

# Enhancing Crop Productivity and Sustainability through Biological and Organic Fertilizers: Strategies for Food Security

Godswill Ntsomboh-Ntsefong<sup>1\*</sup>, Toukam Gabriel Mahbou-Somo<sup>1</sup>, Samuel Namuene Kato<sup>2</sup>, Célestine Mélanie Dzeufouo-Tapinfo<sup>1</sup>

<sup>1</sup>Department of Plant Biology, Faculty of Science, University of Yaounde 1, Yaounde, Cameroon

<sup>2</sup>Department of Forestry and Wildlife, Faculty of Agriculture and Veterinary Medicine, University of Buea, Buea, Cameroon

Email: \*ntsomboh@yahoo.fr

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## Abstract

The increasing global population demands innovative approaches to enhance food security while promoting sustainable agricultural practices. This review explores the potential of biological and organic fertilizers as effective alternatives to conventional chemical fertilizers. By examining various types of fertilizers, including biological agents such as nitrogen-fixing bacteria and organic materials like compost, the article highlights their mechanisms of action, which improve nutrient availability, enhance soil structure, and promote beneficial microbial interactions. Case studies demonstrate significant increases in crop productivity, illustrating the long-term benefits on soil health and ecosystem sustainability. Furthermore, the review addresses environmental considerations, such as reduced chemical runoff and carbon sequestration potential, emphasizing the role of these fertilizers in biodiversity conservation. However, challenges related to farmer adoption and variability in effectiveness necessitate further research and policy support. Recommendations for integrating biological and organic fertilizers into national agricultural strategies are provided to encourage sustainable practices among farmers. Ultimately, this review underscores the importance of biological and organic fertilizers in enhancing crop productivity and sustainability, contributing to global food security.

## Keywords

Biological Fertilizers, Organic Fertilizers, Crop Productivity, Sustainable Agriculture, Food Security

## 1. Introduction

As the global population continues to rise at an unprecedented rate, the demand for food has reached critical levels, posing significant challenges to global food security [1]. Current projections indicate that by the year 2050, the world's population may exceed 9 billion, a growth trajectory that will place immense pressure on existing food systems and finite natural resources. This demographic surge is occurring in a context where environmental and economic factors are already straining agricultural production. Climate change, for example, is not a distant threat but an active force disrupting farming communities worldwide. It manifests through altered precipitation patterns, an increased frequency and intensity of extreme weather events such as droughts and floods, and the gradual shifting of climatic zones. These changes can severely disrupt traditional farming practices and lead to substantial reductions in crop yields, directly threatening the livelihoods of millions of smallholder farmers [2]. Beyond climate, persistent issues like widespread land degradation and volatile market conditions further exacerbate these challenges, leading to increased hunger and malnutrition in many regions. Addressing these multifaceted problems requires more than just increasing output; it demands a fundamental shift toward innovative agricultural solutions that holistically address both the social and environmental dimensions of food production. Ensuring equitable access to nutritious food is not merely an economic goal but a critical prerequisite for achieving sustainable development and a more just global society [3].

To meet these complex demands, a paradigm shift toward sustainable agricultural practices is essential. These methods are designed to maintain the health of ecosystems, enhance the resilience of farming systems to climate change, and ensure long-term food production for future generations [4] [5]. At their core, these practices focus on minimizing environmental impact, conserving precious resources, and promoting biodiversity within agricultural landscapes [6] [7]. Techniques such as crop rotation, which replenishes soil nutrients naturally, agroforestry, which integrates trees into farming systems to improve soil health and water retention, and organic farming, which avoids synthetic inputs, are all crucial components of this approach. By adopting such sustainable methods, farmers can achieve multiple benefits: they can improve soil health and structure, increase crop yields over time, and reduce their dependency on costly and environmentally harmful chemical inputs. This approach fosters a more resilient and self-sufficient food system that supports the well-being of both the current generation and those to come. The move towards sustainability is not just a trend but a necessity for building an agricultural model that is robust enough to withstand future shocks and stressors.

Within this framework of sustainable agriculture, fertilizers play a pivotal role in boosting crop productivity by supplying essential nutrients to plants [8]. Effective nutrient management is central to agricultural success, as it directly influences plant growth, health, and overall yields. However, while chemical fertilizers have

been the cornerstone of modern agriculture for decades, their overuse has created significant environmental and health concerns. Mineral (chemical) fertilizers have raised significant environmental concerns due to their negative impacts. The overreliance on these synthetic inputs has been linked to a cascade of negative effects, including soil degradation, water contamination through nutrient runoff, the emission of greenhouse gases during their production and application and widespread environmental pollution [9]-[11]. Furthermore, the production and application of these fertilizers are major contributors to greenhouse gas emissions, which in turn exacerbate climate change. Given these concerns, the agricultural community is increasingly turning to viable alternatives. Biological and organic fertilizers present a promising solution, as they not only enhance nutrient availability in a more natural way but also promote the long-term health and sustainability of the soil itself [12] [13]. These natural alternatives can significantly improve soil microbial activity, enhance the natural cycling of nutrients, and reduce the need for synthetic inputs, thereby offering a path toward a more balanced and regenerative agricultural system. This review aims to explore these alternatives and their potential contributions to achieving food security, emphasizing the importance of integrating such sustainable practices in agricultural systems to meet the growing demands of the future without compromising the environment.

Despite the proven benefits of these approaches, the adoption of sustainable agricultural practices remains a significant challenge, particularly for smallholder farmers in Sub-Saharan Africa. Based on recent research, a number of specific obstacles currently hinder agricultural practices in this region, ranging from severe environmental pressures to entrenched socio-economic hurdles.

#### **Climate and Environmental Challenges**

Climate variability poses a significant and immediate threat to agricultural stability in Sub-Saharan Africa. The impacts are already visible and are having a direct effect on food production. According to a review of existing literature, countries such as Ethiopia have experienced a significant reduction in total annual rainfall, making farming a more precarious endeavor. Similarly, South Africa has faced severe issues with uneven rainfall distribution, leading to periods of drought followed by destructive floods. In Kenya, rising temperatures have directly led to a notable decrease in maize revenue, a staple crop crucial for food security. In Ghana, changes in rainfall patterns have resulted in reduced crop yields and farm income, pushing many families to the brink of poverty. The review also identifies land degradation as a persistent and widespread problem. South Africa is contending with changes in soil organic matter and the loss of fertile topsoil, while Nigeria and Mali have experienced a reduction in overall land productivity and soil fertility, making it harder for farmers to grow enough food to sustain their families [14] [15].

#### **Pest and Disease Prevalence**

Pests and diseases continue to cause substantial crop losses across the continent, further compounding the challenges faced by smallholder farmers. The article

highlights that Tanzania, for instance, faces chronic pre-harvest maize losses of approximately 15% due to a high incidence of rodent infestation. In Rwanda and Burundi, a devastating combination of pests and diseases has led to significant crop losses, with estimates at 26% for sweet potato, 29% for banana, 33% for potato, and 36% for cassava [14] [15]. These losses represent not only a threat to food security but also a major economic setback for farmers who lack the resources and technology to combat these threats effectively.

### **Socio-economic Barriers**

Beyond environmental and biological threats, farmers in the region face numerous socio-economic challenges that severely impede the adoption of sustainable practices. The lack of secure land tenure, for example, discourages long-term investment in soil health and land improvement, as farmers have no guarantee they will reap the benefits of their labor. Additionally, limited access to essential knowledge and training on new agricultural techniques and a lack of access to financial institutions, such as microloans or credit, act as major obstacles. These barriers make it difficult for farmers to purchase modern equipment, quality seeds, or alternative fertilizers. The article notes that a significant number of smallholder farmers have not yet fully adopted sustainable agricultural practices. A clear example of this is a study from Ghana, which found that only 40% of farmers had adopted improved seed varieties, with the remaining 60% still relying on traditional seeds. This statistic underscores the tangible and widespread nature of the barriers preventing progress [14] [15].

This review presents how the strategic adoption of biological and organic fertilizers can serve as a powerful tool to address these interconnected challenges. By exploring the mechanisms through which these inputs enhance productivity and resilience, this paper provides a comprehensive overview of strategies that can empower smallholder farmers to improve their livelihoods, contribute to global food security, and ensure the long-term sustainability of agricultural systems in a rapidly changing world.

## **2. Types of Fertilizers**

Fertilizers are essential in modern agriculture, providing vital nutrients that support plant growth and enhance crop yields [12] [16]. They can be broadly categorized into three types: chemical, biological, and organic fertilizers [17] [18]. Each type has its own characteristics, benefits, and potential impacts on the environment and sustainability.

### **2.1. Chemical Fertilizers**

Chemical fertilizers, also known as synthetic or inorganic fertilizers, are manufactured through chemical processes to provide essential nutrients to crops [10]. They typically consist of three primary macronutrients: nitrogen (N), phosphorus (P), and potassium (K), commonly referred to as NPK fertilizers [19]. Common types include urea, a widely used nitrogen fertilizer that is highly soluble and rap-

idly available to plants [20]; ammonium nitrate, another nitrogen source that provides quick nutrient uptake [21]; superphosphate, a phosphorus fertilizer that enhances root development and flowering [22] [23] and potassium sulfate, a potassium source that improves drought resistance and overall plant health [24] [25]. While chemical fertilizers can significantly boost crop yields, their use raises several environmental concerns [26] [27]. Over-reliance on synthetic fertilizers can lead to soil degradation, reduced biodiversity, and water pollution [28] [29]. Excessive application may result in nutrient runoff, contaminating nearby water bodies and causing problems such as eutrophication [30]-[32]. This process depletes oxygen in water, harming aquatic life and disrupting ecosystems. Additionally, the production of chemical fertilizers is energy-intensive, contributing to greenhouse gas emissions and climate change [33] [34]. Sustainability concerns associated with chemical fertilizers have prompted a shift towards more eco-friendly alternatives. The need for integrated nutrient management practices that combine various fertilizer types is increasingly recognized to mitigate these negative impacts while maintaining agricultural productivity [35].

## 2.2. Biological Fertilizers

Microorganisms are fundamental to nutrient cycling by actively breaking down organic matter and transforming essential elements into forms plants can use. In the crucial carbon cycle, soil microbes like bacteria and fungi act as primary decomposers, meticulously breaking down dead plants and animals and converting organic carbon into simpler, absorbable forms for new plant growth. Similarly, in the phosphorus cycle, these microorganisms are essential for the mineralization of organic phosphorus compounds, converting them into inorganic forms that are readily available to plants. These microbial processes are indispensable for recycling key elements, ensuring that vital nutrients such as nitrogen, phosphorus, and sulfur are continually available for new plant growth [36].

Building on this natural process, biological fertilizers, also known as biofertilizers, are natural products that contain living microorganisms which are specifically used to promote plant growth by enhancing nutrient availability [37] [38]. These beneficial fertilizers work by establishing symbiotic and other positive relationships with plants, thereby improving overall soil health and fertility. A classic example is the relationship between nitrogen-fixing bacteria, such as *Rhizobia* species, and leguminous plants. These bacteria form symbiotic associations within the plant roots, converting atmospheric nitrogen into a form that plants can directly use, which significantly reduces the need for synthetic nitrogen fertilizers [39]. Another key example is mycorrhizal fungi, which form associations with plant roots, effectively extending their reach into the soil. This allows for enhanced uptake of water and nutrients, particularly those that are less mobile in the soil, like phosphorus. These fungi also contribute to better soil structure and promote broader microbial diversity within the root zone [40] [41].

The application of biofertilizers enhances plant growth through several interre-

lated mechanisms. First, they facilitate nutrient mobilization. The microorganisms within these fertilizers, such as phosphate-solubilizing bacteria, help convert phosphorus and potassium into forms that are more accessible for plant uptake, particularly in soils where these nutrients are naturally locked up [38] [42] [43]. Second, the use of biological fertilizers significantly boosts overall soil microbial activity, which leads to improved soil structure and fertility over time. A healthy, active soil microbiome is fundamental to efficient nutrient cycling, the decomposition of organic matter, and the suppression of soil-borne pathogens, thereby creating a more robust and resilient growing environment [44]-[46]. Third, some biofertilizers play a crucial role in helping plants withstand both biotic and abiotic stresses, such as disease and drought. For example, the extensive networks formed by mycorrhizal fungi can enhance root systems, allowing plants to better access and absorb moisture and nutrients during prolonged dry periods [47]-[49]. Finally, the widespread use of biological fertilizers promotes sustainable agricultural practices by reducing reliance on synthetic chemical inputs. This shift contributes not only to improved soil health and biodiversity but also to the overall function and resilience of the entire agricultural ecosystem [4] [46] [50].

### 2.3. Organic Fertilizers

Organic fertilizers are derived from natural sources and include materials such as compost, manure, and green manure [13]. These fertilizers provide a variety of nutrients while improving soil structure and health. Compost is decomposed organic matter that enriches soil with nutrients and improves moisture retention [51] [52]. Manure, which is animal waste, supplies essential nutrients and enhances soil microbial activity [53] [54]. Green manure consists of cover crops grown primarily to be tilled back into the soil, adding organic matter and nutrients [55]-[57]. Organic fertilizers generally contain a broader spectrum of nutrients compared to chemical fertilizers [10] [12] [58]. They provide macronutrients (N, P, K) as well as micronutrients essential for plant growth. The slow-release nature of organic fertilizers allows for prolonged nutrient availability [17] [59] [60], reducing the risk of leaching and minimizing environmental impact.

The benefits of organic fertilizers extend beyond nutrient supply. First, organic matter enhances soil texture and aeration, improving water infiltration and retention, which is crucial for maintaining optimal growing conditions, especially in drought-prone areas [61] [62]. Second, organic fertilizers promote a diverse and active soil microbiome, vital for nutrient cycling and disease suppression [45] [63] [64]. Healthy soils foster resilient ecosystems that can better withstand pests and diseases [65]-[67]. Third, incorporating organic fertilizers contributes to carbon storage in soils [68]-[70], helping mitigate climate change impacts. By increasing soil organic carbon levels, these practices promote long-term soil health and fertility [71]-[73]. Finally, organic fertilizers align with sustainable agricultural practices by reducing reliance on synthetic inputs and promoting ecological balance [74]-[76]. They help farmers achieve higher productivity while protecting the en-

vironment. Understanding the different types of fertilizers—chemical, biological, and organic—is crucial for developing effective strategies to enhance crop productivity sustainably. Each type has unique advantages and challenges, and integrating them into agricultural practices can lead to improved soil health, increased yields, and greater food security.

### **3. Mechanisms of Action**

The effectiveness of fertilizers—whether chemical, biological, or organic—depends on their mechanisms of action in enhancing nutrient availability, promoting soil health, and supporting plant growth [10] [58] [77]. Therefore, understanding these mechanisms is crucial for optimizing fertilizer use and improving agricultural sustainability. By grasping how different fertilizers function, farmers and agricultural practitioners can make informed decisions that enhance crop productivity while minimizing environmental impact.

#### **3.1. Nutrient Availability and Uptake Enhancement**

Fertilizers play a critical role in increasing the availability of essential nutrients to plants [78]-[80]. This process can vary significantly between chemical, biological, and organic fertilizers. Chemical fertilizers provide nutrients in readily available forms; for example, nitrogen is often supplied as ammonium or nitrate, phosphorus as superphosphate, and potassium as potassium chloride [10] [19] [81]. The solubility of these nutrients allows for quick uptake by plants. However, excessive application can lead to nutrient leaching, particularly in sandy soils, which can diminish their effectiveness and harm the environment [27] [82]. Biological fertilizers enhance nutrient availability through the action of beneficial microorganisms [83]-[85]. For instance, nitrogen-fixing bacteria convert atmospheric nitrogen into forms usable by plants [86]. Mycorrhizal fungi extend the root systems of plants, increasing their access to phosphorus and other nutrients [87]-[89]. These interactions not only improve nutrient uptake but also enhance the efficiency of nutrient use, reducing the need for chemical inputs. Organic fertilizers release nutrients slowly as they decompose, providing a sustained supply of nutrients over time [17]. The organic matter in these fertilizers improves the soil's nutrient-holding capacity, making nutrients more available to plants [90] [91]. This slow-release characteristic helps prevent nutrient runoff and leaching, ensuring that crops receive nutrients when they need them.

#### **3.2. Soil Microbiome Interactions**

The soil microbiome, consisting of diverse microorganisms such as bacteria, fungi, and protozoa, plays a vital role in soil health and plant growth [92] [93]. Fertilizers influence these interactions in several ways. Both biological and organic fertilizers enhance microbial activity in the soil [94]-[96]. This increased microbial activity promotes nutrient cycling, where microorganisms break down organic matter and release nutrients in forms that plants can absorb. Additionally, biological fertiliz-

ers, particularly those containing mycorrhizal fungi and nitrogen-fixing bacteria, establish symbiotic relationships with plant roots [97]-[99]. These relationships enhance nutrient uptake and increase plant resilience to environmental stresses; for example, mycorrhizal fungi can improve drought tolerance by facilitating water absorption [100]-[102]. Furthermore, a healthy soil microbiome contributes to soil structure and fertility [45] [92]. Microorganisms produce substances that bind soil particles together, improving soil aggregation and porosity [103]-[105]. This leads to better aeration, water infiltration, and root penetration, creating a more favorable environment for plant growth.

### 3.3. Improvement of Soil Structure and Fertility

Fertilizers also play a significant role in enhancing soil structure and fertility. While chemical fertilizers can provide immediate nutrient boosts, their long-term use may lead to soil degradation [106]-[108]. Continuous reliance on synthetic fertilizers can reduce organic matter levels and disrupt soil structure [45] [77] [109]. Therefore, integrating organic matter into the soil is crucial for maintaining soil health. The use of biological fertilizers promotes soil fertility by enriching the microbial community [84] [110] [111]. These fertilizers contribute to the formation of humus, which improves soil structure, enhances moisture retention, and increases nutrient capacity [50] [91] [112]. As a result, soils treated with biological fertilizers tend to have better fertility profiles and support healthier plant growth [8] [10] [54]. Organic fertilizers are particularly effective in improving soil structure [91] [113] [114]. The addition of organic matter enhances soil aggregation, leading to improved aeration and drainage [115]-[117]. This is especially beneficial in compacted soils, as it allows roots to penetrate more easily and access nutrients and water. Additionally, organic fertilizers help build soil organic carbon, which is vital for long-term soil fertility [71] [118] [119].

### 3.4. Disease Suppression and Pest Resistance

Fertilizers can also influence plant health by enhancing disease suppression and pest resistance [120]-[122]. Healthy plants are generally more resistant to pests and diseases [123] [124]. Fertilizers that improve nutrient uptake and overall plant vigor contribute to this resilience [66] [125] [126]. For instance, adequate nitrogen levels can lead to robust growth, making plants less susceptible to insect infestations [120] [127]-[129]. The application of biological fertilizers can promote beneficial microorganisms that suppress soil-borne pathogens [130]-[133]. These beneficial microbes can outcompete harmful pathogens for resources, thereby reducing disease incidence [134]-[136]. For instance, certain bacteria can produce metabolites that inhibit the growth of pathogens, enhancing plant health [123] [137]-[139]. Additionally, organic fertilizers often contain bioactive compounds that can stimulate plant defense mechanisms [140]-[142]. These compounds may enhance the production of secondary metabolites, such as phenolics and flavonoids, which are known for their pest-repelling properties. Consequently, plants

treated with organic fertilizers may exhibit increased resistance to herbivores and pathogens [143]-[146].

Understanding the mechanisms of action of different types of fertilizers is essential for optimizing their use in agriculture. By enhancing nutrient availability, promoting beneficial soil microbiome interactions, improving soil structure, and increasing disease resistance, fertilizers can contribute to sustainable agricultural practices that enhance crop productivity and support food security. Integrating these mechanisms into farming practices can lead to healthier soils, more resilient crops, and a more sustainable agricultural system.

## **4. Impact on Crop Productivity**

The impact of fertilizers on crop productivity is a crucial factor in addressing global food security [12] [147]-[149]. Both biological and chemical fertilizers have been employed to enhance crop yields, but their effects can vary significantly [10] [18] [84]. This section explores comparative studies, case studies, and the long-term effects on crop health and soil quality.

### **4.1. Comparative Studies on Crop Yields with Biological vs. Chemical Fertilizers**

Numerous studies have investigated the comparative effectiveness of biological and chemical fertilizers on crop yields [18] [84]. Research indicates that while chemical fertilizers can produce immediate increases in yield, biological fertilizers often contribute to more sustainable long-term productivity [18] [26]. A meta-analysis of various field studies has shown that crops treated with biological fertilizers can achieve yield increases comparable to those treated with chemical fertilizers, especially in nutrient-deficient soils [150]-[152]. For example, legumes inoculated with nitrogen-fixing bacteria have demonstrated yields similar to those fertilized with synthetic nitrogen sources [99] [153] [154]. Additionally, crops like maize and wheat have shown significant yield improvements when combined with mycorrhizal fungi. While chemical fertilizers can provide rapid results, the cost of continuous applications can be high. Biological fertilizers, particularly when produced locally from organic waste, can reduce input costs for farmers [12] [54] [155]. Studies indicate that the return on investment for biological fertilizers can be favorable over time, especially when considering the reduced need for chemical inputs and the improvement of soil health [84]. Furthermore, research has highlighted that biological fertilizers can enhance nutrient use efficiency, allowing plants to absorb and utilize nutrients more effectively [156]-[158]. This is particularly evident in scenarios where soil health is improved, leading to better nutrient retention and less runoff, which translates into higher yields with lower fertilizer input.

### **4.2. Case Studies Demonstrating Productivity Gains**

Several case studies exemplify the productivity gains achieved through the use of

biological fertilizers. A study conducted in several Southeast Asian countries found that integrating biological fertilizers, such as azolla (a nitrogen-fixing aquatic fern), into rice cultivation systems led to significant yield increases [159]-[161]. Farmers who adopted this practice reported up to a 25% increase in rice yields compared to those using only chemical fertilizers [162] [163]. The use of azolla not only provided nitrogen but also improved soil structure and water retention, contributing to sustainable farming practices [164]-[166]. In sub-Saharan Africa, a project focused on promoting the use of mycorrhizal fungi in maize production showed remarkable results [167]-[169]. Farmers who incorporated these biological fertilizers into their practices experienced yield increases of up to 30% over traditional chemical fertilizer methods [170]-[172]. The improved root development facilitated by mycorrhizal associations allowed maize plants to access moisture and nutrients more effectively, particularly in regions prone to drought. Urban gardening initiatives in various cities have implemented organic fertilizers, such as compost and vermicompost, to enhance vegetable production [173]. Case studies reveal that these practices not only increased crop yields but also improved the nutritional quality of the produce. Gardens utilizing organic amendments reported higher levels of vitamins and minerals in vegetables compared to those relying solely on chemical fertilizers [174] [175].

### **4.3. Long-Term Effects on Crop Health and Soil Quality**

The long-term effects of fertilizer use on crop health and soil quality are critical factors in sustainable agriculture. Continuous use of chemical fertilizers can lead to soil degradation, characterized by reduced organic matter content and diminished microbial activity [10] [50]. In contrast, the application of biological and organic fertilizers contributes to increased soil organic carbon, improved microbial diversity, and enhanced soil structure [96] [176] [177]. Over time, soils treated with biological fertilizers exhibit greater resilience to erosion, compaction, and nutrient depletion [178]-[180]. Healthy soils foster robust plant growth, leading to improved crop health and resilience against pests and diseases [46] [65] [181]. Research indicates that crops grown in biologically enriched soils tend to have thicker cell walls and higher concentrations of natural defense compounds, making them more resistant to biotic stresses [182]-[184]. Long-term studies have shown that fields treated with biological fertilizers experience lower incidences of crop diseases and pest infestations. The use of biological and organic fertilizers promotes a balanced ecosystem by supporting beneficial soil microorganisms [63] [176] [185] [186]. This balance facilitates nutrient cycling and enhances the overall health of the agroecosystem. Long-term reliance on biological fertilizers can lead to sustainable agricultural practices that not only yield higher productivity but also contribute to environmental conservation [187]-[190].

The impact of fertilizers on crop productivity is multifaceted, with both biological and chemical options offering unique benefits and challenges. Comparative studies and case examples illustrate that while chemical fertilizers can provide im-

mediate yield boosts, biological fertilizers often lead to more sustainable, long-term improvements in crop productivity, soil health, and ecosystem resilience. By integrating biological and organic fertilizers into agricultural practices, farmers can achieve improved yields while promoting sustainable practices that benefit the environment and contribute to food security.

## **5. Sustainability and Environmental Considerations**

The use of fertilizers in agriculture has significant implications for sustainability and environmental health [10] [191] [192]. While fertilizers are essential for enhancing crop productivity, their impact on the environment necessitates careful consideration. This section discusses the reduction of chemical runoff and pollution, the carbon sequestration potential of organic practices, and the role of fertilizers in biodiversity conservation.

### **5.1. Reduction of Chemical Runoff and Pollution**

One of the primary environmental concerns associated with chemical fertilizers is the potential for nutrient runoff, which can lead to pollution of water bodies [193]-[195]. Excessive application of nitrogen and phosphorus fertilizers can result in nutrient leaching into rivers, lakes, and coastal areas [31] [196]-[198]. This process contributes to eutrophication, characterized by harmful algal blooms that deplete oxygen levels in water, leading to dead zones where aquatic life cannot survive [199]-[201]. The adoption of biological and organic fertilizers can significantly mitigate these issues. Organic fertilizers, such as compost and manure, release nutrients slowly, reducing the risk of nutrient leaching compared to their chemical counterparts [71] [90] [202]. Their application not only enhances nutrient retention in the soil but also improves soil structure, which can further reduce runoff. Biological fertilizers can enhance the soil's buffering capacity, allowing it to better retain nutrients and water. This is particularly important in areas prone to heavy rainfall, where chemical fertilizers are more likely to wash away [84] [203] [204]. By improving soil health through organic amendments, farmers can achieve better nutrient management and minimize environmental impacts. Implementing integrated nutrient management practices that combine chemical, biological, and organic fertilizers can optimize nutrient use efficiency [35] [205]-[207]. This approach not only enhances crop yields but also minimizes negative environmental impacts, promoting a more sustainable agricultural system.

### **5.2. Carbon Sequestration Potential of Organic Practices**

Carbon sequestration refers to the process of capturing and storing atmospheric carbon dioxide, which is crucial for mitigating climate change [208]. Organic practices, including the use of organic fertilizers, play a significant role in enhancing carbon sequestration in agricultural soils. Organic fertilizers contribute to the buildup of soil organic matter, which is essential for carbon storage [91] [209]. When organic materials decompose, they enrich the soil with carbon compounds,

increasing its organic content. Soils rich in organic matter not only sequester carbon but also improve soil fertility and structure. Research indicates that agricultural practices incorporating organic fertilizers can lead to significant increases in soil carbon stocks over time [119] [210] [211]. For example, studies have shown that fields managed with cover crops and organic amendments can sequester substantial amounts of carbon, offsetting greenhouse gas emissions from agricultural activities [212] [213]. The integration of organic practices, such as crop rotation, agroforestry, and reduced tillage, further enhances carbon sequestration potential [214]-[217]. These practices promote biodiversity and improve soil health, creating a more resilient agricultural system capable of sequestering carbon.

### 5.3. Role in Biodiversity Conservation

Biodiversity is vital for ecosystem stability and resilience, and agricultural practices have a significant impact on biodiversity levels [218]-[220]. The use of biological and organic fertilizers can contribute positively to biodiversity conservation in several ways. Biological fertilizers enhance the diversity of soil microorganisms, which play critical roles in nutrient cycling, organic matter decomposition, and plant health [63] [221] [222]. A diverse microbial community contributes to improved soil fertility and resilience against pests and diseases, reducing the need for chemical inputs [223] [224]. Organic farming practices, which often involve the use of organic fertilizers, promote the conservation of habitats for various organisms, including beneficial insects, birds, and other wildlife [225] [226]. These practices can create a more balanced ecosystem that supports pollinators and natural pest predators, contributing to overall agricultural biodiversity. The use of biological and organic fertilizers often aligns with practices that promote crop diversity, such as intercropping and polyculture [227] [228]. Diverse cropping systems can enhance ecosystem services, improve pest management, and increase resilience to climate change. By improving soil health and plant resistance to pests and diseases, biological and organic fertilizers can reduce reliance on chemical pesticides [10] [58] [77]. This not only conserves beneficial insect populations but also minimizes the ecological footprint of agricultural practices.

In summary, the sustainability and environmental considerations associated with fertilizer use are critical for fostering a resilient agricultural system. The reduction of chemical runoff and pollution, the carbon sequestration potential of organic practices, and the role in biodiversity conservation all highlight the importance of integrating biological and organic fertilizers into farming practices. By prioritizing sustainable methods, farmers can enhance productivity while protecting the environment, ultimately contributing to global food security and ecological health.

## 6. Challenges and Limitations

While biological and organic fertilizers present significant advantages for sustainable agriculture, their adoption and effectiveness are not without challenges. Un-

Understanding these limitations is crucial for developing strategies to enhance their use in farming practices [90] [229].

### **6.1. Adoption Barriers for Farmers**

One of the primary barriers to adopting biological and organic fertilizers is the initial cost [54] [230]. While these fertilizers can be more cost-effective in the long run, the upfront investment in purchasing, producing, or applying them can be a significant hurdle for many farmers, especially those with limited financial resources [231] [232]. Farmers may be hesitant to transition from chemical fertilizers, which they perceive as more reliable and immediately effective. Many farmers may lack the knowledge or training necessary to effectively use biological and organic fertilizers [233]. This includes understanding how to properly apply these fertilizers, the timing of applications, and the specific benefits they provide. Educational programs and extension services are essential for providing farmers with the knowledge and skills needed to make informed decisions [234]. For organic fertilizers, market access can be a challenge. Farmers may struggle to find reliable sources of organic materials or may not have access to markets that value organic produce [235]. The lack of established supply chains for organic inputs can further discourage farmers from switching practices. In many regions, there is a strong reliance on traditional agricultural practices that favor chemical fertilizers [236] [237]. Changing long-standing perceptions and practices can be difficult, as farmers may be skeptical of the performance and reliability of biological and organic alternatives.

### **6.2. Variability in Effectiveness Depending on Soil Type and Crop**

The effectiveness of biological and organic fertilizers can vary significantly depending on soil type and its inherent characteristics [238] [239]. Factors such as soil pH, texture, and nutrient status play critical roles in determining how well these fertilizers perform [240]-[242]. For instance, sandy soils may require more frequent applications of organic fertilizers to achieve desired results, whereas clay soils may retain nutrients more effectively [198]. Different crops have varying nutrient requirements and responses to fertilization [243]. While some crops may thrive with biological fertilizers, others may not exhibit the same level of benefit. For example, legumes may respond exceptionally well to nitrogen-fixing bacteria, while cereal crops may require specific mycorrhizal fungi to enhance phosphorus uptake [244] [245]. Farmers need to understand the specific needs of their crops to effectively utilize these fertilizers. Climatic and environmental conditions also affect the performance of biological and organic fertilizers [90] [246]. For example, the effectiveness of biological fertilizers may be reduced in extremely dry or wet conditions, which can influence microbial activity and nutrient availability. Adapting fertilizer strategies to local conditions is crucial for maximizing their benefits [238].

### **6.3. Need for Further Research and Development**

While there is a growing body of research on biological and organic fertilizers,

further studies are needed to understand the underlying mechanisms of action in various soil types and climatic conditions [44] [247]. This research can help identify the most effective practices for different agricultural systems. Developing improved formulations and application techniques for biological and organic fertilizers is essential. Research should focus on optimizing the concentration of beneficial microorganisms [248]-[250], enhancing nutrient release rates, and identifying the best application methods to maximize effectiveness. Long-term field studies are necessary to evaluate the sustainability and impact of using biological and organic fertilizers on soil health [71] [251] [252], crop productivity, and environmental outcomes. These studies can provide valuable data for farmers and policymakers, helping to build confidence in adopting these practices. Supportive policies and incentives can facilitate the transition to biological and organic fertilizers [253]-[255]. Governments and agricultural organizations can play a crucial role in promoting research and development, providing financial assistance, and creating educational programs to support farmers in adopting sustainable practices [234] [256].

While biological and organic fertilizers offer promising benefits for sustainable agriculture (**Table A1**), several challenges and limitations must be addressed. Overcoming adoption barriers, understanding variability in effectiveness, and investing in further research and development are essential steps toward promoting the widespread use of these fertilizers. By addressing these challenges, the agricultural sector can move towards more sustainable practices that enhance productivity while protecting the environment.

## **7. Policy Implications and Recommendations**

To effectively promote the adoption of biological and organic fertilizers and enhance sustainable agricultural practices, robust policy frameworks and targeted recommendations are essential [253] [255] [257]. This section outlines key policy implications and recommendations that can facilitate the transition toward more sustainable agricultural systems.

### **7.1. Support for Research and Education on Biological and Organic Fertilizers**

#### **Funding for Research Initiatives**

Governments and agricultural institutions should prioritize funding for research initiatives focused on biological and organic fertilizers [258]-[260]. This research should aim to understand their effectiveness across different soil types, crops, and climatic conditions. Emphasis should be placed on developing innovative formulations and application techniques that optimize nutrient availability and enhance soil health [66] [261] [262].

#### **Education and Training Programs**

Comprehensive education and training programs are vital for equipping farmers with the necessary knowledge and skills to utilize biological and organic ferti-

lizers effectively [256] [263]. Extension services should be strengthened to provide farmers with hands-on training, workshops, and resources on sustainable practices [264]-[266]. Collaborations with universities and research institutions can facilitate the dissemination of best practices and the latest research findings.

#### **Public Awareness Campaigns**

Increased public awareness about the benefits of biological and organic fertilizers can help shift perceptions and encourage adoption [267] [268]. Campaigns should focus on demonstrating the environmental and economic advantages of sustainable practices, highlighting success stories from farmers who have successfully transitioned to these fertilizers [269] [270].

## **7.2. Incentives for Farmers to Adopt Sustainable Practices**

#### **Financial Incentives**

Governments should consider providing financial incentives, such as subsidies or grants, to encourage farmers to adopt biological and organic fertilizers [254] [271] [272]. These incentives can help offset the initial costs associated with transitioning from chemical fertilizers and support the development of local supply chains for organic inputs.

#### **Tax Breaks and Low-Interest Loans**

Implementing tax breaks or low-interest loan programs for farmers investing in sustainable practices can further encourage adoption [273] [274]. These financial mechanisms can make it more feasible for farmers to incorporate biological and organic fertilizers into their operations.

#### **Certification Programs**

Establishing certification programs for organic and sustainable farming practices can enhance market access for farmers [275]-[277]. By providing a recognized label for sustainably produced crops, farmers can potentially command higher prices, incentivizing them to transition to biological and organic fertilizers.

## **7.3. Integration into National Agricultural Policies**

#### **Holistic Agricultural Policy Frameworks**

National agricultural policies should prioritize sustainability and resilience in food systems [278]-[280]. Integrating biological and organic fertilizers into these frameworks can promote a balanced approach that enhances productivity while protecting environmental resources [54] [90] [187]. Policymakers should consider the long-term impacts of fertilizer use and promote practices that build soil health and biodiversity.

#### **Support for Agroecological Practices**

Policies that support agroecological practices, which emphasize the integration of biological and organic fertilizers, should be developed [281] [282]. This includes promoting crop rotation, intercropping, and the use of cover crops, all of which can enhance soil fertility and reduce dependency on chemical inputs.

#### **Monitoring and Evaluation**

Establishing monitoring and evaluation frameworks to assess the effectiveness

of policies related to biological and organic fertilizers is crucial [283] [284]. This data-driven approach can help policymakers understand the impacts of these practices on crop yields, soil health, and environmental outcomes, allowing for adjustments and improvements in policy implementation.

#### **Collaboration with Stakeholders**

Engaging with a wide range of stakeholders, including farmers, agricultural organizations, researchers, and environmental groups, is essential for developing effective policies [285] [286]. Collaborative efforts can ensure that policies are informed by practical experiences and scientific research, leading to more successful implementation and outcomes. Promoting the use of biological and organic fertilizers through supportive policies and targeted recommendations is essential for advancing sustainable agriculture. By investing in research and education, providing financial incentives, and integrating sustainable practices into national agricultural policies, governments can facilitate the transition toward more resilient and environmentally friendly farming systems. These efforts not only enhance crop productivity but also contribute to long-term food security and environmental sustainability.

### **8. Conclusions**

In this paper, the exploration of biological and organic fertilizers reveals their significant potential for enhancing sustainable agricultural practices and supporting food security. Biological and organic fertilizers can enhance crop productivity, improve soil health, and support sustainable farming practices. Studies indicate that these fertilizers can lead to comparable or even superior yields compared to chemical fertilizers, particularly in nutrient-deficient soils [66] [261]. The use of biological and organic fertilizers reduces chemical runoff and pollution, enhances carbon sequestration, and promotes biodiversity conservation [253] [255]. These practices contribute to healthier ecosystems and mitigate the negative environmental impacts associated with conventional farming methods [54] [90]. Despite their benefits, barriers such as economic constraints, lack of knowledge, and varying effectiveness based on soil type and crop need to be addressed [229] [257].

Policymakers and agricultural organizations must work to overcome these challenges to facilitate wider adoption. Continued research is crucial for understanding the mechanisms of action of biological and organic fertilizers across diverse agricultural contexts [258] [259]. Investigating their long-term effects on soil health, crop productivity, and environmental outcomes will provide valuable insights for farmers and policymakers. The development of innovative formulations and application methods for biological and organic fertilizers can optimize their effectiveness [262]. Research should also explore integrated nutrient management strategies that combine various types of fertilizers for improved sustainability [66]. Expanding educational programs and training opportunities for farmers is essential for promoting the effective use of biological and organic fertilizers [256] [263]. Knowledge-sharing platforms can facilitate the dissemination of best prac-

tices and success stories.

Collaboration among various stakeholders—farmers, researchers, policymakers, and agricultural organizations—is vital for achieving food security and promoting sustainable agricultural practices. Collaborative efforts can facilitate the exchange of information and resources, empowering farmers to make informed decisions about fertilizer use and sustainable practices [285] [286]. Engaging stakeholders in policy development ensures that the needs and perspectives of farmers are considered, leading to more effective and practical policies that promote sustainability [253] [255]. By fostering partnerships and collective action, stakeholders can build resilience in agricultural systems, enabling them to better adapt to climate change, resource scarcity, and other challenges [187] [280].

The transition to biological and organic fertilizers represents a crucial step toward sustainable agriculture and food security. By addressing the challenges to adoption, prioritizing research and education, and promoting collaboration among stakeholders [286], we can create a more resilient and environmentally friendly agricultural system that benefits both farmers and the planet.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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## Appendix

**Table A1.** Qualitative and quantitative synthesis of fertilizers and sustainable agricultural practices.

Overview/Quantitative Yield Increases and References	Yield Outcomes and Variability by Soil, Climate and Practice	Nutrient Mobilization, Cycling and Use Efficiency/Productivity Gains, Soil Health and Sustainable Practices
<p>A meta-analysis of 165 studies found that starter fertilization increased crop yields by an average of 7.5%. Cereal crops like winter wheat and maize showed a strong response, with increases of 8.4% and 8.2% respectively. Herrmann <i>et al.</i> [152]</p>	<p>The benefits of starter fertilization were greatest in soils with low nutrient availability and in colder climates. The yield increase varied by crop.</p>	<p>Starter fertilization improved Phosphorus Use Efficiency (PUE) by 14.3% and Nitrogen Use Efficiency (NUE) by 5.5%. This indicates that plants were better able to acquire nutrients, reducing waste and environmental impact.</p>
<p>A qualitative review of agroecological cropping practices that avoid chemical-synthetic inputs. The focus is on practices like agroforestry and intercropping, with highly variable yield outcomes. von Cossel <i>et al.</i> [287]</p>	<p>Yield outcomes are highly variable due to a complex interplay of factors. For example, a meta-analysis showed that trees in the Mediterranean region had a negative effect on crop yield, ranging from a -75.8% change with ash trees to a +3.3% change with walnuts. In Africa, integrating trees with rice production increased yields by an average of 38%. Intercropping also increased total nitrogen uptake by 25% and provided more stable yields.</p>	<p>Agroecological practices enhance the resilience of farming systems by improving soil microbial activity and nutrient mobilization. They also promote recycling nutrients and energy on the farm, which is essential for sustainable agricultural practices.</p>
<p>The meta-analysis, based on 83 studies, confirmed that fertilizer application significantly increased oat hay yield by 48.9% and grain yield by 36.2%. Balanced fertilization generally enhances yields despite variations. Mao <i>et al.</i> [288]</p>	<p>Changes in yield were dominated by soil pH and nitrogen fertilizer. Fertilizer was more effective in acidic soils, and elevation was a key factor. Climatic conditions were not the dominant factor affecting yield changes.</p>	<p>Findings can help with site-specific fertilization management, leading to higher yields and reduced fertilizer use. This supports sustainable agricultural practices by increasing nutrient use efficiency.</p>
<p>A meta-analysis found that entomopathogenic fungi (EPF) had a positive effect on plant growth metrics, including plant height, leaf surface area, and shoot dry mass. The study highlights the potential of EPF as a biofertilizer and a sustainable agricultural practice. Crosby <i>et al.</i> [289]</p>	<p>The effectiveness of EPF is highly heterogeneous and depends on factors like fungal genus, inoculation method, dosage, and environmental conditions such as soil pH and temperature.</p>	<p>EPF is a promising biofertilizer for sustainable farming, promoting plant growth and reducing reliance on chemicals. It supports resilient, environmentally friendly agriculture.</p>
<p>A qualitative analysis discusses the potential of alternative fertilizers from organic waste streams to support sustainable agricultural practices and improve soil health. Marcinek &amp; Smol [11]</p>	<p>A growing interest in these alternatives is driven by the need for more sustainable agricultural practices and improved soil health. The document notes that alternative fertilizers are increasingly popular.</p>	<p>Alternative fertilizers aid nutrient recycling, closing nutrient loops for a circular economy. They improve soil health by enhancing soil microbial activity and soil structure.</p>

## Continued

**A qualitative review of microbial ecology provides a discussion on how microbes, a component of biofertilizers, enhance sustainable agricultural practices and soil health. It focuses on the fundamental roles of microorganisms in ecosystems.**  
Chinthala [36]

Soil microbial activity is central to ecosystem health. Microbes break down organic matter, release essential nutrients for plants, and help suppress soil-borne pathogens.

Microbes like nitrogen-fixing bacteria and mycorrhizal fungi are vital for nutrient mobilization. They break down organic matter and convert nutrients like nitrogen and phosphorus into forms that are readily available for plant uptake.

**A meta-analysis of 61 studies on cotton found that reducing over-optimal water input increased seed cotton yield by 12.3% and optimizing nitrogen input increased yield by 16.0%.**  
Wang *et al.* [290]

The potential for optimizing water and N inputs was greatest in arid and hot desert climates. Surface irrigation had a greater potential to optimize inputs than drip irrigation.

Optimal water and N management balances economic and environmental benefits. By reducing over-optimal inputs, farmers can achieve higher yields while improving NUE and WUE, which represents a significant productivity gain and key strategy for sustainable agriculture.

**A meta-analysis of 24 studies revealed that the combined application of drip irrigation and nitrogen fertilization resulted in significant yield increases for both wheat (+17.32%) and maize (+9.20%).**  
Cui *et al.* [291]

Yield outcomes varied widely due to heterogeneous effect sizes, influenced by climate, soil, and agricultural practices. This highlights the importance of tailored sustainable agricultural practices to maximize productivity and minimize negative impacts.

The research suggests that combining effective field management methods with nitrogen fertilizer and irrigation can achieve sustainable, climate-resilient agricultural production while mitigating soil and environmental damage.

**A global meta-analysis found that biofertilizers generally lead to significant yield increases, with the highest response (+20.0 ± 1.7%) in dry climates. The yield response was generally small at low soil phosphorus levels.**  
Schütz *et al.* [292]

The efficacy of biofertilizers varied by soil properties. Arbuscular mycorrhizal fungi (AMF) were more successful in soils with low organic matter content and a neutral pH.

Biofertilizers enhance nutrient use efficiency and reduce reliance on conventional inorganic fertilizers. The paper notes that nutrient mobilization increased with higher soil P levels.

**A meta-analysis found that biochar application resulted in an overall mean increase in crop productivity of 10%. A high application rate of 100 t·ha<sup>-1</sup> resulted in a 39% increase in productivity.**  
Jeffery *et al.* [293]

Biochar's effectiveness is highly site-specific. The most positive effects were seen in acidic soils (+14% increase) and in soils with coarse or medium texture (+10% - 13% increase).

Biochar application improves soil quality by enhancing water-holding capacity and nutrient retention. It also affects soil microbial activity and can increase nitrogen fixation by nitrogen-fixing bacteria, which supports plant growth.

**Review of methods for attributing crop yield responses to organic amendments.**  
Celestina *et al.* [294]

Yield responses to organic amendments are due to a mix of nutrient and non-nutrient effects.

Organic amendments and inorganic fertilizers can be equally effective at increasing yields under certain conditions.

Continued

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**Higher soil organic carbon (SOC) boosts maize & wheat yields, with biggest gains between 0.1% & 2.0% SOC.**

Oldfield *et al.* [295]

Yield variability is attributed to management, climate, and soil type.

Increasing SOC may reduce reliance on N fertilizer, with estimated reductions of 7% for maize and 5% for wheat.

**Incomplete fertilizers yield less than NPK. Adding organic amendments boosts yields by 2.4% - 10%.**

Shang *et al.* [296]

Increased soil fertility correlates with yield stability. Lowest variability seen with organic residues.

Organic amendments improve soil's inherent capacity for nutrient mobilization and overall fertility.

**Combined organics + fertilizers boosted yields 8% over fertilizers alone and 29% over organics alone.**

Wei *et al.* [209]

Yield benefits from organics + fertilizers varied by crop: wheat (+53%), maize (+40%), and rice (+8%).

This combined approach enhances sustainability by increasing long-term productivity and soil organic matter (SOM).

**First-season crop yields increased by 43% ± 7% with organic amendments. Poultry manure yielded the largest increase.**

Wortman *et al.*, [297]

Short-term yield response to organics is highly variable, with fewer benefits in high-organic-matter soils.

Organic amendments lead to long-term soil quality improvements, including increased microbial abundance and activity.

**Combined compost+NP fertilizer (CF) led to a 178% relative maize harvest in the initial season.**

Bedada *et al.* [298]

Maize yield trend shows compost becoming increasingly effective over time for long-term productivity.

Compost and combined treatments increased SOC and nitrogen stocks, critical for long-term nutrient mobilization.

**A study of organically managed vs. chemicalized vegetable fields in South India found soil fertility parameters in organic fields did not differ significantly from chemicalized ones.**

George and Ray [299]

The study found significant variations in soil fertility parameters specific to certain fields, but no overall significant difference between organic and chemicalized fields.

The study analyzed soil quality parameters including total organic carbon (TOC), soil available nitrogen (SAN), phosphorus (SAP), and potassium (SAK).

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