefits of organic cultivation, there has been limited adoption of organic practices during the early years of the expansion of organic farmland (71). Moreover, the successful adoption of organic farming is restricted to a few countries across the globe. Several hypotheses have been proposed to explain these difficulties. The major issues surrounding organic farming concern the establishment of reliable fertilizer supply chains and the management of field and crop residues to optimize fertilizer use efficiency (72). All of these factors represent significant bottlenecks hindering the adoption of organic farming on a global scale. Additionally, policy frameworks, marketing strategies, and infrastructure provide little support for organic farming, making access to organic inputs expensive and often unaffordable for many small-scale producers and farmers (73). However, it is important to note that organic farming contributes to sustainable development goals, facilitates a just transition to a low-carbon, green economy, and improves the livelihoods of smallholder farmers, making the promotion of bioorganic practices vital.

The current adoption of organic farming is constrained by limited access to sustainable supply chains, smallholder farmers' lack of market power, local producers spare limited land for organic matter production, availability and access to certified organic seed are low, and there is a lack of extension on organic farming and crop pest management practices. These factors are central causes and major challenges hindering wider adoption of organic farming, impeding the opportunity of fully harnessing economic, environmental, and trade benefits from organic cultivation. Moreover, limited availability of fertilizers and their high cost, coupled with limited access to export markets and the resulting low profitability, act as major limitations to

the expansion of organic farming to date in most countries with arid and semi-arid agro-ecological zones (74).

10. Future Directions in Research

The future of bio-fertilization lies in innovating strategies to maximize productivity, quality, and ecological protection. Biofertilization enhances crop yields through mechanisms including nitrogen fixation, phosphorus solubilization, nutrient mobilization, uptake stimulation, hormonal effects, and organic residue decomposition. Yet, full farming-system benefits require microbial inputs beyond a few decades and remain underexploited in intensive agriculture (75). Concepts such as Site-Specific Bio-management (SSB) and precision bio-fertilization integrate spatiotemporal nutrient supply with microbial inoculant functions to tailor applications to particular field heterogeneity patterns and current crop requirements (76). Concentrating on microbial consortia capable of coexisting and colonizing particular crops can amplify efficacy and potentially improve productivity and resilience beyond single strains. Consequent progress depends on a sound regulatory framework and close collaboration among farmers, industry, scientists, and policymakers to cultivate integrated, efficient, and profitable agroecosystems. Combining bio-fertilization with artificial intelligence and machine learning further facilitates applying principles of climate-smart bio-fertilizers in agricultural systems (2,4,32).

10.1. Innovations in Biofertilization

Over the last 50 years, the expansion of fertilizer, pesticide, and agricultural machinery industries has enabled per-acre global food production to more than triple. Biofertilizers are formulated preparations containing living microorganisms that, when applied to seed, plant surfaces, or soil, colonize the rhizosphere or the interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant (4). Several microorganisms, living either freely or symbiotically

with plants, have been employed as biofertilizers. Biofertilization involves the application of the nitrogen-assimilating bacterial inoculant to the soil and is recognized as an important constituent for increasing crop yield by augmenting the soil nutrient status and improving soil health (2). Humic or fulvic acid can be added to the soil with other fertilizers to increase nutrient availability and improve the efficiency of chemical fertilizers and biofertilizers (77).

10.2. Integrating Organic Practices with Technology

In the embarkation of smarter agricultural practices, the amalgamation of organic and technological approaches holds savoury prospects for fruition. Indeed, a combination of technologies with sustainable agricultural practices becomes necessary for a food-secure yet ecologically sound future (78). As an illustrative case, incorporation of organic manures with judicious application of chemical fertilizers and pesticides led to a 30 to 40% decline in the requirement in vegetable cultivation (79). Such savings validate appreciable augmentation of soil health and its industrial potential as a resource and stock for future utilization.

Better results than the use of mineral fertilizers alone can be achieved by their balanced application together with organic manures, stressing the need for synchronizing nutrient release that can still be realized or extended by future advancements (80).

11.1. Support for Sustainable Practices

Agriculture's role in maintaining livelihood and economic security is indispensable, necessitating enhancements in the productivity and efficiency of systems such as rice, wheat, maize, cotton, pulses, and sugarcane (81). Increasing crop nutrients and yield sustainably, in tandem with soil health and resource conservation, has become imperative due to rising food demand and environmental concerns. Both organic and bio fertilizers play a vital role in this endeavour. Organic fertilizers—derived from plant, animal, and mineral sources—offer essential

primary nutrients while enriching soil organic matter and moisture content. Biofertilizers involve specific microorganisms that promote nutrient availability and other beneficial soil processes. Their effective use has demonstrated significant improvements in crop productivity, addressing the dual challenges of food security and environmental sustainability (67). These considerations underpin the growing emphasis on eco-friendly agricultural inputs and the imperative to reduce the environmental footprint of fertilization strategies.

12. Environmental Impact of Fertilizer Use

Chemical fertilizers synthesize macro- and micronutrients, but their intensive use seriously affects soil and water environments (4). Overapplication of chemical fertilizers leads to eutrophication and acidification of aquatic ecosystems, resulting in excessive fertilization coupled with chemical pollution. Despite increasing use worldwide, the soil absorption of these nutrients fails to match agricultural productivity requirements, causing nutrients to leach into the environment. Meanwhile, soil fertilizer stocks diminish and water pollution arises (82).

12.1. Eutrophication

Eutrophication generally refers to nutrient enrichment of water bodies with consequent adverse effects, including oxygen depletion and life loss. Anthropogenic eutrophication, as a consequence of excessive nutrients in surface waters, is one of the greatest threats to aquatic systems globally. It forms the major cause of impairment for inland waters; groundwater and transitional and coastal waters often suffer from the effects of eutrophication as well (4). Atmospheric inputs of nutrients from the combustion of fossil fuels add more nutrients to the environment, which will be deposited onto terrestrial and aquatic ecosystems. Chemical fertilizers are the main agents of global eutrophication. Unwanted enrichment of artificial waters is well recognized as having an adverse impact on ecosystems and causing excessive blooms of aquatic plants and subsequent

hypoxia. The presence of excess nutrients (usually phosphorus and nitrogen) in soils can also lead to some types of land degradation, including acidification, salinization, and toxicity (83).

12.2. Soil Degradation

Soil degradation is the decline in soil quality caused by improper management, such as organic carbon loss and erosion, leading to low fertility and increased risks of desertification. These processes decrease the provision of essential ecosystem services needed to support life (84). The widespread use of synthetic fertilizers and pesticides in intensive agriculture to improve the quality of agricultural products has contributed to the deterioration of natural resources such as soil, water, and biodiversity, resulting in environmental problems such as water pollution and soil degradation (7). Soil degradation impacts nitrogen availability, soil fertility, and organic matter content, and thus agricultural productivity. This, in turn, influences soil microbial biomass and enzyme activities and hence carbon sequestration. Long-term management options such as organic and inorganic fertilization can help fight land degradation and return the soil to its original condition. Maintaining soil organic carbon is therefore necessary for the improved and sustained fertility and productivity of farming systems. Consequently, targeted use of organic resources and fertilization strategies for maintaining soil organic carbon would play an important role in land reclamation and sustainable farming (85). Application of organic fertilizer has a considerable impact on the physiology, growth, development, and yield of the soybean crop. Increasing the application rate of organic fertilizer from 15 to 25 t/ha resulted in higher plant dry weight per plot compared to 0 to 10 t/ha. Yield of dry seeds per plot was also significantly improved when organic fertilizer was applied at the rate of 20 to 25 t/ha, compared to 0 to 15 t/ha. Application of dry field rice residues was more effective in improving the growth and yield of soybean than maize residues. Dry field rice combined with 15- to 25-t/ha organic fertilizer

application was accordingly recommended to improve growth and yield of soybean cultivated under dry land system (86). Practices such as manure application, mineral fertilizer application, crop residue incorporation, and tillage strongly influence soil microbial biomass, soil C storage, and crop yields with time. Organic carbon storage, crop yield, and nitrogen availability are generally improved in degraded systems and reduced in intensive systems. Soil microbes are considered key indicators of soil quality, and the assessment of soil microbial biomass reflects the impact of various land use amendments and contaminants on soil quality (87).

13. Conclusion

Bio and organic fertilization of field crops has attracted world research attention because they are sustainable alternatives to the use of synthetic fertilizers. The sites of application or sources of bio and organic fertilizers are diverse, and these include soil, seeds, leaves, varied residues, and others. Various reports demonstrate the prospects of bio and organic fertilizers for supporting food security and increasing biomass production. They are the products of natural organic materials and microbes, vermicast, animal excreta, liquid decanted manure, bone meal, and some other materials. Bio and organic fertilizers are known to contain significant amounts of N, P, K, and other macro- and microelements needed for growth and development. Their capacity to interact and supplement deficiencies in chemical fertilizers has brought them to the forefront of modern farming practice. Bio-fertilizers involve the use of microbes containing Bacteria, Fungi, and Algae that increase the availability of major nutrients to crops through mobilization, nitrogen fixation, production of growth-promoting substances, and solubilization of unavailable nutrients, especially phosphates. The application of biomass for food production poses a threat to the sustainability of the environment and increases the risk of eutrophication. It is therefore necessary to find alternatives to biomass that can ensure sustainable food production without

compromising the environment and health. The use of bio- and adjusted organic fertilizers could give a way out as a source of low-cost and environmentally friendly fertilizers and will significantly reduce the dependence, exchange, and flow of fertilizers from one region to another (2,29).

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