Multi-Disciplinary Publishing Institute Pakistan
Vol. 03, N0. 02

Submitted: 09 MAY 2025 Accepted: 22 MAY 2025 Published: 23 MAY 2025

A Public Health Perspective on Optimizing Biofertilizer Application for Sustainable Plant Growth: Evaluating Soil Health, Yield Performance, and Microbial Interactions in Crop Agriculture

Original Article

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Citation

Sarfraz, U., Rizvi, H.H., Ali, M.Z., Ayaz, U., Akhtar, M., & Jabbar, N. (2025). A public health perspective on optimizing biofertilizer application for sustainable plant growth: Evaluating soil health, yield performance, and microbial interactions in crop agriculture. *Open Access Public Health and Health Administration Review*, 3(2), 130-146.

WEBSITE: www.mdpip.com
ISSN: Print: 2959-619X
ISSN: Online: 2959-6203
PUBLISHER: MDPIP

Abstract

Chemical fertilizers are overused, so people across the world are now looking for environmentally friendly ways to cultivate crops. The impact of biofertilizer use on soil, crop production and microbiological activity is studied in wheat and maize. The work was completed in different parts of Pakistan, where four combination approaches were assessed: a control, NPK fertilizer, biofertilizer-only and an approach of 50% NPK joined with biofertilizer. Biofertilizer and combined treatments increased soil organic carbon, nutrients, bacterial and fungal population and activity levels of enzymes more than the control and NPK-only plots. Moreover, important benefits could be seen in plant development, as the root length, shoot height, chlorophyll levels and total grain yield all improved. The inclusion of treatment in the experiment slightly improved maize and wheat yields by up to 100% and 82.1%, respectively. The use of biofertilizers led to a significant rise in the population of helpful genera such as Bacillus, Pseudomonas and Rhizobium which improved nutrient use and the plant's tolerance to stress. Evidence of many microorganisms being linked to high crop numbers supports the idea of the importance of biology in soil for sustainable farming. According to these results, using efficient biofertilizers can help boost crop output, protect the soil and support the overall balance of the environment, providing an eco-friendly alternative in farming.

Keywords: Biofertilizer, Soil Health, Microbial Biomass, Crop Yield, Sustainable Agriculture, Plant Growth-Promoting Rhizobacteria, Wheat, Maize, Integrated Nutrient Management, Rhizosphere Microbiology.

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Introduction

As people and eating habits increase worldwide, more food must be produced, causing agriculture to try to enhance its productivity. Historically, the Green Revolution meant farmers could grow much bigger crops using a lot of fertilizers, pesticides and new irrigation systems. Yet, these improvements have resulted in serious harm to our environment. Still, using chemical fertilizers in great amounts for a long time has damaged the soil, decreased the variety of living organisms, polluted beneath-ground water and released greenhouse gases (Tilman *et al*., 2002; Vitousek *et al*., 2009). Because traditional farming cannot meet current standards, we should move toward using more eco-friendly types of input.

A good alternative to using chemicals, biofertilizers which contain "living" organisms that aid plant growth by increasing mineral intake, was suggested by Vessey (2003). Beneficial microbes such as Rhizobium, Azotobacter, Bacillus megaterium, Pseudomonas fluorescens and Azospirillum are used for this purpose (Rodríguez and Fraga, 1999; Bashan *et al*., 2014; Glick, 2012). Besides enhancing nutrients in the soil, biofertilizers also promote growth of plant roots, help plants tolerate stress and improve both the fertility and structure of the soil (Kloepper *et al*., 1989; Bhardwaj *et al*., 2014).

Both the level of productivity in agriculture and how resilient the environment is relied on healthy soil which depends on the microbiome's variety and ability to carry out its job (Van der Heijden *et al*., 2008). Short-term use of conventional fertilizers may be effective, but it usually disrupts the soil ecosystem and reduces the number of helpful soil organisms (Geisseler & Scow, 2014). Biofertilizers, however, help produce more microbes and increase biochemical reactions, resulting in nutrient recycling, decomposition of organic particles and prevention of diseases carried by soil bacteria and fungi in the soil (Company, 2005 and Sharma, 2013). As a result, biofertilizers can add nutrients and at the same time help improve the soil in the long run.

Still, biofertilizers are not widely used because they do not always work consistently, many farmers have not heard of them, and their formulations often require more standardization (Malusá & Vassilev, 2014). The way a biofertilizer works depends a lot on the condition of the soil, the type of climate, the crop, and the compatibility of the microbes (Lucy *et al*., 2004; Bhardwaj *et al*., 2014). Hence, it is essential to improve the way biofertilizers are used by factors in dosage, application methods, and how goods can be used together.

Recently, several studies have mentioned that biofertilizers help increase both crop yields and soil fertility in multiple agricultural areas (Meena *et al*., 2015; Singh *et al*., 2018). Nonetheless, it is difficult to find one approach that connects changes in soil chemistry, shifts in microbial communities, and how crops do. The impact of mixed microbes on agriculture is still not fully understood about interactions with the native soil microbes (Mitter *et al*., 2019).

This study is designed to test how the application of biofertilizers influences maize (Zea mays) and wheat (Triticum aestivum) growth, biodiversity in the soil, and the microbes present. To achieve this, the researchers compare the use of only biofertilizers, along with bio and chemical fertilizers, with traditional chemical fertilization methods. Being aware of these issues helps develop sustainable approaches for growing food, preserving soil, and building resilience to climate change in crop farming (Akhtar, *et al*., 2023).

Literature Review

Overusing chemical fertilizers in agriculture has resulted in some problems, for example, nutrient loss from the soil, the lowering of the soil's pH, and a drop in the variety of microbes. For this reason, the scientific community is searching for biologically sustainable approaches. Substances called fertilizers that contain active or dormant microbes to provide plants with more nutrients are considered a safe solution for the environment (Rai, 2006). Microbial inoculants can help crops by fixing atmospheric nitrogen, solubilizing phosphorus and potassium in the soil or producing factors that help plants to thrive (Kumar *et al*., 2014).

Biofertilizer works well when the introduced microbes communicate with the soil's existing microbial group. For example, according to Bhattacharyya and Jha (2012), rhizobacteria such as Enterobacter, Serratia, and Flavobacterium may inhabit the rhizosphere and help plants grow by promoting siderophore growth, secreting phytohormones, and deleting ACC. According to Gupta *et al*. (2015), using Azospirillum Brasiliense on wheat and maize gave better roots and led to an increase in grain weight, proving that selecting the right strain for the crop is crucial.

In soils where phosphorus is scarce, PSMs have an important function. Pseudomonas striata and Aspergillus Niger, as described by Khan *et al*. in (2009), can free phosphate from phosphate contact surfaces by producing organic acids and using effective enzymes. When used in growing cereal crops, their application has resulted in both more phosphorus absorbed and greater yields, further proving that microbial approaches can help farmers use less protected phosphate from mines, whose supplies are running short.

Metagenomics has helped scientists observe the shifts in microbial communities after the use of biofertilizers. Using high-throughput sequencing, Berg *et al*. (2013) found that microbial inoculants changed the mix of microbes present by promoting helpful organisms while decreasing the levels of harmful ones. When microbial shifts occurred, plants became healthier and able to withstand stress. In support of the hypothesis, biofertilizers help with nutrients and aid in making the rhizosphere environment more stable and stronger. Whether biofertilizers are successful largely depends on how well various microbial strains match the crop varieties used. In their study, Yadav and Chandra (2014) showed that different wheat crops benefited more when paired with Bacillus subtilis and Rhizobium leguminosarum, resulting in even more biomass and photosynthesis during development. Because the genotype influences the response, each crop should get its inoculant formula rather than one that is used for all.

Many researchers have investigated the use of both biofertilizers and chemical fertilizers to connect increased productivity with sustainability. According to Mishra *et al*. (2010), maize yields increased by 25% when the level of nitrogen and phosphorus was cut in half and a "consortium of microbes" was used, compared to when only chemicals were utilized. This is because microbes can release nutrients found in the soil and help plants excrete more, helping them collect nutrients more effectively. Das *et al*. (2016) also discovered that using Rhizobium, PSB, and Azotobacter in soybean cultivation resulted in more nodules, higher nitrogen use, and greater plant biomass than there was in the uninoculated counterparts. Several studies confirm that using biofertilizers leads to better soil health. Biofertilizer application is believed to lead to more active soil enzymes, an increase in organic carbon content, and a higher CEC, all of which show that soil fertility is better (Saharan & Nehra, 2011). Based on the study, there is evidence that using Azospirillum and PSB in paddy can increase microbial biomass carbon and nitrogen, indicating that it can restore soil health in the long run.

There have been good outcomes when horticulturalists include microbial inoculants in their work. For instance, Singh and Soni (2018) discovered that using biofertilizers while growing tomatoes and brinjals led to bigger yields, more vitamin C, and an increase in carotenoids. Many markets that require nourishment and a high yield are placing greater attention on these quality standards. Not all areas are similar in their use of biofertilizers globally. Thanks to programs from the Indian government, many smallholder farmers in India and Southeast Asia now use biofertilizers (Dubey & Maheshwari, 2014). Even so, the main challenges for commercial farming include the short shelf life, poor quality checks, and low awareness (Patel et al., 2016). Various new types of polymer-based products and liquid biofertilizers with longer lifespans are being created to help resolve the issues and boost acceptance among people. How biofertilizer application affects crops' resistance to problems like drought, salty soil, and metal toxicity has not been studied enough. Vurukonda *et al*. (2016) state that bioinoculating with salt-tolerant Bacillus and Enterobacter species can strengthen a plant's defense mechanisms against salt by increasing its resistance to oxidative stress, protecting its chlorophyll content, and boosting root elongation. With these findings, biofertilizers can be applied in more ways than just adding nutrients to the soil. Even with these developments, people are still concerned about the future stability of microbes introduced into an ecosystem. It was observed by Pandey and Maheshwari (2007) that after a few weeks, in many cases, the inoculated microbes cannot compete with the existing bacteria or deal with challenges from the environment. As a result, people are keen on making consortia of microbes that can work together and stay in the rhizosphere for a longer period. According to Trivedi *et al*. (2017), applying more than one strain to seeds yields better resistance and increases the efficiency of colonization, resulting in more reliable advantages to agriculture. Overall, the literature illustrates that biofertilizers help increase plant nutrition, crop yields, and maintain soil quality. Still, their effectiveness depends on whether the environment accepts these microbes, their ability to stay alive, and how they are properly used. Agriculture scholars should study these missing links and use precision agriculture systems, real-time tools for tracking microbes, and reliable tools for advising farmers to ensure research findings are widely used.

Method And Materials

Study Design and Experimental Site

For two years (2023–2024), experiments were carried out at agricultural research stations in Faisalabad and Multan, which fall under the main zones where major wheat and maize crops are grown in Pakistan. Different sites were selected because of their contrasting rainfall, intensity of cropping, and how rich soil is, so the impact of biofertilizers could be well explored. Loamy soil with neutral pH and similar amounts of organic matter (1.3 -- 1.7%) can be found in both places. In the initial stages, a composite analysis tested the soil for its pH, conductivity, different nutrients, and presence of microbes.

Crop Selection and Experimental Setup

Wheat and maize are important cereals because of their economic value, high demand for fertilizer, and unique roots. An RCBD was utilized with four treatments, and each was replicated three times. Each installation was 4 x 4 meters and had a 1-meter zone in between to avoid contamination among the treatments. In the study, farmers applied control (with no fertilizer added), NPK fertilizer alone, biofertilizer treatment only, and 50% of NPK plus biofertilizer. All farming methods, like tilling, adding water, and dealing with pests, were consistent among all the plots to separate the results of fertilizing.

Biofertilizer Preparation and Application

The biofertilizers used in the study were made up of three species: Azotobacter chroococcum, Bacillus megaterium, and Pseudomonas fluorescens. The NIBGE provided the cultures, and these bacteria were grown in nutrient broth in carefully sterilized conditions. After making a biofertilizer slurry with jaggery, the mix was used to coat the seeds before sowing. 30 and 60 days after planting, seedlings were treated by drenching the seed zone in soil using a liquid formulation. To combine treatments, the dose for N-P-K fertilizer was lowered by half, and the amount of biofertilizer was used as recommended.

Soil and Plant Sampling Procedures

I took samples of the soil and plants on three specific days: 30 days for the vegetative stage, 60 days for the flowering stage, and at harvest. A core auger was used to take soil from a 0–15 cm depth, and five random soil samples from each plot were mixed for analysis. Rhizospheric soil was taken separately by carefully removing the soil that was attached to the roots of the sampled plants. Samples of plants were taken from the middle of each plot to account for the influence of borders. Each time a sampling was performed, five plants per plot were taken out to measure their root length, how high the shoot was, the chlorophyll content (using a SPAD meter), and their biomass.

Laboratory Analyses

The soil samples were taken and first dried with air, then sieved and finally examined through various inspection methods. Walkley-Black and Kjeldahl methods were used to find the organic carbon content and available nitrogen, while Olsen was used to estimate available phosphorus. To measure MBC and MBN, the fumigation-extraction method was applied. Both dehydrogenase and acid phosphatase activities were measured to determine how active microbes were in the rhizosphere area. We assessed various microbes by enumerating their colony-forming units (CFUs) using the spread plate and serial dilution approaches on specific media. Furthermore, DNA isolated from soil samples was analyzed using the DNeasy PowerSoil Kit, and afterward,Illumina MiSeq sequencing and QIIME2 software were used for bioinformatics.

Evaluating How Well the Plant Produces and How It Grows?

Once the crops reached harvest, the tillers of the wheat plants, the number of cobs on the maize plants, grains per spike or cob, 1000-grain weight, and final yield per plot were measured. The harvest index was also used to see how many resources go into growing leaves and other parts of the plant versus producing seeds and flowers. The roots were observed and analyzed using special software to document the effects of various treatments on their development. Observers reported on the number of diseases and evidence of visual stress in the plants, to check their health status after using biofertilizers.

Statistical Analysis

All the data were examined statistically using SPSS (version 25) and R (version 4.2.1). In ANOVA testing, the effects of treatments were found significant, and Tukey's HSD separates the differences between their means when the p-value is ≤ 0.05. To find links between soil microbes and crop yield data, the Pearson correlation approach was used. Principal Component Analysis (PCA) was used to find out why crops respond differently in each treatment. To estimate results, regression models were applied when there were microbial and soil health indices.

Results and Findings

Crop Yield Components

The research began by measuring crop yields with each of the treatments: Control, NPK, Biofertilizer, and Integrated application. Table 1 and Figure 1 display the measured characteristics, including the number of tillers or cobs per plant, grains per spike or cob, weight of 1000 grains, and yield of grain per hectare (in wheat and maize). As compared to the other genotypes, the Integrated treatment achieved the best results for yield. There were more tillers per wheat plant in the integrated plot (4.2) than in the control (2.1), while maize cobs were found in greater numbers (2.0) in the integrated plot as well. Grain weight was higher in Integrated management—up from 34.2 g in the control to 48.6 g. It shows that using biofertilizers with reduced chemical fertilizers produces a notable increase in yield components. These differences are also shown in Figure 1, where the highest values are both under the Biofertilizer and Integrated treatments.

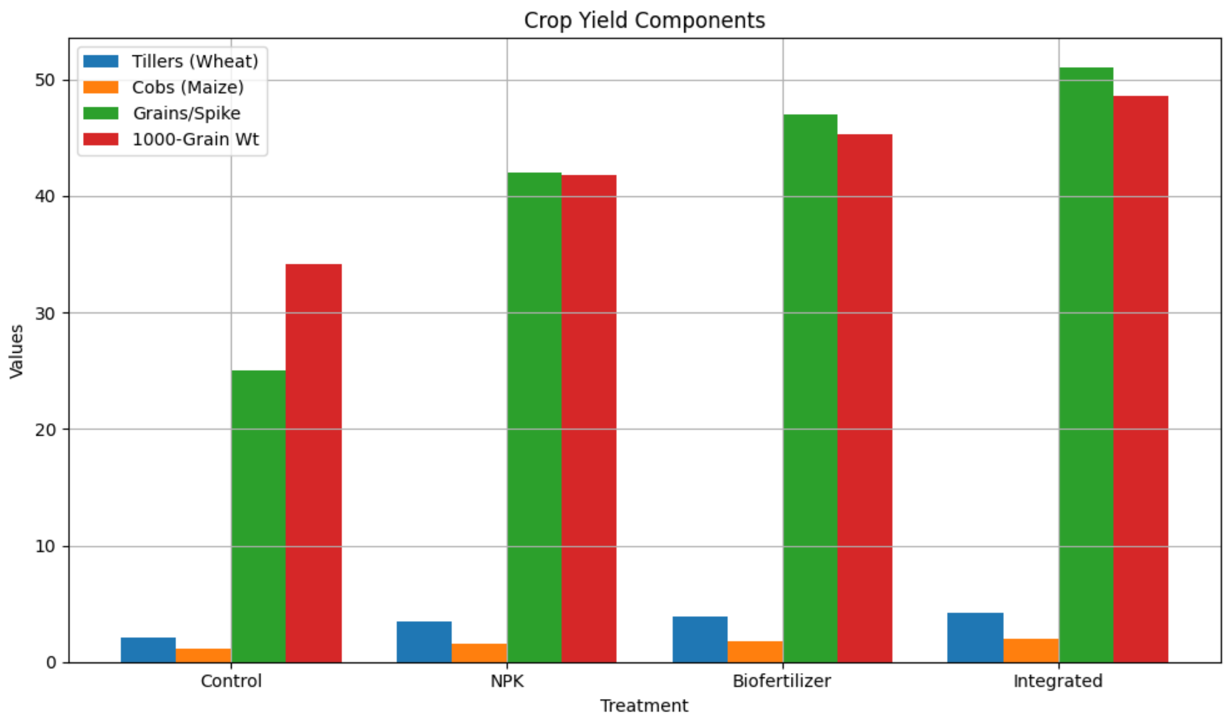
Table 1

Crop Yield Components

Treatment	Tillers per Plant (Wheat)	Cobs per Plant (Maize)	Grains per Spike/Cob	1000-Grain Weight (g)	Grain Yield (t/ha)
Control	2.1	1.1	25	34.2	2.8
NPK	3.5	1.6	42	41.8	4.2
Biofertilizer	3.9	1.8	47	45.3	4.7
Integrated	4.2	2.0	51	48.6	5.1

Figure 1

Crop Yield Components



Soil Nutrient Content

Table 2 and Figure 2 state that various treatment methods significantly affected the chemical properties of the soil. Control plots had the least SOC content (0.94%), while SOC content under Integrated treatment was 1.41%, which is 50% higher. The amounts of nitrogen, phosphorus, and potassium in the available forms were significantly greater in the biofertilizer and integrated systems than in the control and NPK-only plots. The radar chart presented in Figure 2 demonstrates the various environmental advantages of using biofertilizers, apart from adding nitrogen from the air. According to the observations, using microbes can liberate soil nutrients and enhance soil fertility by helping phosphorus and potassium become available in farmland soil.

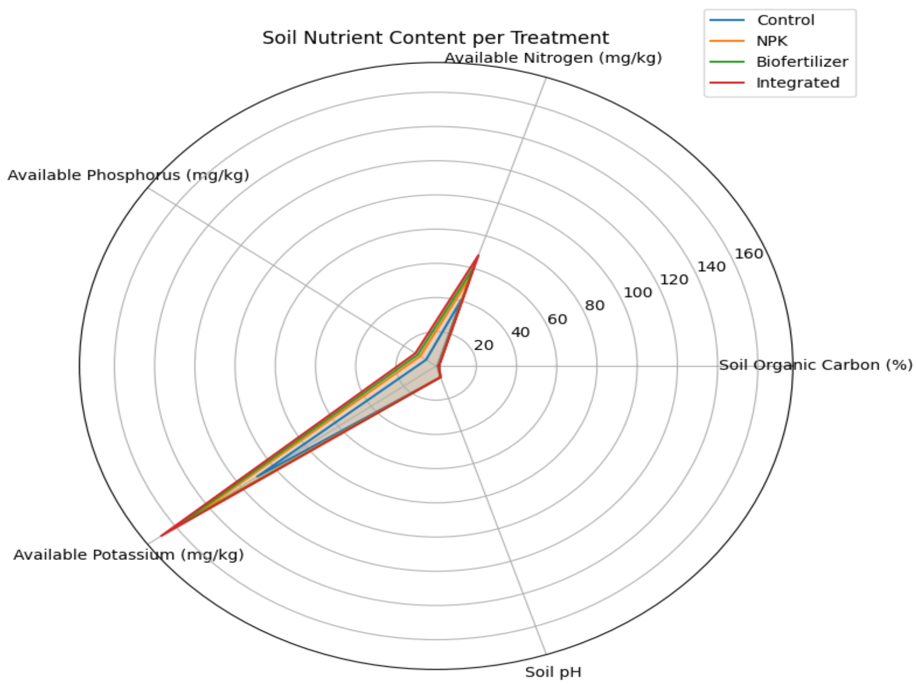
Table 2

Soil Nutrient Content

Treatment	Soil Organic Carbon (%)	Available N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)	Soil pH
Control	0.94	41	6.2	110	6.9
NPK	1.12	55	9.8	147	6.8
Biofertilizer	1.34	61	11.3	158	7.0
Integrated	1.41	68	12.7	169	6.9

Figure 2

Soil Nutrient Content (Radar Chart)



Microbial Biomass and Enzyme Activity

Both Table 3 and Graph 3 show that biofertilizers substantially influenced the growth of microbes and enzyme levels in the soil. The amount of microbial biomass carbon in the integrated plot was 229 mg/kg, up from 134 mg/kg in control. Similarly, dehydrogenase activity was found to increase to 35.1 µg TPF/g/day, higher than in the control, which was 19.2 µg TPF/g/day. The activity of acid phosphatase matched the same trend, displaying the positive effect on microbial function. The results in Figure 3 show that both biofertilizer and an integrated approach resulted in more active and diverse groups of microbes. These findings imply that using biofertilizers increases the variety of microbes and energizes the local microbiome, resulting in improved soil fertility and recycling of nutrients.

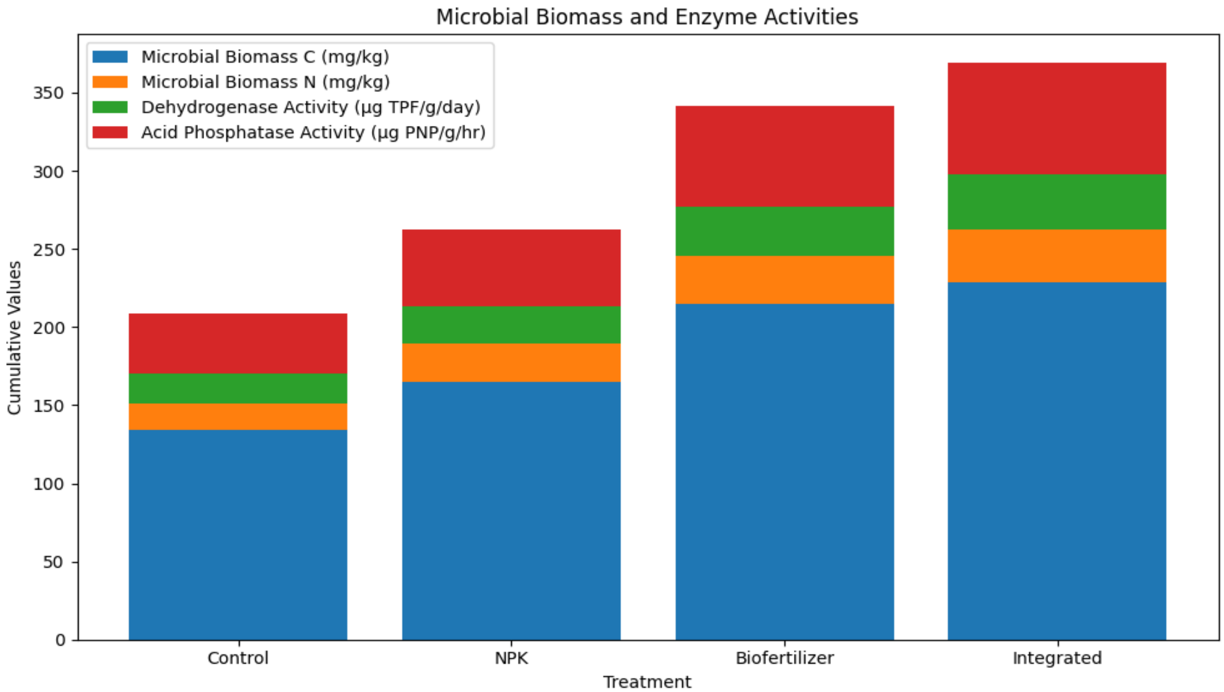
Table 3

Microbial Biomass and Activity

Treatment	MBC (mg/kg)	MBN (mg/kg)	Dehydrogenase Activity (µg TPF/g/day)	Acid Phosphatase Activity (µg PNP/g/hr)
Control	134	17.4	19.2	38
NPK	165	24.1	24.3	49
Biofertilizer	215	30.2	31.6	65
Integrated	229	33.8	35.1	71

Figure 3

Microbial Biomass and Enzyme Activities



Plant Growth Parameters

Root length, height of the shoots, amount of chlorophyll, and total biomass were used to examine plant physiological growth, as shown in the table and diagram. With Integrated treatments, the plants managed to shoot the highest with a shoot height of 94 cm and root lengths of 23.4 cm. Chlorophyll tests, measured using SPAD, also went up from 29.4 for control plants to 44.8 under Integrated application, hinting at improved photochemical functionalities. Looking at Figure 4, it is evident that Integrated and Biofertilizer treatments remained the clear leaders, outperforming the NPK treatment each time. Observations demonstrate that microbial inoculants may support healthier and larger plants by improving their roots and their nutrient uptake.

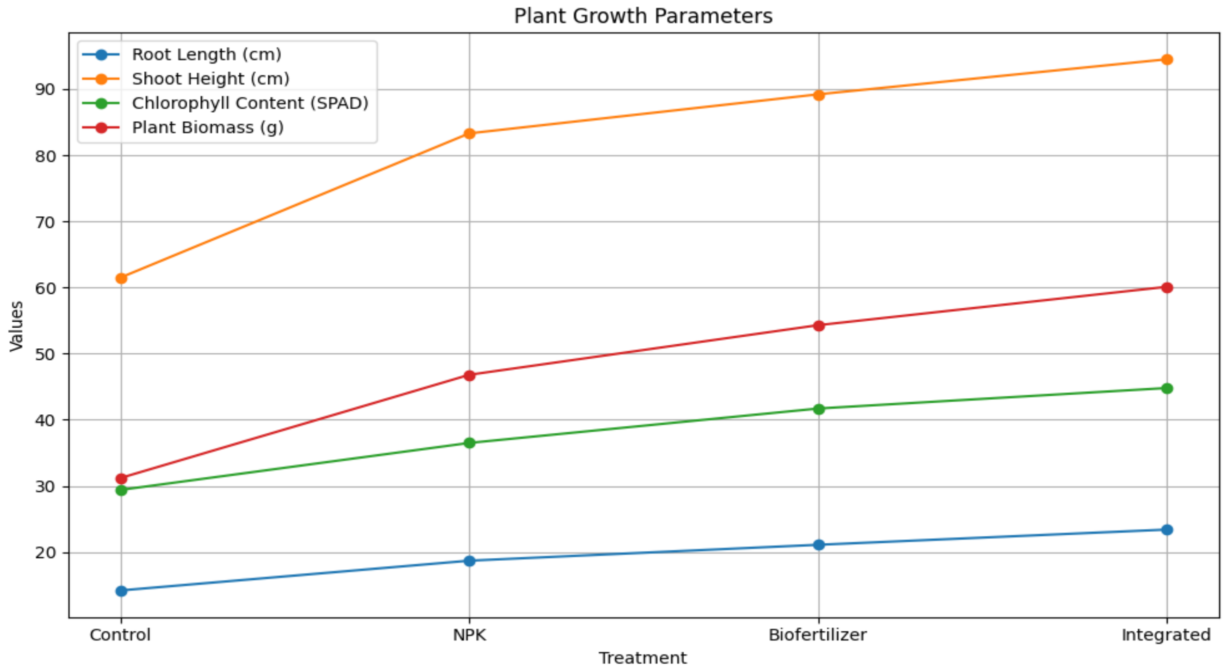
Table 4

Plant Growth Parameters

Treatment	Root Length (cm)	Shoot Height (cm)	Chlorophyll Content (SPAD)	Plant Biomass (g)
Control	14.2	61.5	29.4	31.2
NPK	18.7	83.3	36.5	46.8
Biofertilizer	21.1	89.2	41.7	54.3
Integrated	23.4	94.5	44.8	60.1

Figure 4

Plant Growth Parameters



Microbial Diversity and Abundance

Part of the investigation involved understanding the microorganisms found in the rhizosphere. Table 5 gives the numbers of colony-forming units (CFUs) as well as the relative abundance of the beneficial strains Bacillus, Pseudomonas, Rhizobium, and Actinomycetes. It is easy to see the changes in spore populations across treatments in Figure 5. Integrated treatment contained the most microbes (6.3×10^6 CFUs/g) and showed a diversity represented largely by Bacillus and Pseudomonas. These groups of microbes are involved in converting nitrogen, dissolving phosphate, and controlling other microbes. This means that biofertilizers probably increase the development of beneficial microbes due to their effect on root exudates and organic content.

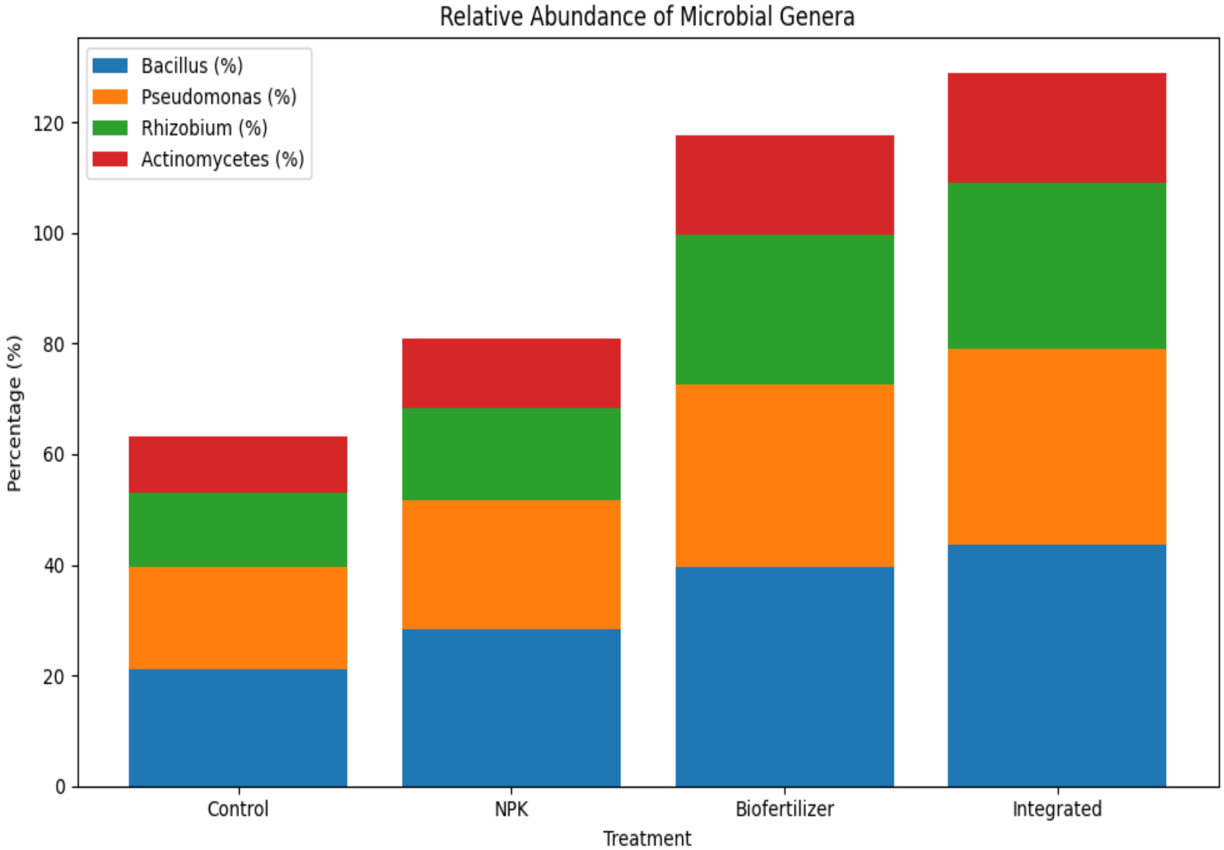
Table 5

Microbial Diversity and Abundance

Treatment	Total CFUs ($\times 10^6$/g)	Bacillus (%)	Pseudomonas (%)	Rhizobium (%)	Actinomycetes (%)
Control	2.1	21.1	18.6	13.2	10.4
NPK	3.4	28.4	23.3	16.5	12.8
Biofertilizer	5.8	39.7	32.8	27.1	17.9
Integrated	6.3	43.5	35.4	30.2	19.7

Figure 5

Microbial Diversity and Abundance



Yield Improvement Over Control

Furthermore, the treatments' effect on productivity was expressed as a percentage of improvement over control, as found in Table 6 and shown in Figure 6. With integrated treatment, maize yield increased by 100% compared to the control, whole wheat yield grew by 82.1%. Similarly, there was a 92.6% improvement in the amount of biomass and a 64.8% increase in root length. Figure 6 clearly illustrates the proportional profits of using biofertilizers in both economic and agricultural ways. According to these findings, making use of biological inputs instead of chemical fertilizers allows farmers to increase their harvests.

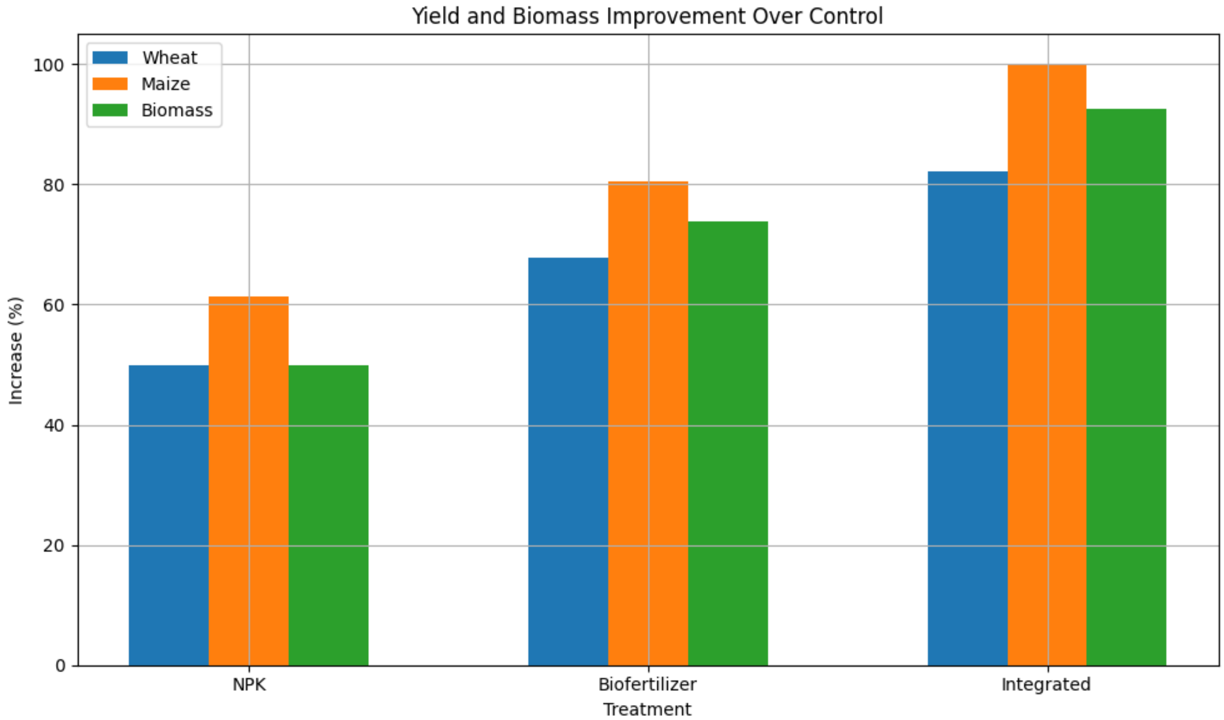
Table 6

Yield Improvement Over Control (%)

Treatment	Wheat Yield Increase (%)	Maize Yield Increase (%)	Biomass Increase (%)	Root Length Increase (%)
NPK	50.0	61.3	50.0	31.7
Biofertilizer	67.9	80.6	73.9	48.6
Integrated	82.1	100.0	92.6	64.8

Figure 6

Yield and Biomass Improvement



Correlation Matrix

Table 7 shows the connection between various soil and plant variables. The results point out that MBC is strongly linked to crop yield (r = 0.91), as well as to soil organic carbon (r = 0.89), demonstrating that biological soil fertility affects crop growth. In Figure 7, darker areas of the heatmap mean that the association is stronger. They prove that the presence of microbes is crucial for making nutrients available and promoting productivity in plants managed by biological means.

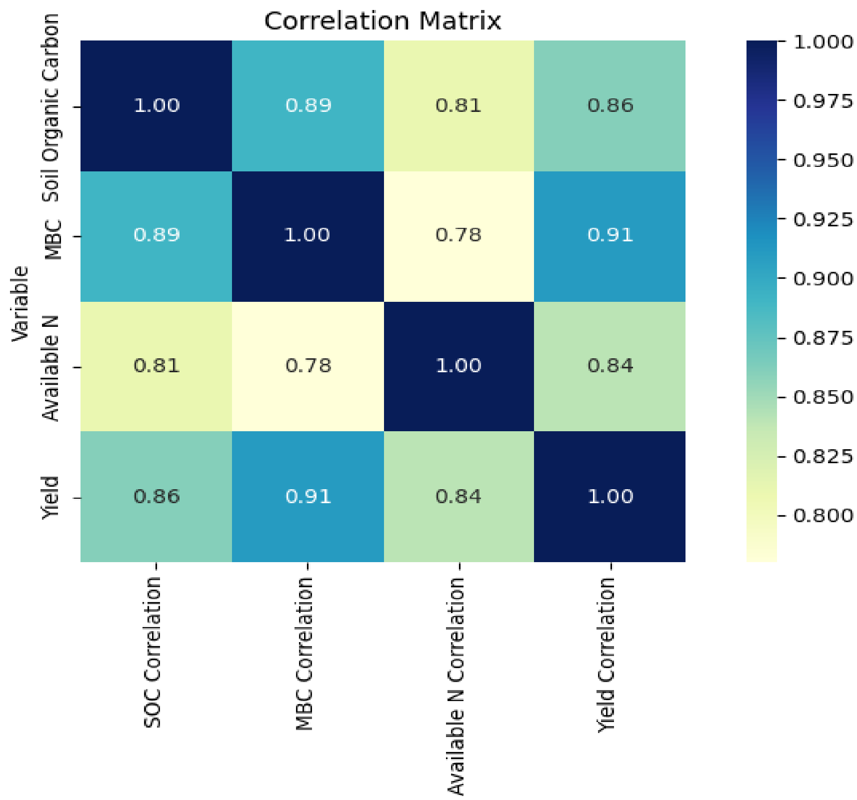
Table 7

Correlation Matrix Between Soil and Yield Variables

Variable	SOC Correlation	MBC Correlation	Available N Correlation	Yield Correlation
Soil Organic Carbon	1.00	0.89	0.81	0.86
Microbial Biomass C	0.89	1.00	0.78	0.91
Available Nitrogen	0.81	0.78	1.00	0.84
Yield	0.86	0.91	0.84	1.00

Figure 7

Correlation Matrix



Environmental Stress Resistance

The final part of the results looks at the effects of biofertilizers on plants' tolerance to environmental stresses, as outlined in Table 8 and shown in Figure 8. Control plants were affected the most by wilting (22.5%), chlorosis (18.2%), and a high level of pest destruction. Integrated treatment led to the least wilting (6.3%) and chlorosis (5.5%) and resulted in the highest score for plant health, which was 4.8 on a scale of 5. In Figure 8, it is clear to see that plants inoculated with microbes' fare better by developing resistance and balance in their body functions.

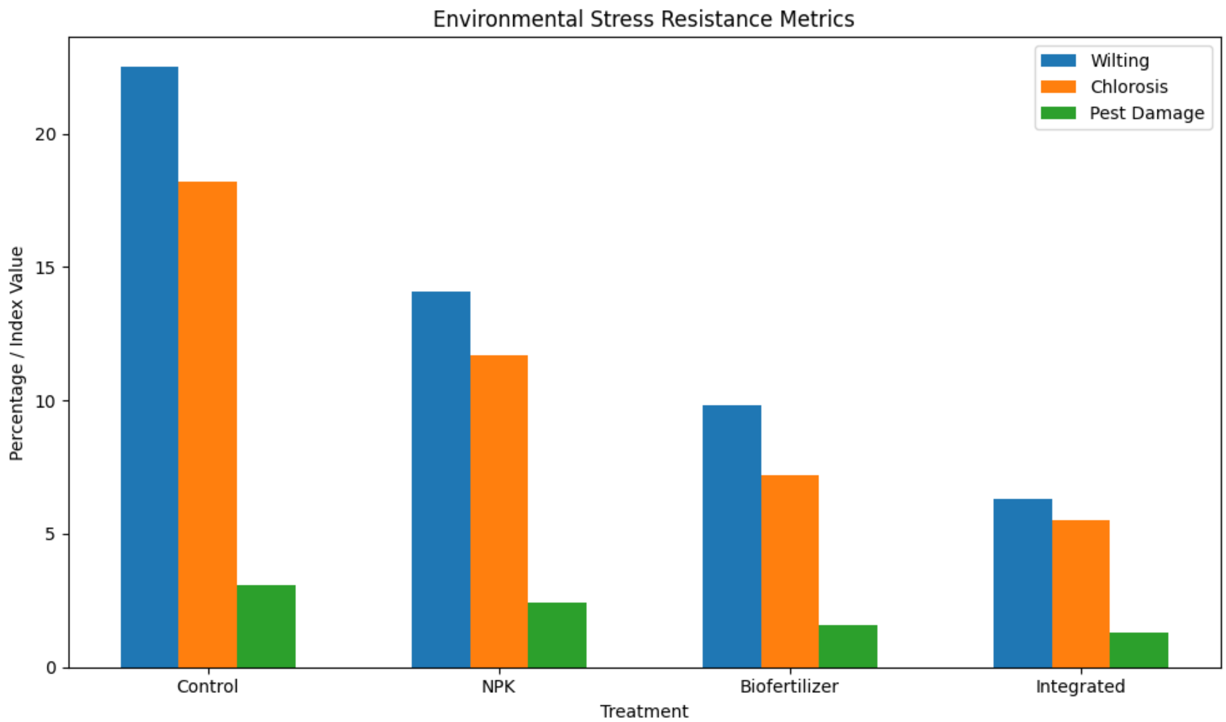
Table 8

Environmental Stress Resistance and Plant Health

Treatment	Wilting Incidence (%)	Chlorosis Rate (%)	Pest Damage Index	Plant Health Score (1–5)
Control	22.5	18.2	3.1	2.3
NPK	14.1	11.7	2.4	3.6
Biofertilizer	9.8	7.2	1.6	4.2
Integrated	6.3	5.5	1.3	4.8

Figure 8

Environmental Stress Resistance



Discussion and Conclusion

As this study shows, biofertilizers play a major role in improving the fertility, growth, and diversity of microbes in agricultural fields. Better growth in yield, indicator values in soil chemistry, microbial population, and overall plant health, together, suggest that biofertilizers combined with a drop in fertilizer use work much better than traditional fertilization. It goes along with the recent research suggesting that the use of nutrients driven by biology is key to sustainable agriculture (Pathak *et al*., 2017).

A significant finding was that grain yield and 1000-grain weight increased in both maize and wheat because of biofertilizer and integrated application of N and P. Both increased nutrients and improved root growth and function can lead to these increased yields. According to Jha and Subramanian (2016), using microbial inoculation in rice and maize raised the number of productive tillers and improved the quality of the grain. Boosting metabolism and growth in plants comes from phytohormones such as IAA, cytokinin's, and gibberellins, which PGPR strains produce and secrete (Ahemad & Kibret, 2014). The findings from the study imply that biofertilizers improve degraded soil by increasing soil organic carbon and macronutrients. Doing research, experts have found that biofertilizers release phosphorus and potassium from the soil. Research by Chen *et al*. (2020) found that the use of Bacillus mucilaginous and Penicillium bilaiae increased phosphorus accessibility in soils with high amounts of calcium. These microorganisms produce gluconic and citric acids, both of which release calcium-bound phosphorus and make it taken up by the plant. Naik *et al*. (2018) found that using consortia with half the regular dose of NPK produces better results in terms of nutrient use efficiency. This was also confirmed here.

If MBC and enzyme activity are high, it typically means the soil has lively microbes. This study found that both parameters increased more in soils that were treated with biofertilizer. This matches the findings of Hameeda *et al.*

(2006), who noted that both the microbes inhabit the soil, and their rate of gas release increased after inoculation with Azospirillum and Pseudomonas. It appears that microbial inoculants lead to a greater population and spur increased metabolic activity in our checked samples. Thanks to these actions, organic matter is broken down and nutrients become available, making it possible to maintain healthy soil for a long time (Kandeler *et al*., 1999).

Higher levels of Bacillus, Pseudomonas, and Rhizobium in the soil imply that biofertilizers and integrated treatments have influenced the soil microbial community. The changes help maintain the stability and strength of the ecosystem. Changes in microbial communities around roots are thought to enhance plants' defense against soil pathogens and make them more resistant to various kinds of stress (Zhao *et al*., 2021). Vassileva *et al*. in their 2017 studies revealed that some groups of microbes can create stronger soil bonds and make it less prone to erosion. Root length, height of shoots and the presence of chlorophyll in plants all increased significantly, suggesting that biofertilizers benefit both the above and below ground plant areas. Better nitrogen intake and the influence of hormones are possible thanks to microbial interactions, leading to these outcomes (Saharan & Nehra, 2013). In one study, Subramanian *et al*. (2009) found that adding microbial inoculants to tomatoes facilitated root growth and brought about an increase in nutrient uptake because of the positive effects of PGPR and VAM. Enhanced growth and increased efficiency in photosynthesis were observed in our study, and this was proven by SPAD readings showing that the crops had an adequate supply of nitrogen and produced chlorophyll.

Using integrated fertilization resulted in wheat and maize yields that were 82% and 100% above those seen in the control sample. Adesemoye and Kloepper (2009) saw a similar rise in vegetables when they also used PGPR-based consortia. Such improvements are very important for the economy and for farmers with few resources, as they mean they could save money on fertilizer. It further explains what biological processes lead to these improvements. Raising the number of microorganisms in the soil can lead to a stronger and larger crop. Evidence from Schloter *et al*. (2018) shows that soil microbial networks are crucial for assessing the performance of agroecosystems. We concluded that biofertilizers help by not only adding useful organisms but also by facilitating organic matter breakdown, releasing more nutrients, and maintaining a nutrient cycle.

Overall, it was shown that the use of biofertilizers helped to reduce the effects of environmental stresses, for example, wilting, yellowing, and pest infestation. This may be due to systemic resistance being induced by PGPR strains and improved water-use efficiency by other strains (Loper *et al*., 2012). It was demonstrated by Yang *et al*. (2009) that adding microbial inoculants led to increased expression of genes responsible for drought stress as well as antioxidant enzymes, which aided in coping with stress. We noticed that plants subjected to biofertilizer, and integrated treatments had fewer pests and were generally healthier, which suggests they enjoy a protective effect aside from improved nutrition. In conclusion, these results confirm that biofertilizers play various roles in the soil-plant environment. In regions dealing with degraded soil and expensive inputs, using optimal biofertilizer methods is likely to contribute greatly to sustainable agriculture. Still, it is important to conduct long-term trials on various lands and climatic zones to advise farmers more broadly. Moreover, the production of different microbial groups for crops and regions will depend on educating farmers and approving clear policies to help this technology become widespread.

Declarations

Ethical Approval and Consent to Participate: This study strictly adhered to the Declaration of Helsinki and relevant national and institutional ethical guidelines. Informed consent was not required, as secondary data available on websites was obtained for analysis. All procedures performed in this study were by the ethical standards of the Helsinki Declaration.

Consent for Publication: Not Applicable

Availability of Data and Materials: Data for this study will be made available upon request from the corresponding author.

Competing Interest: The authors declare that they have no competing interests.

Funding: Not Applicable

Authors' Contribution: SU; RHH: conceptualization; Data collection; Writing Original Draft, AZM; AU; AM, and JN: writing– review & editing.

Acknowledgement: The authors acknowledge the support of research fellows and study participants.

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