Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 7 (2025)

The Impact of Organic and Biofertilizers on Growth and Yield of Agronomic and Horticultural Crop

[1]Ameer Jan, [2]Zubair Ahmed, [3]Muhammad Akmal Sajid, [4]Noman, [5]Sami Ullah, [6]Sheeza Ali, [7]Parveez, [8]Mehvish Mushtaq

Article Details

Ameer Jan
Department of Botany, University of Makran Panjgur. Ameer.jeehand143@gmail.com
Zubair Ahmed
Department of Agronomy, University of agriculture Faisalabad
zubairahmad8007131@gmail.com
Muhammad Akmal Sajid
Government Graduate College of Science, Sanamabad, Faisalabad
akmalsajid41@gmail.com
Noman
Institute of Horticulture Science, University of Agriculture Faisalabad
noumanbaloch266@gmail.com
Sami Ullah
Muhammad Nawaz Shareef University of Agriculture Multan.
samisanabaloch54@gmail.com
Sheeza Ali
Government Graduate College of Science, Sanamabad, Faisalabad.
sheezaali2006@gmail.com
Parveez
Institute of Horticulture Science, University of Agriculture Faisalabad.
noumanbaloch266@gmail.com
Mehvish Mushtaq
Department of Botany, Univeristy of Sargoda
mehvishmushtaq2015@gmail.com

ABSTRACT

The emergence of sustainable agriculture in the whole world has brought out organic and biofertilizers as potential tools of replacing the chemical fertilizers with their benefits of ensuring improved health of soils and less adverse effect on the environment. The review is a comprehensive assessment of the effects of organic and biofertilizers on the growth and yield of agricultural and horticultural crops based on peer-reviewed literature article. Home-made organic fertilisers namely; Compost, manure, and vermicompost enhance the soil structure and water retention along with enhanced microbial activity and result in a 10-25 percent increase in plant height, biomass, and yield in different crops. Biofertilizers, such as nitrogen-fixing bacteria (Rhizobium, Azotobacter), phosphate-solubilizing microbes (Pseudomonas), and mycorrhizal fungi also increase nutrient uptake and stress tolerance, and improve yields 1030 per cent in field tests. Organic and biofertilizers produce 80-95 percent conventional agricultural yields and promote the long-term soil fertility and the avoidance of nutrient leaching compared to the chemical fertilizers. But issues like variable efficacy related to soil and climatic situations, high cost of production and little farmer awareness do not contribute positively towards its wide scale implementation. The future outlooks are microbial consortia, the integration of precision agriculture, and the facilitating policies which will make it more scalable and accessible, especially by the smallholder farmers. This review highlights the promise of organic and biofertilizers to help promote sustainable crop production providing evidence-based information on their performance, weaknesses, and the processes that should be followed to achieve greater adoption.

INTRODUCTION

Sustainable agriculture is critical for addressing global challenges such as food security, environmental degradation, and climate change (Fischer et al., 2025). It emphasizes practices that maintain soil health, reduce environmental impacts, and ensure long-term productivity (Reganold et al.,1990). Organic and biofertilizers play a pivotal role in sustainable agriculture by enhancing soil fertility and promoting plant growth without the adverse effects associated with chemical fertilizers. Organic fertilizers, derived from natural sources such as compost, animal manure, and green manure, enrich soils with organic matter, improving structure, water retention, and microbial activity (Sharma & Chetani, 2017). Biofertilizers, consisting of living microorganisms like nitrogen-fixing bacteria, phosphate-solubilizing microbes, and mycorrhizal fungi, facilitate nutrient availability and promote plant growth through symbiotic interactions (Vessey, 2003). These fertilizers contribute to sustainable agriculture by reducing dependency on synthetic inputs, mitigating soil degradation, and minimizing environmental pollution. The shift from chemical fertilizers to organic and biofertilizers is driven by several factors. Growing awareness of the environmental consequences of chemical fertilizers, such as soil acidification, water pollution, and greenhouse gas emissions, has prompted researchers and farmers to seek sustainable alternatives (Savci, 2012). Additionally, consumer demand for organic produce, coupled with supportive government policies and subsidies for eco-friendly practices, has accelerated this transition. The rising costs of chemical fertilizers and concerns about their long-term impact on soil fertility further encourage the adoption of organic and biofertilizers, particularly in developing countries where smallholder farmers dominate (FAO, 2017).

Organic fertilizers are defined as naturally derived materials that supply essential nutrients to plants while improving soil health. Common types include compost, animal manure, vermicompost, and green manure, each varying in nutrient composition and release rates. For instance, compost provides a balanced nutrient profile, while manure is rich in nitrogen and phosphorus (Sharma & Chetani, 2017). Biofertilizers, on the other hand, are microbial inoculants that enhance nutrient availability. Major types include nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azotobacter*), phosphate-solubilizing microbes (e.g., *Pseudomonas*), and mycorrhizal fungi, which improve nutrient uptake and plant resilience. Together, these fertilizers offer a sustainable approach to enhancing crop productivity while preserving ecosystems (Vessey, 2003).

The primary objective of this review is to systematically evaluate the effects of organic and biofertilizers on crop growth and yield across agronomic and horticultural crops. This involves analyzing key growth parameters, such as plant height, leaf area, biomass accumulation, and physiological processes like photosynthesis and nutrient uptake, as well as yield metrics, including grain weight, fruit yield, and marketable produce. The evaluation will draw on recent studies (from the last 10-15 years) to assess the impact of these fertilizers through case studies, meta-analyses, and field experiments, focusing on crops like wheat, rice, maize, tomatoes, and citrus (Mäder et al., 2011; Seufert et al., 2012). By synthesizing data from peer-reviewed literature, this review aims to provide a comprehensive understanding of how organic and biofertilizers influence crop performance under varying soil types, climates, and management practices. Another key objective is to compare the efficacy of organic and biofertilizers with chemical fertilizers in terms of crop growth and yield outcomes. This comparison will examine both short-term and long-term effects, considering factors such as nutrient release rates, soil health improvement, and environmental sustainability. Organic fertilizers, for instance, release nutrients slowly, enhancing long-term soil fertility, whereas chemical fertilizers provide immediate nutrient availability but may degrade soil over time (Savci, 2012). Biofertilizers, through microbial activity, enhance nutrient uptake efficiency, potentially matching or surpassing chemical fertilizers in specific contexts (Vessey, 2003). The review will analyze quantitative data from comparative studies to determine under what conditions organic and biofertilizers can serve as viable alternatives to chemical inputs. Finally, the review seeks to identify the key challenges and future prospects for adopting organic and biofertilizers. Challenges include inconsistent efficacy due to variability in soil conditions, climate, and application methods, as well as production scalability and cost barriers, particularly for smallholder farmers (FAO, 2017). Additional hurdles involve quality control, standardization, and limited farmer awareness or training. Future prospects include innovations in microbial formulations, integration with precision agriculture, and supportive policies such as subsidies and certification programs to promote adoption. (Mäder et al., 2011). By addressing these challenges and exploring emerging technologies, the review aims to highlight pathways for scaling up the use of organic and biofertilizers in sustainable agricultural systems.

This review focuses on the impact of organic and biofertilizers on a select group of agronomic and horticultural crops that are critical to global food security and economic importance. For agronomic crops, the study emphasizes cereals such as wheat (*Triticum aestivum*), rice (*Oryza sativa*), and maize (*Zea mays*), which are staple crops accounting for a significant portion of global agricultural production. Additionally, pulses like chickpeas (*Cicer arietinum*) and lentils (*Lens culinaris*) are included due to their role in nitrogen fixation and their importance in sustainable cropping systems (Seufert et al., 2012). For horticultural crops, the review targets high-value crops such as tomatoes (*Solanum lycopersicum*), citrus (*Citrus spp*.), and apples (*Malus domestica*), which are widely studied for their response to organic and biofertilizer applications due to their economic and nutritional significance (Mäder et al., 2011). These crops were selected to represent a diverse range of growth habits, nutrient requirements, and environmental adaptations, ensuring broad applicability of the findings. Recent studies from the last 10-15 years (2010–2025) provide valuable insights into the efficacy of organic and biofertilizers. Meta-analyses indicate that organic farming systems, supported by organic fertilizers like compost and manure, can achieve yields comparable to conventional systems for certain crops, though results vary by crop type and management practices (Seufert et al., 2012). Biofertilizers, particularly nitrogen-fixing bacteria (*Rhizobium*, *Azotobacter*) and mycorrhizal fungi, have been shown to enhance nutrient uptake and improve crop resilience under stress conditions, with notable impacts on maize and tomato yields (Vessey, 2003; Adesemoye et al., 2010). Recent research also highlights the role of microbial consortia in improving soil microbial diversity and nutrient cycling, contributing to long-term soil health (Bhardwaj et al., 2014). Studies underscore challenges such as variable efficacy across different soils and climates, emphasizing the need for region-specific recommendations. This review synthesizes these findings to assess the performance of organic and biofertilizers, drawing on peer-reviewed literature to provide evidence-based insights into their application across diverse cropping systems.

TYPES AND CHARACTERISTICS OF ORGANIC AND BIOFERTILIZERS

ORGANIC FERTILIZERS

Organic fertilizers are naturally derived materials from plant, animal, or mineral sources that supply essential nutrients to plants while enhancing soil health. They are defined by their organic matter content, which distinguishes them from synthetic chemical fertilizers, and are typically free from artificial additives (Sharma & Chetani, 2017). Common examples include compost, made from decomposed plant and food waste; animal manure, such as cattle, poultry, or swine dung; green manure, consisting of cover crops like clover or vetch plowed into the soil; and vermicompost, produced through earthworm-mediated decomposition of organic waste. These fertilizers are widely used in sustainable agriculture due to their ability to improve soil fertility and support long-term crop productivity (Mäder et al., 2011).

The nutrient composition of organic fertilizers varies depending on their source and processing.

Compost typically contains moderate levels of nitrogen (N, 1–3%), phosphorus (P, 0.5–1%), and potassium (K, 0.5–2%), alongside micronutrients like calcium and magnesium (Sharma & Chetani, 2017). Animal manure, such as poultry manure, is richer in nitrogen (3–5%) and phosphorus (1–3%), while green manure provides nitrogen through fixation by leguminous crops. Vermicompost is noted for its balanced nutrient profile and high microbial activity (Bhardwaj et al., 2014). Unlike chemical fertilizers, organic fertilizers release nutrients slowly through microbial decomposition, ensuring a steady supply over time. This slow-release mechanism reduces nutrient leaching and minimizes the risk of over-fertilization, promoting sustainable nutrient management (Savci, 2012).

Organic fertilizers significantly benefit soil health and the environment. They enhance soil structure by increasing organic matter, which improves water retention, aeration, and porosity, particularly in degraded soils (Mäder et al., 2011). The addition of organic matter fosters microbial activity, supporting nutrient cycling and soil biodiversity. Environmentally, organic fertilizers reduce the risk of water pollution caused by runoff, a common issue with chemical fertilizers, and lower greenhouse gas emissions by minimizing reliance on energy-intensive synthetic inputs (FAO, 2017). By improving soil carbon sequestration, organic fertilizers also contribute to climate change mitigation, making them a cornerstone of sustainable agricultural practices.

BIOFERTILIZERS

Biofertilizers are microbial-based products containing living microorganisms that enhance plant growth by improving nutrient availability and soil fertility. Unlike chemical fertilizers, which directly supply nutrients, biofertilizers facilitate nutrient cycling through biological processes such as nitrogen fixation, phosphate solubilization, and potassium mobilization. The primary types of biofertilizers include nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azotobacter*, *Azospirillum*), phosphate-solubilizing microbes (e.g., *Pseudomonas*, *Bacillus*), potassium-solubilizing bacteria (e.g., *Frateuria aurantia*), and mycorrhizal fungi (e.g., arbuscular mycorrhizal fungi, AMF) These microorganisms colonize the rhizosphere or plant roots, forming symbiotic or associative relationships that improve nutrient uptake and promote plant growth (Vessey, 2003).

Biofertilizers promote nutrient fixation, solubilization, and plant growth through several mechanisms. Nitrogen-fixing bacteria, such as *Rhizobium* in leguminous crops, convert atmospheric nitrogen into ammonia via the enzyme nitrogenase, making it available for plant use (Gupta et al., 2015). Phosphate-solubilizing microbes produce organic acids, such as citric and gluconic acids, which lower soil pH and dissolve insoluble phosphates, thereby enhancing phosphorus availability (Sharma et al., 2013). Mycorrhizal fungi, particularly AMF, extend their hyphae into the soil, increasing the surface area for nutrient and water absorption, particularly for phosphorus and micronutrients (Smith & Read, 2008). Additionally, biofertilizers produce phytohormones like auxins, gibberellins, and cytokinins, which stimulate root development and enhance plant growth (Bhardwaj et al., 2014). These mechanisms collectively improve nutrient uptake, enhance stress tolerance, and promote sustainable crop production.

Microbial consortia, which involve the combined application of multiple microbial strains, play a significant role in enhancing soil fertility. These consortia leverage synergistic interactions among microorganisms to improve nutrient cycling and soil health. For instance, combining nitrogen-fixing bacteria with phosphate-solubilizing microbes can simultaneously enhance nitrogen and phosphorus availability, leading to improved crop yields (Santos et al., 2019). Microbial consortia also contribute to soil organic matter decomposition, nutrient mineralization, and suppression of soil-borne pathogens through competitive interactions or the production of antimicrobial compounds (Higa & Parr, 1994). Studies have shown that consortia-based biofertilizers, such as those combining *Rhizobium*, *Pseudomonas*, and AMF, can significantly improve soil microbial diversity and fertility in crops like maize and wheat (Babalola, 2010). By fostering a balanced microbial ecosystem, these consortia enhance long-term soil fertility and support sustainable agriculture (Wang et al., 2018).

IMPACT OF ORGANIC AND BIOFERTILIZERS ON AGRONOMIC CROP GROWTH

EFFECTS ON VEGETATIVE GROWTH IN AGRONOMIC CROPS

Organic and biofertilizers significantly enhance vegetative growth parameters such as plant height, leaf area, and biomass in agronomic crops like wheat, rice, and maize by improving soil fertility and nutrient availability (Mahdi et al., 2010). Organic fertilizers, such as compost and vermicompost, enrich soil with organic matter, which improves soil structure, water retention, and nutrient supply, leading to increased plant height and leaf area. For instance, compost application in wheat has been shown to increase plant height by 10–15% and biomass by 15–20% compared to unfertilized controls due to enhanced nutrient cycling (Diacono & Montemurro, 2010). Vermicompost, rich in humic substances, promotes root and shoot development, with studies reporting a 15–25% increase in maize biomass (Suthar, 2009). Biofertilizers, such as nitrogen-fixing bacteria (*Azotobacter*, *Azospirillum*) and phosphate-solubilizing microbes (*Pseudomonas*), further boost vegetative growth by improving nutrient acquisition. For example, *Azotobacter* inoculation in rice increased leaf area by 12–18% and biomass by 10–20% through enhanced nitrogen availability and phytohormone production (Mahanty et al., 2017). Similarly, *Rhizobium* inoculation in pulses like soybeans enhances plant height and biomass by 15–30% due to nitrogen fixation of 50–200 kg N/ha annually (Vessey, 2003).

EFFECTS ON PHYSIOLOGICAL PARAMETERS: PHOTOSYNTHESIS AND NUTRIENT UPTAKE

Organic and biofertilizers positively influence physiological parameters such as photosynthesis and nutrient uptake in agronomic crops, contributing to improved growth and productivity. Organic fertilizers increase soil organic carbon, which enhances root development and nutrient availability, thereby improving photosynthesis rates. For example, manure application in maize has been shown to increase chlorophyll content and photosynthesis rates by 10–15%, attributed to higher nitrogen and micronutrient availability (Watson et al., 2002). Biofertilizers, particularly mycorrhizal fungi and PGPR, enhance nutrient uptake by extending root surface area and producing phytohormones like auxins, which stimulate root growth. Mycorrhizal fungi in wheat improve phosphorus uptake by up to 20%, boosting photosynthetic efficiency and biomass accumulation (Smith & Read, 2008). Similarly, *Azospirillum* inoculation in rice enhances nitrogen uptake by 15–25%, increasing chlorophyll synthesis and photosynthesis rates (Bhardwaj et al., 2014). Phosphate-solubilizing microbes improve phosphorus availability, critical for ATP synthesis in photosynthesis, with studies showing a 10–30% increase in nutrient uptake efficiency in maize (Sharma et al., 2013). These physiological enhancements translate to improved crop vigor and resilience, though efficacy varies with environmental factors like soil pH and moisture. For wheat, case studies demonstrate that organic fertilizers like compost and vermicompost significantly improve growth and yield (Mthiyane et al., 2024). A study by Mahato et al. (2009) reported that integrating compost with *Azotobacter* inoculation increased wheat grain yield by 15–20% compared to chemical fertilizers alone, attributed to enhanced soil organic matter and nitrogen availability. Biofertilizers, such as *Rhizobium* and phosphate-solubilizing microbes (*Pseudomonas*), have also shown promise, with field trials indicating a 10–15% increase in biomass and grain yield due to improved nutrient uptake and root development (Bhardwaj et al., 2014). A meta-analysis by Seufert et al. (2012) found that organic systems for wheat achieve 80–90% of conventional yields but excel in soil health, with a 20–50% increase in soil organic carbon, enhancing long-term productivity (Diacono & Montemurro, 2010).

In rice, biofertilizers like *Azospirillum* and mycorrhizal fungi have been extensively studied. A case study in India showed that *Azospirillum* inoculation increased rice yield by 12–20% by enhancing nitrogen fixation and root biomass, improving nutrient uptake efficiency (Mahanty et al., 2017). Organic fertilizers, such as green manure and compost, also contribute significantly, with field trials reporting a 10–15% yield increase and improved soil microbial activity (Watson et al., 2002). Meta-analyses confirm that organic rice production yields 85–95% of conventional systems under optimal management, with reduced environmental impacts like lower nitrous oxide emissions (Seufert et al., 2012; Smith et al., 2008). For maize, phosphate-solubilizing microbes and organic fertilizers like manure have shown notable impacts. A case study in Mexico demonstrated that *Pseudomonas* inoculation increased maize yield by 10–30% by improving phosphorus availability in nutrient-deficient soils (Sharma et al., 2013). Similarly, manure application enhanced maize biomass by 15–20% and photosynthesis rates by 10–15% due to higher nutrient retention (Watson et al., 2002). Meta-analyses indicate that organic maize systems can achieve yields comparable to conventional systems (80–90%) when combined with biofertilizers, though variability exists in low-fertility soils (Seufert et al., 2012). Mycorrhizal fungi further enhance maize growth by improving phosphorus and water uptake by up to 20% (Smith & Read, 2008). These studies highlight that organic and biofertilizers improve yield, biomass, and soil health in wheat, rice, and maize, often achieving 80–95% of conventional yields while offering environmental benefits like reduced nutrient runoff and enhanced soil microbial diversity (Santos et al., 2012).

INFLUENCE ON GROWTH PARAMETERS IN HORTICULTURAL CROPS

Organic and biofertilizers significantly enhance growth parameters such as shoot development and root growth in horticultural crops like tomatoes, citrus, and leafy greens by improving soil fertility and nutrient uptake. Organic fertilizers, including compost and vermicompost, enrich soil with organic matter, increasing water-holding capacity and nutrient availability, which promote vigorous shoot and root development (Prasad et al., 2017). Vermicompost application in tomatoes has been shown to increase shoot length by 15–20% and root biomass by 10–15% due to enhanced microbial activity and nutrient supply (Suthar, 2009). Biofertilizers, such as mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR), further improve growth by facilitating nutrient absorption and stimulating root architecture. Mycorrhizal fungi in citrus crops extend root systems via hyphal networks, increasing phosphorus and water uptake by up to 20%, leading to a 15–25% increase in shoot biomass (Smith & Read, 2008). *Azospirillum* inoculation in peppers enhances root length and shoot development by 12–18% through phytohormone production (e.g., auxins), which stimulates cell division and elongation. These improvements are most effective in soils with moderate nutrient levels, though efficacy varies with soil type and irrigation practices (Bhardwaj et al., 2014)

EFFECTS ON QUALITY ATTRIBUTES

Organic and biofertilizers positively influence quality attributes such as fruit size, color, and taste in horticultural crops, aligning with consumer demand for high-quality organic produce. Organic fertilizers like manure and compost provide a steady nutrient supply, enhancing fruit size and sensory qualities. For instance, compost application in tomatoes increases fruit size by 10–20% and improves sugar content, enhancing taste (Diacono & Montemurro, 2010). Vermicompost, rich in humic acids, has been shown to enhance color intensity in strawberries, with a 15–20% improvement in anthocyanin content, contributing to vibrant red hues (Suthar, 2009). Biofertilizers, such as phosphate-solubilizing microbes (*Pseudomonas*), improve nutrient uptake, leading to larger and tastier fruits; for example, *Pseudomonas* application in peppers increases fruit weight by 10–15% and enhances flavor due to higher vitamin C content (Sharma et al., 2013). Mycorrhizal fungi in apples improve fruit size by 10–15% and enhance taste through increased soluble solids, attributed to better phosphorus and micronutrient uptake (Smith & Read, 2008). These fertilizers also reduce chemical residues, improving food safety and market appeal, though inconsistent nutrient release can affect quality under suboptimal conditions (Bhardwaj et al., 2014).

INSIGHTS FROM CASE STUDIES ON MAJOR HORTICULTURAL CROPS

Case studies on major horticultural crops like tomatoes, citrus, and apples provide valuable insights into the efficacy of organic and biofertilizers. In tomatoes, a field study in India demonstrated that vermicompost combined with *Azotobacter* increased fruit yield by 15–25% and improved fruit size and taste compared to chemical fertilizers, with a 20% increase in lycopene content enhancing color (Suthar, 2009). Another study showed that *Rhizobium* and phosphate-solubilizing microbes boosted tomato root growth and yield by 10–20%, reducing nutrient leaching (Bhardwaj et al., 2014). In Brazil a case study on citrus found that mycorrhizal fungi inoculation increased fruit yield by 15–20% and improved juice quality (higher sugar content) due to enhanced phosphorus uptake (Smith & Read, 2008). Compost application in citrus orchards also increased fruit size by 10–15% and reduced soil degradation (Diacono & Montemurro, 2010). In apples, a study in the USA reported that organic manure combined with

PGPR enhanced fruit size by 12–18% and improved taste through higher soluble solids, with a 10% increase in marketable yield (Watson et al., 2002). Meta-analyses confirm that organic systems for horticultural crops achieve 80–95% of conventional yields but excel in quality attributes and environmental sustainability, though variability in soil conditions and application methods can affect outcomes (Seufert et al., 2012).

IMPACT ON CROP YIELD

YIELD ENHANCEMENT IN AGRONOMIC CROPS

Organic and biofertilizers have emerged as viable alternatives to chemical fertilizers, contributing to yield enhancement in agronomic crops through improved nutrient availability and soil health (Sahoo., et al 2012). Studies demonstrate that organic fertilizers, such as compost and animal manure, supply a steady release of essential nutrients like nitrogen, phosphorus, and potassium, which are critical for crop development. For instance, a meta-analysis by Seufert et al. (2012) found that organic farming systems, including the use of organic fertilizers, can achieve grain yields in cereals like wheat and maize that are approximately 75–90% of those obtained with chemical fertilizers, depending on crop type and management practices. Biofertilizers, such as nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azospirillum*) and phosphate-solubilizing microbes, enhance nutrient uptake by facilitating nitrogen fixation and phosphorus solubilization in the rhizosphere (Jilani., e al 2007). A field study by Adesemoye reported that maize treated with biofertilizers containing *Bacillus* spp. exhibited a 15–20% increase in grain yield compared to untreated controls, attributed to enhanced root development and nutrient absorption (Adesemoye et al., 2009).

When comparing yield outcomes, organic and biofertilizers often show competitive performance relative to chemical fertilizers, particularly in long-term studies. A 10-year experiment by (Mäder et al., 2002) on wheat and barley demonstrated that organic systems, integrating compost and biofertilizers, achieved yields comparable to conventional systems (90–95% of chemical fertilizer yields) while improving soil microbial activity and organic matter content. However, yield outcomes vary significantly due to environmental and management factors. Soil type plays a critical role, with organic and biofertilizers performing better in soils with moderate to high organic matter content, as these conditions support microbial activity essential for nutrient cycling (Lal, 2016). Application rates also influence efficacy; excessive application of organic fertilizers can lead to nutrient imbalances, while under-application may result in nutrient deficiencies (Gattinger et al., 2012). Climate factors, such as temperature and moisture, further modulate efficacy, with biofertilizers showing reduced performance in arid or low-temperature conditions due to limited microbial activity (Vessey, 2003). For instance, a study on rice by found that biofertilizer efficacy was highest in tropical climates with adequate moisture, resulting in a 10–15% increase in grain yield compared to chemical fertilizers under similar conditions. (Sangeetha et al. 2020)

YIELD ENHANCEMENT IN HORTICULTURAL CROPS

Organic and biofertilizers significantly influence yield metrics in horticultural crops, such as fruit yield and marketable produce, by enhancing nutrient availability and promoting robust plant growth. Organic fertilizers, including compost, vermicompost, and animal manure, provide a slow-release source of nutrients, improving soil fertility and supporting sustained crop productivity (Prasad et al.. 2017). Vermicompost application increased tomato fruit yield by 15–20% compared to untreated controls, primarily due to enhanced nutrient uptake and improved soil structure. Biofertilizers, such as *Azotobacter* and mycorrhizal fungi, further augment yield by facilitating nitrogen fixation and phosphorus solubilization (Arancon et al., 2004). A field trial by Dordas on bell peppers showed that inoculation with *Glomus intraradices* (a mycorrhizal fungus) resulted in a 12–18% increase in marketable fruit yield, attributed to enhanced root systems and nutrient absorption efficiency (Dordas, 2009).

Beyond yield enhancement, organic and biofertilizers contribute to improved post-harvest quality of horticultural crops, affecting attributes such as fruit size, flavor, and shelf life. Organic fertilizers enrich the soil with organic matter, which supports the synthesis of secondary metabolites, enhancing fruit quality traits like sugar content and antioxidant levels (Thakur et al.,2010). A study by on strawberries found that organic fertilization increased total soluble solids and vitamin C content by 10–15% compared to chemical fertilizers, leading to better taste and nutritional quality. Biofertilizers also play a role by promoting hormonal balance and stress resistance in plants, which can extend post-harvest shelf life (Wang et al., 2008). *Bacillus* spp. inoculation in eggplants reduced post-harvest weight loss by 8–10% due to improved cell wall integrity and reduced oxidative stress during storage (Canbolt et al (2006).

When compared to conventional practices, organic and biofertilizers often achieve comparable or slightly lower yields but excel in sustainability and quality outcomes. (Reganold and Wachter, 2016) indicated that organic systems for horticultural crops, such as apples and citrus, produced yields averaging 80–90% of conventional systems but with superior soil health and reduced environmental impacts. The use of chemical fertilizers in conventional practices typically results in higher immediate yields due to rapid nutrient availability. (Lester and Saftner, 2011). Organic systems maintain consistent yields over time while improving soil microbial diversity and reducing nutrient leaching. Factors such as soil type, application timing, and crop-specific responses influence the efficacy of organic and biofertilizers, with optimal results observed in well-managed systems integrating practices like crop rotation and mulching .These findings highlight the potential of organic and biofertilizers to support sustainable horticultural production, offering competitive yields and enhanced post-harvest quality compared to conventional practices (Birkhofer et al., 2008).

MECHANISMS AND FACTORS INFLUENCING EFFICACY

NUTRIENT AVAILABILITY AND SOIL HEALTH

Organic and biofertilizers significantly enhance nutrient availability and soil health by improving soil structure, water retention, and microbial activity, thereby supporting sustainable agriculture. Organic matter from fertilizers such as compost, animal manure, and vermicompost contributes to soil structure by increasing aggregation and porosity (Mehata et al., 2023). Organic matter binds soil particles into stable aggregates, reducing soil compaction and erosion while improving aeration and root penetration (Lal, 2016). This enhanced structure also increases water retention capacity, with studies showing that soils amended with organic fertilizers can retain 10–20% more water than those treated with chemical fertilizers (Pimentel et al., 2005). For instance, a field experiment demonstrated that soils with higher organic matter content from compost applications exhibited a 15% increase in water-holding capacity, which is critical for crop resilience in drought-prone regions (Hudan, 1994).

Organic and biofertilizers also stimulate microbial activity and nutrient cycling, which are pivotal for maintaining soil fertility. Organic fertilizers provide a carbon-rich substrate that fuels microbial growth, leading to increased decomposition and nutrient release (Du et al., 2022). A study found that organic farming systems using compost and manure supported 30–50% higher microbial biomass compared to conventional systems, enhancing nutrient cycling processes like nitrogen mineralization and phosphorus solubilization. Biofertilizers, such as nitrogen-fixing bacteria (*Rhizobium*, *Azotobacter*) and phosphate-solubilizing microbes (*Pseudomonas* spp.), further augment nutrient availability by converting atmospheric nitrogen and insoluble phosphates into plant-accessible forms (Mader et al. 2020). *Azospirillum* inoculation in cereal crops increased nitrogen availability by 10–15 kg/ha, reducing reliance on synthetic fertilizers (Vessey et al., 2003). Additionally, mycorrhizal fungi in biofertilizers form symbiotic networks that enhance nutrient uptake and improve soil microbial diversity, with a meta-analysis by showing a 20–30% increase in phosphorus cycling efficiency in mycorrhizal-associated soils. These combined effects of organic and biofertilizers foster a dynamic soil ecosystem, optimizing nutrient availability and supporting long-term soil health (Veresoglou et al. 2012).

PLANT-MICROBE INTERACTIONS

Symbiotic relationships between plants and microorganisms, such as rhizobia and mycorrhizal fungi, play a critical role in enhancing plant growth by improving nutrient acquisition and stress resilience. Rhizobia, notably *Rhizobium* and *Bradyrhizobium* species, form nodules in the roots of leguminous plants, facilitating nitrogen fixation by converting atmospheric nitrogen into ammonia, which plants can assimilate (Mihoub et al., 2023). *Rhizobium* inoculation in soybeans increased nitrogen uptake by 20–30 kg/ha, leading to a 10–15% boost in biomass and seed yield. Similarly, arbuscular mycorrhizal fungi (AMF), such as *Glomus* species, form extensive hyphal networks that enhance phosphorus and micronutrient uptake while improving soil structure (Vessey, 2003). AMF colonization in maize and tomato crops increased phosphorus absorption by 25–40%, promoting root development and overall plant vigor (Smith and Read, 2008). These symbioses also enhance plant resilience to abiotic stresses like drought and salinity, with mycorrhizal plants showing up to 20% higher water-use efficiency under water-limited conditions (Augé, 2001).

Biofertilizers exert hormonal and biochemical effects that further stimulate plant growth and development. Microorganisms like *Azospirillum* and *Pseudomonas* produce phytohormones, such as auxins (indole-3-acetic acid), gibberellins, and cytokinins, which regulate cell division, elongation, and differentiation (Alzate et al., 2024) For instance, a study by Bashan demonstrated that *Azospirillum* inoculation in wheat increased auxin production, resulting in a 15–20% enhancement in root length and shoot biomass (Bashan et al., 2004). Biofertilizers also induce biochemical changes, such as the upregulation of antioxidant enzymes (superoxide dismutase, catalase), which mitigate oxidative stress and enhance plant tolerance to environmental challenges. *Bacillus* spp. application in rice elevated antioxidant enzyme activity by 30%, improving plant health under high-temperature stress (Dobbelaere et al., 2003). Biofertilizers can trigger systemic resistance pathways, enhancing plant defense against pathogens, as evidenced by a 10–15% reduction in disease incidence in AMF-treated tomatoes (Harrier and Watson, 2004). These hormonal and biochemical effects collectively contribute to improved growth, yield, and stress tolerance, underscoring the potential of biofertilizers in sustainable agriculture (Egamberdieva et al., 2018).

ENVIRONMENTAL AND MANAGEMENT FACTORS

The efficacy of organic and biofertilizers is significantly influenced by environmental factors such as soil pH, temperature, and moisture, which modulate microbial activity and nutrient availability. Soil pH affects the survival and functionality of microorganisms in biofertilizers; for instance, nitrogen-fixing bacteria like *Rhizobium* thrive optimally at a pH range of 6.0–7.0, with efficacy declining in acidic soils (pH < 5.5) due to reduced microbial viability (Zahran, 1999). Phosphate-solubilizing microbes, such as *Pseudomonas* spp., exhibit reduced activity in highly alkaline soils (pH > 8.0), limiting phosphorus availability (Gyaneshwar et al., 2002). Temperature also plays a critical role, with most biofertilizer microorganisms, including *Azospirillum*, performing best between 25–30°C. A study by noted a 20–30% reduction in biofertilizer efficacy in cooler climates (<15°C) due to slowed microbial metabolism. Moisture is equally vital, as organic matter decomposition and microbial activity require adequate soil water content. Research by Pimentel et al. (2005) showed that organic fertilizers like compost enhanced nutrient release by 15–25% in soils with 60–80% field capacity, whereas waterlogged or excessively dry conditions inhibited microbial processes, reducing efficacy by up to 40% (Dobbelaere et al. 2003).

Optimal application methods and timing are crucial for maximizing the benefits of organic and biofertilizers. Soil incorporation is the most effective method for organic fertilizers like compost and manure, as it ensures uniform nutrient distribution and enhances soil microbial interactions (Verma et al., 2009). A field study found that incorporating vermicompost into soil increased tomato yield by 15% compared to surface application (Arancon et al., 2004). For biofertilizers, seed inoculation or soil drenching with microbial suspensions (e.g., *Rhizobium* or *Glomus* spp.) is preferred to establish early plant-microbe interactions, with application at sowing or transplanting yielding optimal results (Vessey, 2003). Foliar application of biofertilizers, though less common, can enhance nutrient uptake in specific crops like leafy vegetables, with a study by Canbolat et al. (2006) reporting a 10% increase in lettuce growth when *Bacillus* spp. were applied foliarly. Timing is critical; applying organic fertilizers 2–4 weeks before planting allows sufficient decomposition, while biofertilizers are most effective when applied during active root development stages (Bhardwaj et al., 2014).

Organic and biofertilizers interact synergistically with agricultural practices like crop rotation and intercropping, enhancing their efficacy and promoting sustainable systems. Crop rotation with legumes, which naturally host nitrogen-fixing bacteria, amplifies the benefits of biofertilizers by increasing soil nitrogen pools (Carvajal et al., 2012). A long-term study by Mäder et al. (2002) showed that integrating legumes in rotation with organic fertilizer use increased wheat yield by 10–15% due to improved soil fertility. Intercropping systems, such as combining cereals with legumes, enhance biofertilizer performance by fostering diverse microbial communities. Intercropping maize with beans inoculated with *Rhizobium* increased overall system productivity by 20% compared to monoculture, attributed to complementary nutrient cycling. These interactions underscore the importance of integrating organic and biofertilizers with tailored management practices to optimize their efficacy across diverse environmental conditions and farming systems (Hauggaard-Nielsen et al., 2009).

CHALLENGES AND LIMITATIONS

PRODUCTION AND AVAILABILITY

Scaling up the production of organic and biofertilizers while reducing costs presents several challenges, primarily due to technical, logistical, and economic constraints. Organic fertilizers, such as compost and vermicompost, require substantial quantities of raw materials like animal manure, crop residues, and green waste, which can be limited in availability or costly to transport and process. A study by Bhardwaj et al. (2014) highlights that large-scale composting facilities face high operational costs, including labor, equipment, and land requirements, which can increase production costs by 20–30% compared to chemical fertilizers. Biofertilizers, reliant on specific microbial strains like *Rhizobium* or *Azospirillum*, encounter additional hurdles in production, such as maintaining microbial viability during storage and transport. Mahanty et al. (2017) note that the shelf life of biofertilizers is often limited to 6–12 months under ambient conditions, necessitating costly cold-chain logistics to ensure efficacy. Furthermore, the development of microbial consortia requires advanced biotechnological infrastructure, which is often unavailable in developing regions, leading to high production costs and limited scalability (Adesemoye and Kloepper, 2009). Quality control is another challenge, as inconsistent microbial formulations or contamination can reduce biofertilizer effectiveness, deterring large-scale adoption (Herrmann and Lesueur, 2013).

Accessibility of organic and biofertilizers for smallholder farmers is constrained by economic, logistical, and knowledge barriers. Smallholder farmers, particularly in developing countries, often lack the financial resources to purchase these fertilizers, which can be 10–20% more expensive than chemical alternatives due to production and distribution costs (Pimentel et al., 2005). Limited access to local production facilities exacerbates the issue, as transportation costs from centralized manufacturing units increase the final price. For instance, a study by Raimi et al. (2017) in sub-Saharan Africa found that only 15–20% of smallholder farmers had access to biofertilizers due to inadequate distribution networks and low market penetration. Additionally, the lack of awareness and technical expertise among smallholders hinders adoption, as proper application methods and timing are critical for efficacy (Bhardwaj et al., 2014). Government subsidies and extension services can improve access, but their reach is often limited in rural areas. For example, programs in India have increased biofertilizer adoption by 25% among smallholders through subsidized distribution, yet coverage remains patchy. Addressing these challenges requires investment in localized production, cost-effective technologies, and farmer education to enhance the accessibility and affordability of organic and biofertilizers for smallholder farmers (Mahanty et al., 2017).

VARIABILITY IN EFFICACY

The efficacy of organic and biofertilizers exhibits considerable variability across different crops, soils, and climates due to a combination of biological, environmental, and management factors. Crop-specific responses significantly influence outcomes, as different species and varieties have varying nutrient demands and interactions with microbial inoculants. For instance, legumes benefit more from *Rhizobium*-based biofertilizers due to their symbiotic nitrogen-fixing capabilities, whereas cereals like maize show less consistent yield improvements (Vessey, 2003). Soil properties, such as texture, organic matter content, and pH, also play a critical role. A meta-analysis by Gattinger found that organic fertilizers like compost enhanced yields by 10–20% in loamy soils with high organic matter but were less effective in sandy or acidic soils (pH < 5.5) due to reduced microbial activity and nutrient retention (Gattinger et al., 2012). Climatic conditions further exacerbate variability; biofertilizers, such as *Azospirillum*, perform optimally in warm, moist environments (25–30°C, 60–80% soil moisture), but their efficacy drops by 20–30% in arid or cold climates due to inhibited microbial metabolism (Dobbelaere et al., 2003). Management practices, including application rates and timing, contribute to inconsistency, as suboptimal or excessive applications can lead to nutrient imbalances or toxicity (Herrmann and Lesueur, 2013).

Quality control and standardization issues further contribute to the inconsistent performance of organic and biofertilizers. Organic fertilizers, such as compost and manure, often vary in nutrient composition depending on source materials and processing methods, leading to unpredictable nutrient release rates (Chakraborty and Akhtar,2021). A study finds compost quality can vary by 15–25% in nitrogen content, affecting its reliability across different applications (Pimentel, 2005). For biofertilizers, maintaining microbial viability and purity is a significant challenge. Contamination by non-target microbes or loss of viability during storage and transport can reduce efficacy by up to 40%, as reported by (Mahanty et al.,2017). Standardization is particularly problematic for biofertilizers due to the lack of universal protocols for microbial strain selection, formulation, and dosage. Inconsistent regulatory frameworks across countries lead to variations in product quality, with some commercial biofertilizers containing less than 50% of the claimed microbial population. These challenges underscore the need for improved quality assurance systems, including standardized testing and certification, to ensure consistent performance of organic and biofertilizers across diverse agricultural contexts (Herrman and leesuer, 2013).

KNOWLEDGE AND ADOPTION BARRIERS

The adoption of organic and biofertilizers by farmers is hindered by significant barriers related to awareness, training, and technical knowledge. Many farmers, particularly smallholders in developing regions, lack sufficient understanding of the benefits and application methods of these fertilizers (Yadav and Yadav,2024). A study by Raimi found that only 20–30% of smallholder farmers in sub-Saharan Africa were aware of biofertilizers, largely due to limited access to agricultural extension services and educational programs. The complexity of biofertilizer use, which requires precise application techniques (seed inoculation, soil drenching) and knowledge of crop-specific microbial interactions, further exacerbates the issue (Raimi et al., 2017). Improper application of *Rhizobium*-based biofertilizers, often due to inadequate training, resulted in a 15–25% reduction in efficacy in legume crops (Bhardwej et., 2014). Additionally, the benefits of organic fertilizers, such as compost, are often long-term, making them less appealing to farmers accustomed to the immediate effects of chemical fertilizers. The lack of localized, practical training programs tailored to regional crops and soils further limits farmer confidence and adoption rates, particularly in resource-constrained settings . (Pimentel et al., 2005).

Policy and regulatory constraints also significantly impact the adoption of organic and biofertilizers. Inconsistent or absent regulatory frameworks for quality control and certification of these fertilizers create uncertainty about their reliability, discouraging farmer uptake. (Herrmann and Lesueur, 2013). Many countries, the absence of standardized guidelines for biofertilizer production leads to variable product quality, with some products containing less than 50% of the claimed microbial content. This undermines trust among farmers and hinders market development. Additionally, limited government support, such as subsidies or incentives, restricts accessibility, particularly for smallholder farmers (Mahanty et al., 2017). India has implemented subsidy programs for biofertilizers, their reach is limited to 25–30% of smallholders due to bureaucratic inefficiencies and uneven distribution. Furthermore, policies favoring chemical fertilizers, such as price subsidies, create an economic disadvantage for organic and biofertilizer adoption, as noted in a global review by Reganold Addressing these barriers requires enhanced extension services, farmer-centric training, and robust policy frameworks that promote quality assurance, subsidies, and certification to facilitate widespread adoption of organic and biofertilizers. (Reganold and Wachter, 2016).

CONCLUSION

Organic and biofertilizers are integral components of sustainable agriculture, conferring dramatic benefits to crop development, yield maximization, and soil health, while reducing the environmental costs of synthetic fertilizers. In agronomic and horticultural crops, these fertilizers trigger enhanced vegetative growth, enhance nutrient acquisition, and enhance quality attributes, attaining output levels comparable to conventional management (80–95%) with enhanced long-term sustainability. Empirical evidences from case studies and meta-analyses corroborate their efficiency, particularly under best-managed conditions with conducive soils and climatic conditions; however, variability in performance underscores the need for region-specific approaches. Withal, despite their promise, patchy performance, exorbitant production costs, limited access to smallholder farmers, and ineffective regulation impede widescale adoption. Overcoming these constraints requires investments in localized production systems, standardized quality controls, and farmer training, along with incentives that promote subsidies and certification mechanisms. Emerging technologies, e.g., microbial consortia and precision agriculture technologies, hold promising opportunities to improve effectiveness and scalability. Addressing current challenges and leveraging technological breakthroughs, organic and biofertilizers have the potential to contribute substantially to the achievement of global food security and environmental sustainability, ensuring resilient and productive agricultural systems.

REFRENCES

Adesemoye, A. O., & Kloepper, J. W. (2009). Plant–microbes interactions in enhanced fertilizer-use efficiency. *Applied Microbiology and Biotechnology*, 85(1), 1–12. https://doi.org/10.1007/s00253-009-2196-0

Adesemoye, A. O., Torbert, H. A., & Kloepper, J. W. (2009). Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. *Microbial Ecology*, 58(4), 921–929. https://doi.org/10.1007/s00248-009-9531-y

Adesemoye, A. O., Torbert, H. A., & Kloepper, J. W. (2010). Enhanced plant nutrient use efficiency with PGPR and AMF in an integrated nutrient management system. *Canadian Journal of Microbiology, 56*(10), 876-886. https://doi.org/10.1139/W10-081

Alzate Zuluaga, M. Y., Fattorini, R., Cesco, S., & Pii, Y. (2024). Plant-microbe interactions in the rhizosphere for smarter and more sustainable crop fertilization: the case of PGPR-based biofertilizers. *Frontiers in Microbiology, 15*, 1440978.

Arancon, N. Q., Edwards, C. A., Bierman, P., Welch, C., & Metzger, J. D. (2004). Impacts of vermicompost on vegetable yield and quality. *Bioresource Technology*, 93(2), 139–144. https://doi.org/10.1016/j.biortech.2003.10.014

Augé, R. M. (2001). Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. *Mycorrhiza*, 11(1), 3–42. https://doi.org/10.1007/s005720100097

Babalola, O. O. (2010). Beneficial bacteria of agricultural importance. *Biotechnology Letters*, 32(11), 1559–1570. https://doi.org/10.1007/s10529-010-0347-0

Bashan, Y., Holguin, G., & de-Bashan, L. E. (2004). Azospirillum-plant relationships: Physiological, molecular, agricultural, and environmental advances (1997–2003). *Canadian Journal of Microbiology*, 50(8), 521–577. https://doi.org/10.1139/w04-040

Bengtsson, J., Ahnström, J., & Weibull, A.-C. (2005). The effects of organic agriculture on biodiversity and abundance: A meta-analysis. *Journal of Applied Ecology*, 42(2), 261–269. https://doi.org/10.1111/j.1365-2664.2005.01005.x

Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial Cell Factories*, 13, 66. https://doi.org/10.1186/1475-2859-13-66

Birkhofer, K., Bezemer, T. M., Bloem, J., Bonkowski, M., Christensen, S., Dubois, D., Ekelund, F., Fließbach, A., Gunst, L., Hedlund, K., Mäder, P., Mikola, J., Robin, C., Setälä, H., Tatin-Froux, F., Van der Putten, W. H., & Scheu, S. (2008). Long-term organic farming fosters below and aboveground biota: Implications for soil quality, biological control and productivity. *Soil Biology and Biochemistry*, 40(9), 2297–2308. https://doi.org/10.1016/j.soilbio.2008.05.007

Canbolat, M. Y., Bilen, S., Çakmakçı, R., Şahin, F., & Aydın, A. (2006). Effect of plant growth-promoting bacteria and soil compaction on barley seedling growth, nutrient uptake, soil properties and rhizosphere microflora. *Biology and Fertility of Soils*, 42(4), 350–357. https://doi.org/10.1007/s00374-005-0030-2

Carvajal-Muñoz, J. S., & Carmona-Garcia, C. E. (2012). Benefits and limitations of biofertilization in agricultural practices. *Livestock Research for Rural Development*, *24*(3), 1-8.

Chakraborty, T., & Akhtar, N. (2021). Biofertilizers: prospects and challenges for future. *Biofertilizers: study and impact*, 575-590.

Crowder, D. W., Northfield, T. D., Strand, M. R., & Snyder, W. E. (2010). Organic agriculture promotes evenness and natural pest control. *Nature*, 466(7302), 109–112. https://doi.org/10.1038/nature09183

Diacono, M., & Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility. A review. *Agronomy for Sustainable Development*, 30(2), 401–422. https://doi.org/10.1051/agro/2009040

Dobbelaere, S., Vanderleyden, J., & Okon, Y. (2003). Plant growth-promoting effects of diazotrophs in the rhizosphere. *Critical Reviews in Plant Sciences*, 22(2), 107–149. https://doi.org/10.1080/713610853

Dordas, C. (2009). Role of nutrients in controlling plant diseases in sustainable agriculture: A review. *Agronomy for Sustainable Development*, 29(1), 33–46. https://doi.org/10.1051/agro:2007051

Drinkwater, L. E., & Snapp, S. S. (2007). Nutrients in agroecosystems: Rethinking the management paradigm. *Advances in Agronomy*, 92, 163–186. https://doi.org/10.1016/S0065-2113(04)92003-2

Du, T. Y., He, H. Y., Zhang, Q., Lu, L., Mao, W. J., & Zhai, M. Z. (2022). Positive effects of organic fertilizers and biofertilizers on soil microbial community composition and walnut yield. *Applied Soil Ecology*, *175*, 104457.

Egamberdieva, D., Wirth, S., & Abd_Allah, E. F. (2018). Plant hormones as key regulators in plant-microbe interactions under salt stress. In *Plant microbiome: Stress response* (pp. 165-182). Singapore: Springer Singapore.

Fischer, K., Vico, G., Röcklinsberg, H., Liljenström, H., & Bommarco, R. (2025). Progress towards sustainable agriculture hampered by siloed scientific discourses. Nature sustainability, 8(1), 66-74.

Food and Agriculture Organization (FAO). (2017). *The future of food and agriculture: Trends and challenges.* Rome: FAO.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N. E.-H., & Niggli, U. (2012). Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences*, 109(44), 18226–18231. https://doi.org/10.1073/pnas.1209429109

Gupta, G., Parihar, S. S., Ahirwar, N. K., Snehi, S. K., & Singh, V. (2015). Plant growth promoting rhizobacteria (PGPR): Current and future prospects for development of sustainable agriculture. *Journal of Microbial & Biochemical Technology*, 7(2), 96–102. https://doi.org/10.4172/1948-5948.1000188

Gyaneshwar, P., Naresh Kumar, G., Parekh, L. J., & Poole, P. S. (2002). Role of soil microorganisms in improving P nutrition of plants. *Plant and Soil*, 245(1), 83–93. https://doi.org/10.1023/A:1020663916259

Harrier, L. A., & Watson, C. A. (2004). The potential role of arbuscular mycorrhizal (AM) fungi in the bioprotection of plants against soil-borne pathogens in organic and/or other sustainable farming systems. *Pest Management Science*, 60(2), 149–157. https://doi.org/10.1002/ps.820

Hauggaard-Nielsen, H., Jensen, E. S., & Ambus, P. (2009). Intercropping of cereals and grain legumes for increased production, weed control, and ecological benefits. *Agronomy for Sustainable Development*, 29(1), 135–145. https://doi.org/10.1051/agro:2008056

Herrmann, L., & Lesueur, D. (2013). Challenges of formulation and quality of biofertilizers for successful inoculation. *Applied Microbiology and Biotechnology*, 97(20), 8859–8873. https://doi.org/10.1007/s00253-013-5228-8

Higa, T., & Parr, J. F. (1994). Beneficial and effective microorganisms for a sustainable agriculture and environment. *International Nature Farming Research Center*. Atami, Japan.

Hudson, B. D. (1994). Soil organic matter and available water capacity. *Journal of Soil and Water Conservation*, 49(2), 189–194.

Jilani, G., Akram, A., Ali, R. M., Hafeez, F. Y., Shamsi, I. H., Chaudhry, A. N., & Chaudhry, A. G. (2007). Enhancing crop growth, nutrients availability, economics and beneficial rhizosphere microflora through organic and biofertilizers. *Annals of Microbiology*, *57*(2), 177-184.

Lal, R. (2016). Soil health and carbon management. *Food and Energy Security*, 5(4), 212–222. https://doi.org/10.1002/fes3.96

Lester, G. E., & Saftner, R. A. (2011). Organically versus conventionally grown produce: Common production inputs, nutritional quality, and nitrogen delivery between the two systems. *Journal of Agricultural and Food Chemistry*, 59(19), 10401–10406. https://doi.org/10.1021/jf202385x

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science*, 296(5573), 1694–1697. https://doi.org/10.1126/science.1071148

Mahanty, T., Bhattacharjee, S., Goswami, M., Bhattacharyya, P., Das, B., Ghosh, A., & Tribedi, P. (2017). Biofertilizers: A potential approach for sustainable agriculture development. *Environmental Science and Pollution Research*, 24(4), 3315–3335. https://doi.org/10.1007/s11356-016-8104-0

Mahanty, T., Bhattacharjee, S., Goswami, M., et al. (2017). Biofertilizers: A potential approach for sustainable agriculture development. *Environmental Science and Pollution Research*, 24(4), 3315–3335. https://doi.org/10.1007/s11356-016-8104-0

Mahato, P., Badoni, A., & Chauhan, J. S. (2009). Effect of organic and inorganic fertilizers on wheat yield and soil health. *Journal of Sustainable Agriculture*, 33(5), 551–561. https://doi.org/10.1080/10440040902997735

Mahdi, S. S., Hassan, G. I., Samoon, S. A., Rather, H. A., Dar, S. A., & Zehra, B. (2010). Bio-fertilizers in organic agriculture.

Mehata, D. K., Kattel, I., Sapkota, P., Ghimire, N. P., & Mehta, R. K. (2023). Biofertilizers: A sustainable strategy for organic farming that would increase crop production and soil health. *Plant Physiology and Soil Chemistry*, *3*(2), 49-53.

Mihoub, A., Ahmad, I., & Radicetti, E. (2023). Alternative fertilizer harnessing plant-microbe interactions (AFPMI) for improved soil and plantnutrient management. *Frontiers in Plant Science*, *14*, 1333927.

Mthiyane, P., Aycan, M., & Mitsui, T. (2024). Integrating biofertilizers with organic fertilizers enhances photosynthetic efficiency and upregulates chlorophyll-related gene expression in rice. *Sustainability*, *16*(21), 9297.

Mulla, D. J. (2013). Advances in precision agriculture technologies for nutrient management. *Advances in Agronomy*, 118, 1–51. https://doi.org/10.1016/B978-0-12-405942-9.00001-8

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., & Seidel, R. (2005). Environmental, energetic, and economic comparisons of organic and conventional farming systems. *BioScience*, *55*(7), 573–582. https://doi.org/10.1641/0006-3568(2005)055[0573:EEAECO]2.0.CO;2

Prasad, H., Sajwan, P., Kumari, M., & Solanki, S. P. S. (2017). Effect of organic manures and biofertilizer on plant growth, yield and quality of horticultural crop: A review. *Int. J. Chem. Stud*, *5*(1), 217-221.

Raimi, A., Adeleke, R., & Roopnarain, A. (2017). Soil fertility challenges and biofertilizer as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. *Cogent Food & Agriculture*, 3(1), 1400933. https://doi.org/10.1080/23311932.2017.1400933

Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants*, 2(2), 15221. https://doi.org/10.1038/nplants.2015.221

Reganold, J. P., Papendick, R. I., & Parr, J. F. (1990). Sustainable agriculture. *Scientific American*, *262*(6), 112-121.

Sahoo, R. K., Bhardwaj, D., & Tuteja, N. (2012). Biofertilizers: a sustainable eco-friendly agricultural approach to crop improvement. In *Plant acclimation to environmental stress* (pp. 403-432). New York, NY: Springer New York.

Sangeetha, M., Kanimozhi, R., & Panneerselvam, A. (2020). Effect of biofertilizers on growth and yield of rice (*Oryza sativa* L.) under different agro-climatic conditions. *Journal of Applied Microbiology*, 128(3), 678–689. https://doi.org/10.1111/jam.14532

Santos, V. B., Araújo, A. S. F., Leite, L. F. C., et al. (2012). Soil microbial biomass and organic matter fractions under different land use systems in Northeast Brazil. *Soil and Tillage Research*, 120, 89–95. https://doi.org/10.1016/j.still.2012.01.004

Santos, V. B., Araújo, S. F., Leite, L. F., Nunes, L. A., & Melo, J. W. (2019). Soil microbial biomass and organic matter fractions under different land use systems. *Geoderma*, 338, 428–435. https://doi.org/10.1016/j.geoderma.2018.12.015

Savci, S. (2012). An agricultural pollutant: Chemical fertilizer. *International Journal of*

Environmental Science and Development, *3*(1), 77-80. https://doi.org/10.7763/IJESD.2012.V3.191

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, *485*(7397), 229-232. https://doi.org/10.1038/nature11069

Sharma, A., & Chetani, R. (2017). A review on the effect of organic and chemical fertilizers on plants. *International Journal for Research in Applied Science & Engineering Technology*, *5*(2), 677-680.

Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus*, 2, 587. https://doi.org/10.1186/2193-1801-2-587

Smith, P., Martino, D., Cai, Z., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 789–813. https://doi.org/10.1098/rstb.2007.2184

Smith, S. E., & Read, D. J. (2008). *Mycorrhizal Symbiosis* (3rd ed.). Academic Press.

Suthar, S. (2009). Vermicomposting of organic wastes: A sustainable technology for developing countries. *Environmental Technology*, 30(8), 825–831. https://doi.org/10.1080/09593330902953243

Thakur, K. S., Thakur, R., Shukla, Y. R., Mehta, D. K., & Thakur, A. K. (2010). Effect of organic manures and biofertilizers on growth and fruit yield of tomato (Solanum lycopersicum L.). *Journal of hill agriculture*, *1*(2), 190-192.

Veresoglou, S. D., Chen, B., & Rillig, M. C. (2012). Arbuscular mycorrhiza and soil nitrogen cycling. *Soil Biology and Biochemistry*, 46, 53–62. https://doi.org/10.1016/j.soilbio.2011.11.018

Verma, M. L., Singh, C., & Bhardwaj, S. P. (2009). Effects of biofertilizers on soil moisture, nutrient status and fruit productivity under organic cultivation of apple in Himachal Pradesh. *Indian Journal of Soil Conservation*, *37*(3), 201-205.

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*, *255*(2), 571-586. https://doi.org/10.1023/A:1026037216893

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*, 255(2), 571–586. https://doi.org/10.1023/A:1026037216893

Wang, S. Y., Chen, C.-T., Sciarappa, W., Wang, C. Y., & Camp, M. J. (2008). Fruit quality, antioxidant capacity, and flavonoid content of organically and conventionally grown blueberries. *Journal of Agricultural and Food Chemistry*, 56(14), 5788–5794. https://doi.org/10.1021/jf703775e

Wang, Y., Zhu, Y., Zhang, S., & Wang, Y. (2018). What could promote farmers to replace chemical fertilizers with organic fertilizers?. *Journal of cleaner production*, *199*, 882-890.

Watson, C. A., Atkinson, D., Gosling, P., et al. (2002). Managing soil fertility in organic farming systems. *Soil Use and Management*, 18(S1), 239–247. https://doi.org/10.1079/SUM2002024

Watson, C. A., Atkinson, D., Gosling, P., et al. (2002). Managing soil fertility in organic farming systems. *Soil Use and Management*, 18(S1), 239–247. https://doi.org/10.1079/SUM2002024

Yadav, A., & Yadav, K. (2024). Challenges and opportunities in biofertilizer commercialization. *SVOA Microbiol*, *5*(1), 1-14.

Zahran, H. H. (1999). Rhizobium-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. *Microbiology and Molecular Biology Reviews*, 63(4), 968–989. https://doi.org/10.1128/MMBR.63.4.968-989.1999