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Soil health and crop productivity: implications of integrating biofertilizers with chemical fertilizers

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Abstract

Conventional farming systems rely on the use of chemical fertilizers, herbicides, and pesticides. The unintended consequences of these chemicals range from reduced soil fertility to soil degradation, biodiversity loss, and environmental pollution, among others. Despite these well-reported adverse environmental impacts of chemical fertilizers, their role in achieving high crop yields cannot be disregarded. Biofertilizers provide a promising alternative by promoting nutrient cycling, supplying vital micronutrients to crops often deficient in conventional chemical fertilizers, and minimizing the environmental footprint of conventional agriculture. The aim of this article is to review the recent research on the combined application of biofertilizers and chemical fertilizers towards optimization of their use for preserving soil health and crop productivity. This approach could bring a balance to the need to achieve high crop yields in an environmentally sustainable manner and reasonable prices for everyone, minimize the high use of chemical fertilizers, and enhance soil health.

Keywords: Biofertilizers, Chemical fertilizers, Crop productivity, Nutrient management, Soil health.

Introduction

Over the past decade, the global shift towards sustainable agriculture has increased organic farmland from 31.7 million hectares in 2000 to 76.4 million hectares in 2021 (Martin, 2021). In the same vein, the adoption of alternative nutrient management strategies such as the use of biofertilizers has increased. This trend can be partly attributed to the unintended negative consequences of prolonged use of chemical fertilizers and pesticides such as soil degradation, biodiversity loss, environmental pollution, and climate change (Zulfiqar et al., 2019; Atieno et al., 2020; Vejan et al., 2021). This trend is also part of a robust traction toward the quest for more sustainable options in agriculture. Organic farming is among these sustainable options and at the moment receives additional governmental financial support, but organic outputs generally command higher prices (European Commission, 2023). This suggests that while organic farming yields may be lower, they are sold at premium prices to offset the high costs of production making some of these products unaffordable for some customers.

Despite that NPK chemical fertilizers are the backbone of conventional agriculture, they have been reported for their inability to provide essential micronutrients to crops (Arora et al., 2022). Highlighting the importance of micronutrient supply, biofertilizers could play a crucial role in providing these elements to plants thus contributing to the optimal growth and overall development of crops. An approach of mixing biofertilizer with chemical fertilizer has been reported to significantly improve the growth of oil palm trees supplying balanced and adequate nutrients while also preserving the beneficial microorganisms in the soil (Zainuddin et al. 2022). As the need for a more balanced and cost-effective approach becomes evident, an opportunity arises to integrate biofertilizers with chemical fertilizers in a synergistic manner. This integrated approach aligns with a broader commitment to cultivating crops that are both environmentally responsible and economically viable, striking a balance between the demands of food production and the preservation of ecosystems. The beneficial effects of combining biofertilizer with reduced doses of chemical fertilizer have been reported by several researchers (Kaur and Reddy, 2015; Ning et al., 2017; Yao et al., 2018; Wang et al., 2023).

This article reviews the results of several fertilization research focusing on the combined use of biofertilizers and chemical fertilizers and sheds light on these approaches as strategies incorporated into sustainable agricultural systems.

The role of chemical fertilizers since the Green Revolution

Chemical fertilizers have long been recognized as a cornerstone of agriculture and to date are still continuously used in agricultural production in conventional farming practices (Zainuddin et al., 2022). In fact, chemical fertilizers were the fulcrum that brought success to the era of the Green Revolution, a period in the mid-20th century marked by agricultural intensification that led to increased agricultural yields, and the reduction in global hunger and poverty (John et al., 2021). Chemical fertilizers provide a quick and efficient way to deliver essential nutrients to crops, often resulting in impressive yield increases (Esmaeilian et al., 2022). However, the growing demand for increased crop production makes conventional farming systems dependent on the heavy use of chemical fertilizers and pesticides, which have often resulted in nutrient imbalances, soil acidification, soil degradation, loss of biodiversity, and environmental pollution (Zulfiqar et al., 2019; Atieno et al., 2020; Vejan et al., 2021; Kumar et al., 2022). Particularly, when chemical fertilizers are applied in abundant quantity the plants cannot use them immediately and completely, and the excess leaches into the groundwater causing soil fertility to decline (Zulfiqar et al., 2019). This triggers a cycle of reapplications which inevitably results in higher production costs. Additionally, conventional chemical fertilizers typically lack the capacity to provide necessary micronutrients to crops (Arora et al., 2022). Deficiency in micronutrient supply has the potential to hinder the optimal growth and overall development of crops. Therefore, there is a need to explore avenues to combine new sustainable fertilization approaches such as biofertilizers with chemical fertilizers to produce enough food for the teaming human population while causing minimal damage to the environment.

The application of biofertilizers as environmentally responsible and sustainable option in agriculture

Biofertilizers offer a viable solution as a more environmentally responsible and sustainable alternative to chemical fertilizers (Bhattacharyya et al., 2020; Atieno et al., 2020). Arora et al. (2022) put it more emphatically that "chemical fertilizers caused risks to the environment but biofertilizers came to the rescue of the environment". Generally, biofertilizers are comprised of formulations of live beneficial microbes such as bacteria, fungi, and archaea. Some of them could establish symbiotic relationships with plants and others remain in the bulk soil or in the rhizosphere and succeed in enhancing plant growth and soil fertility through various mechanisms, as shown in Figure 1, including nitrogen fixation, phosphate solubilization, biocontrol qualities, and plant growth-promoting compounds (Arora et al., 2022). These microorganisms play a crucial role in enhancing nutrient availability to crops. For example, nitrogen-fixing bacteria can transform atmospheric nitrogen into a form that plants can readily utilize, thereby decreasing the reliance on chemical nitrogen fertilizers (Guo et al., 2023). Mycorrhizal fungi form mutualistic associations with plant roots and could increase nutrient uptake, especially for phosphorus-containing compounds (Frew et al., 2018). These microorganisms, as a primary concept in the biofertilizer formulations, equally have the potential to enhance soil structure and to promote nutrient cycling, which is expected to have, especially in the long-term, a positive impact on soil health (Singh et al., 2020). Due to the numerous benefits, a great deal of research has focused on developing biofertilizers using a combination of inoculants including Bacillus sp., Acinetobacter sp., Pseudomonas sp., Azotobacter sp., and Azospirillum sp. Currently, the produced biofertilizers are applied as a component of an integrated fertilization approach but very often are accompanied by other strategies (Seenivasagan et al., 2021; Kumar et al., 2022; Zainuddin et al., 2022).

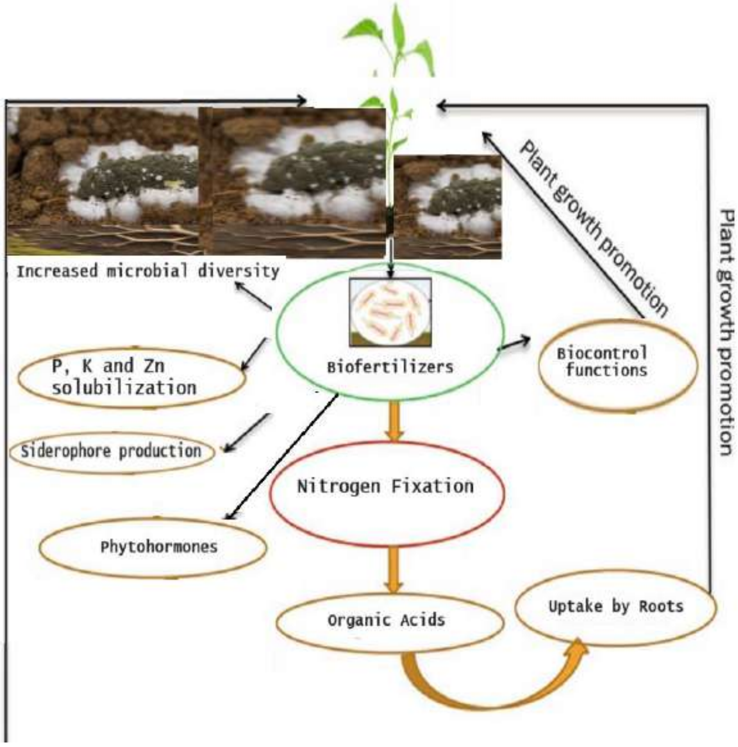

Figure 1. Biofertilizer roles and mechanisms of action *Source:* Mushtaq *et al*. (2021)

Finding the sustainable balance between fertilization strategies, crop yield, and environmental protection

Finding a balance between economic well-being and environmental sustainability has become a major focus of government policy worldwide (Khan et al., 2022). The bulk of this emphasis is focused mainly on minimizing the utilization of chemical fertilizers and pesticides and preserving the natural environment and its resources (Sharma et al., 2023). Thus, adopting alternative nutrient management strategies has gained significant momentum with biofertilizers emerging as promising tools to balance the equation of agricultural sustainability.

Furthermore, with the increasing trend of organic farmland area globally, prices of organic produce have remained on the high side. For instance, farmland under organic farming in the European Union increased by 5.7 % in 2012 and 9.9 % in 2021 (European Commission, 2023). These increases come with very high EU financial support and even so, outputs from organic farms sell at higher prices to be able to recuperate these costs of production. These are factors that must be balanced in the quest for sustainability. Developing environmentally friendly and sustainable food production systems will remain one of the most significant issues in the coming decades (Samani et al., 2019). The answer to the sustainability questions must be the one that brings a recipe that balances the need for high crop yields with minimal environmental impacts at reasonable production prices. This calls for an integrated and holistic approach that reflects a broader commitment to cultivating crops in a manner that is both environmentally responsible, and economically viable, and balances the needs of food with the preservation of ecosystems and essential resources.

Precision agriculture techniques, such as soil testing and nutrient mapping, can help to tailor fertilizer applications with specific crops and soil requirements. Before applying any fertilizers, it is advisable to conduct a thorough soil sample testing in order to determine soil nutrient levels. This information will guide decisions about which nutrients are lacking and which are in excess. In a recent study, Micha et al. (2022) found that soil testing can result in the reduction of chemical fertilizer usage. This finding is also linked to landscape characteristics and farm intensity, highlighting the importance of implementing specific management strategies for decision-making at the farm level. This targeted approach minimizes waste and maximizes the efficiency of nutrient utilization. The successful integration of biofertilizers and chemical fertilizers in agriculture is a critical step that has the potential to revolutionize agricultural practices and provide solutions to both immediate and long-term challenges toward achieving sustainability. By understanding the unique strengths of each approach and employing them strategically, farmers can nurture healthy soils, reduce environmental harm, and continue to meet the global demand for food at affordable prices.

Biofertilizers and chemical fertilizers integration: implications for crop yield and productivity

Biofertilizers and chemical fertilizers serve different purposes in agriculture (Figure 2). Biofertilizers play a crucial role in supplying plants with necessary macro and micronutrients and improving soil health, ultimately leading to enhanced crop yields. On the other hand, chemical fertilizers are efficient at supplying essential nutrients but lack the other benefits associated with biofertilizers. In a recent study, Zainuddin et al. (2022) reported that using a mix of chemical fertilizer and biofertilizer resulted in significant improvements in various growth parameters (plant height, meristem diameter, frond count, leaf area, and dry weight of the leaves) of oil palm trees. According to Jin et al. (2022), the combined application of biofertilizers and reduced doses of chemical fertilizers significantly increased lettuce yield and quality. Esmaeilian et al. (2022), in their three-year experiment with a saffron plant, reported that the combined application of biofertilizer and chemical fertilizer increased the average plant's leaf dry weight, flower number, yield, and dry weight. They further hinted at the possibility of substituting chemical fertilizers with organic and biofertilizers to attain satisfactory yields in areas comparable to the experiment location. Wang et al. (2023) also reported that the combination of biofertilizer and chemical fertilizer significantly improved maize growth, resulting in higher dry matter and nitrogen accumulation and yield, with 8.1% and 7.4% increases compared to only chemical fertilizers in two consequent years (2021 and 2022). This trend was observed by Bam et al. (2022) who found that the incorporation of biofertilizers with other nutrient sources on mungbean crops in Nepal resulted in improved crop yields and increased economic returns. Also, based on the evaluations of the economic and environmental implications of various fertilizer reduction strategies, Wang et al. (2020) reported that the integrated utilization of organic and chemical fertilizers emerged as the best fertilizer reduction treatment. In Indonesia, Simarmata et al. (2018) stated that the integrated use of biofertilizers with chemical fertilizers increased rice grain yield from 5-6 to 6-8 tons ha^{-1}. Similarly, Cong et al. (2011) and Banayo et al. (2012) reported significant rice yield increases following the interaction effects of different chemical fertilizer rates, and biofertilizers.

Some results imply that the combination of biofertilizers and chemical fertilizers provided results that are similar to those obtained with the combination of organic fertilizer and biofertilizer. For instance, Saikia et al. (2018) reported that a consortium of biofertilizers combined with enriched compost at a rate of 3 tons per hectare, seemed a viable alternative to the recommended doses of chemical fertilizer and resulted in increased yields and quality of French beans. Similarly, Wang et al. (2023) found that the utilization of organic fertilizer and biofertilizer under deficit irrigation resulted in significant increases in N uptake, leaf area index, and the rate of photosynthesis. In another study conducted in Zhejiang Province of China, Wang et al. (2020), reported that the highest quality and quantity of tea were produced using a 50% ratio of organic and chemical fertilizers. When compared to chemical fertilizers alone, the addition of biofertilizers increased the output and could offset a 50% reduction in chemical fertilizers (Ennab, 2016). Ennab (2016) recommended that farmers should use 50% NPK plus 55 kg farmyard manure plus biofertilizers to get the best results for lemon trees.

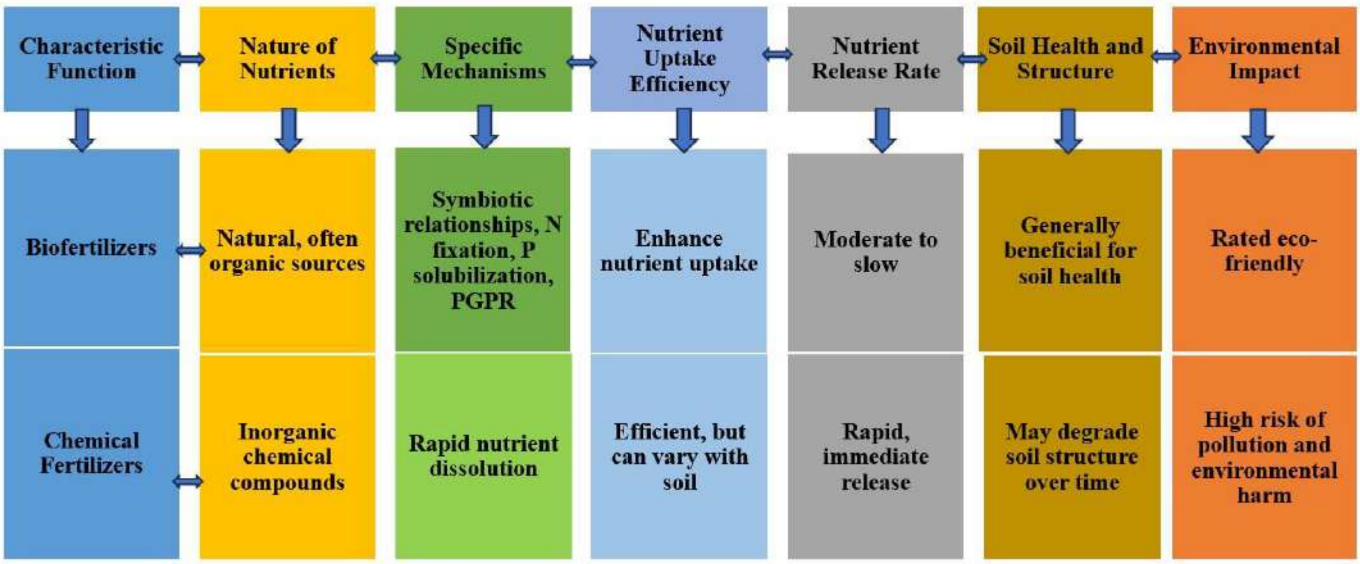

Figure 2: The main features of chemical fertilizers and biofertilizers

Biofertilizers and chemical fertilizers integration: implications for soil health

The stand-alone and prolonged use of chemical fertilizers has been reported to have negative effects on soil health and fertility. It results in the decline of organic matter content in the soil, a decrease in pH levels, and a reduction of essential soil nutrients and minerals which ultimately lead to reduced microbial activity and lower crop yield (Salehi et al., 2017; Pahalvi et al., 2021). According to Zainuddin et al. (2022), the application of biofertilizers along with a reduced amount of chemical fertilizer improved soil health parameters relative to the separate utilization of biofertilizers or chemical fertilizers. Yao et al. (2018) reported that substituting 25% of urea-N with Azolla biofertilizer significantly improved nutrient use efficiency, increased yield, and effectively reduced N loss over the three-year period in China's highly intensive rice cropping systems. Simarmata et al. (2018) reported a substantial reduction (25-50%) in the application of inorganic fertilizers by incorporating 2-5 tons ha^{-1} of biofertilizer which led to improved soil health. Moreover, the combined application of biofertilizer and ground magnesium limestone proved effective in improving rice growth parameters by increasing soil pH and mitigating the widespread aluminum and/or iron toxicity in acid-sulfate soil (Panhwar et al., 2014). Soil pH and soil organic matter (SOM) were reported to be significantly higher in the lettuce plots with the combined application of reduced chemical fertilizers and biofertilizers (Jin et al., 2022). In a two-year field study, Kaur and Reddy (2015) noted that in comparison to chemical P fertilizer (diammonium phosphate, DAP), the combined application of two phosphate-solubilizing bacteria (PSB), Pantoea cypripedii and Pseudomonas plecoglossicida, with rock phosphate significantly improved soil fertility, crop growth, and economic returns in maize and wheat crops. Therefore, the use biofertilizer comprised of phosphate-solubilizing bacteria and its combination with rock phosphate could be a sustainable and cost-effective alternative to the chemical phosphate fertilizer (Kaur and Reddy, 2015).

Furthermore, it is interesting to note that the pattern observed in crop yield and productivity also applies to soil health when biofertilizers and organic fertilizers are combined. There was a strong correlation between the soil quality index and the addition of organic fertilizers and biofertilizers (Du et al., 2022; Du et al., 2023). Integrating organic fertilizers with chemical fertilizers rather than relying entirely on chemical fertilizers is a reasonable method which was applied in various agricultural ecosystems and has been frequently reported to improve the soil's capacity to supply N, P, K, and C (Ning et al. 2017; Salehi et al., 2017, Fayaz et al., 2020; Du et al., 2022; Du et al., 2023). Du et al. (2022) concluded that using a combination of different fertilizers soil fertility could be enhanced and highlighted the crucial role of fungal diversity in sustaining the economic forest tree production. Similarly, Ning et al. (2017) reported that substituting chemical fertilizer with up to 40%-60% with organic fertilizer led to a significant increase in the soil catalase and urease activities as well as organic matter content. According to Fayaz et al. (2020), the combination of four biofertilizers with organic fertilizers had a significant effect on nitrogen, phosphorus, potassium, and microbial populations in the pummelo seedlings (Citrus maxima L) nursery.

However, the application of biofertilizers was not as effective for low phosphorus (P) fertilization as it was for low nitrogen (N) fertilization (Cong et al., 2011). Additionally, Jin et al. (2022) reported increased bacterial community richness and diversity while the fungal community decreased. Achieving a balance between biofertilizers and chemical fertilizers involves adopting synergistic approaches that utilize the strengths of both. Please, remove this figure.

Conclusions

The implications of combining chemical fertilizers with biofertilizers pose many benefits for soil health and crop productivity. The beneficial activities of microorganisms in the biofertilizers alongside the rapid nutrient release of chemical fertilizers could offer a complementary effect towards nutrient deficiencies in the soil. The application of a reduced dosage of chemical fertilizer in combination with biofertilizers could utilize these complementary attributes and provide beneficial interactions toward the optimization of crop productivity and the promotion of long-term soil health. The obtained results may vary from soil to soil, and crop to crop, but this approach could balance the need to simultaneously achieve high crop yields in an environmentally sustainable manner and make this produce available to everyone at reasonable and affordable prices. In the coming years, the wider adoption of the combined use of biofertilizers and chemical fertilizers will depend on the optimization of application and the continued positive effects on maximizing crop yields without destabilizing the agricultural ecosystems.

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