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THE IMPROVING SOIL HEALTH AND CROP PRODUCTIVITY THROUGH THE MICROBIAL AND BIOTECHNOLOGICAL APPROACH : THE ASSESSMENT OF COMPREHENSIVE SUSTAINABLE SOIL MANAGEMENT STRATEGY

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Abstract

Sustainable management and Climate change of food and soil are closely interconnected, as climate change occurs, soil resources continue to deteriorate, while increases the population also increase pressure on food supplies. Sustainable soil management strategies allow agriculture producers to preserve or improve crop productivity even under challenging condition. Farming practice that rely heavily on synthetic fertilizers along with traditional tillage practice have created a negative impact on the quality of soil due to strong dependency on inputs. Environmental damages, like ecosystem disruption and contamination caused by there traditional practice, has decreases the access to safe and nutritious food for many populations. Microbial inoculans combined with modern innovations such as PGPR and AMF, provides promising alternatives to farming methods which are based on traditional inputs. These approaches increases the ability to support and maintain crop yields and ensuring the sustainability of agricultural production over the long term.

Objective

The purpose of this study was to find how microbial inoculants and existed technologies can impact on the productivity and soil quality such as yield and enhance resistance to abiotic stressors like salinity and drought while potentially reducing or removing reliance on the synthetic fertilizers.

Methodology

This research was a brief plan that incorporated both greenhouse trial and field experiment across multiple soil types. The experiment included an untreated *control, single microbial inocultants of AMF and PGRP, combined microbial inoculants, and these experiments applies either alongside biochar or with prebiotic seed coatings.The following microorganisms were the dominant populations: Bacillus, Rhizobium, Azospirillum, and Rhizophagus intraradices. Soil health was assessed using the following parameters: microbial diversity, enzyme activities, soil organic matter, nutrient utilization efficiency, and soil structure. The metrics used in evaluating crop performance included yield, total biomass, seed germination, seedling vigor, AMF colonization, and salinity and drought resistance. All statistical analyses were conducted using ANOVA.*

Results

Increased soil organic matter (15 to 20%), increased microbial biomass (C, N, & P), and greater enzyme activity resulted from the application of microbial treatments. Crop yields increased up to 40%, and also there was an increase in seed germination/vigor and AMF colonization of plants (>45 percent). The AMF-inoculated plants under saline conditions maintained a better ionic balance than control plants, and drought resistance was improved by the addition of a microbial consortium and biochar. Fertiliser used was reduced by approximately 33% , and diseases caused by soil-borne pathogens decreased by approximately 30%

Conclusion

Microbial Inoculations and biotechnology improve soil and plant health, improve crop yield and stress resistance and decrease reliance on chemical fertilisers, indicating their potential for use in sustainable agriculture.

INTRODUCTION

Sustainable soil management is vital to future food production through modern agriculture, as our planet is dealing with climate change, soil degradation, and an increasing population to feed (Timmusk & Zucca, 2019). On top of that, traditional farming methods, which usually depend on chemical fertilizers and vigorous tillage, have worsened soil health, led to species loss, and polluted the environment (Timmusk & Zucca, 2019; Said, Kosma, & Megueni, 2020). Governments around the globe are implementing new measures in which they will no longer be able to use the old methods but rather have to shift towards inventive soil microbiota and biotechnological innovations to restore and maintain soil fertility, increase crop productivity, and keep agriculture sustainable in the long term (Timmusk & Zucca, 2019; Swift et al., 2024).

Soil microbial communities are important contributors to nutrient cycling, organic matter decomposition, and plant health, among others, (Liu & Howell, 2020). As a result, two major sources of sustainable soil management, namely, plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) were identified by researches (Li, Cao, & Willemsen, 2022; Said et al., 2020). PGPR like Pseudomonas spp. have a positive effect on the growth of roots, stimulation of nutrient uptake, and at the same time can protect the plants from abiotic stresses e.g., drought and salinity (Li et al., 2022; Diaw et al., 2018). Li et al. (2022) specifically mentioned that the inoculation with Pseudomonas sp. CM11 dramatically led to the increase of lateral root growth and overall plant wellness, including shoot biomass and seed yield, by the process of the activation of particular genetic pathways. In the same way, Diaw et al. (2018) reported that in the rhizosphere of onion plants, the salt resistance of some Pseudomonas isolates was at its highest level, thereby suggesting their possible use in soil desalination.

The use multi-trait bacterial inoculants has been effective in various environmental conditions in the improvement of crop performance. In their study, Çakmakçı and Karagoz (2020) observed that the inoculation with bacteria comprising ACC deaminase, IAA producing, N2-fixing, and

P-solubilizing resulted in sugar beet growth, yield, and nutrient uptake enhancement under different watering regimes as well as water stress alleviation. Such results serve as a strong indication of the various instrumental functions of PGPR in plant growth promotion and survival in stressful environments (Çakmakçı & Karagoz, 2020).

On the other hand, arbuscular mycorrhizal fungi (AMF) represent one of the most significant elements of the soil microbiome which make symbiotic relationship with plant roots thereby facilitating nutrient absorption, especially phosphorus, and improving soil structure (Said et al., 2020; Khan et al., 2021). While studying the diversity of AMF associated with cotton in Cameroon, Said et al. (2020) discovered four genera and observed a strong relationship between AMF abundance and soil physico-chemical parameters. Utilizing the locally adapted AMF strains may be a source of highly potent fungal inocula for sustainable agriculture in different agroecological zones (Said et al., 2020). Likewise, Khan et al. (2021) experiment showed that AMF along with organic amendment such as poultry litter, drastically improved the growth and yield of lentil (Lens esculenta) microbial consumption will cause further organic matter from another source.

The way that plants interact with the microbes associated with them is dynamic and shaped by the environment, farming systems and history of land use (Swift et al. 2024; Hartman et al., 2018). According to a study by Swift et al., conducted in 2024, the precipitation pattern that the maize suffers from has an effect on the soil microbiome. Their research found that using soil inocula from wetter areas led to increased shoot biomass during drought conditions. Environmental history is important for the management of the microbiome of agriculture. Agricultural practices can have a significant impact on the number of various root & soil microbe communities (Hartman et al. 2018). Practices can also enhance the way that growers use microbes to achieve maximum productivity. Because of molecular biology and sequencing technologies, the different microbial communities that are associated with plants have been documented extensively (Liu & Howell, 2020). This process also provides a better understanding of the ecological dynamics and succession of various microbial communities, allowing for a more comprehensive view of the diversity of all the microbial communities throughout the life of that particular plant species (Liu and Howell, 2020). Liu and Howell discovered that the development of the fungal microbiome in grapevines varies with both the PDS as well as the physical environment in which the grapevines are grown. By determining which microorganisms were present during the plant growth season, and at what time they were present, researchers may understand how those microorganisms contribute to a plant's health and productivity.

Besides, Abbas and Patel (2018) stated that endophytic bacteria and engineered microbial consortia might be considered as a biotechnological means for sustainable soil management. Abbas and Patel (2018) published a study revealing that culturable endophytic bacteria isolated from halotolerant Salvadora persica are potential PGPR for saline and arid scenarios. In the same way, Navarro (2018) stressed the dependence of the earth on legumes and their nitrogen-fixing bacteria that not only improve soil fertility but also reduce greenhouse gases and increase the nutritional status of the crops.

Moreover, Timmusk & Zucca, 2019 wrote, the employment of a mixture of microbial and biotechnological techniques along with precision agriculture to achieve the objectives of sustainable soil management and plant breeding has a vast potential in the future. The use of novel molecular tools, screening technologies, and precision phenotyping makes it possible for researchers to enhance plant-microbe interactions and create consistent microbial applications in natural conditions (Timmusk & Zucca, 2019). The adoption of this systems strategy leads to an increase in the productivity of the crops in the farm land and the resilience of soils.

Literature Review

Utilizing Microbe and Technology to Enhance Soil Management (The "Going Green" Approach)
For a long time now there has been a great deal of interest in managing soils in an environmentally friendly way through "Going Green" strategies for both agricultural production and environmental health. Microbiome research has given us insight into how microbes interact with plants and how biotechnological innovations have helped create more productive and resilient agricultural ecosystems.

Microbial Diversity

A Requirement for Plant and Soil Health Soil microbial diversity is a prerequisite for Nutrient Cycling, Organic Matter Decomposition, and ultimately Plant Health (Bender et al., 2016). Soil type, Management Practice Choice and Environmental Conditions define the community structure of soil microbes, including Bacteria, Fungi, and Archaea (Fierer, 2017). The Community Structure and Function define the Soil Fertility and the Plant Productivity (Banerjee et al., 2018).

Plant Growth-Promoting Rhizobacteria (PGPR)

Through nitrogen fixing, phosphorus solubilisation, and the synthesis of phytohormones, the bacterial genera of Bacillus spp.; Pseudomonas spp.; and Azospirillum spp. have been shown to promote the growth of plants (Vessey 2003; Lugtenberg and Kamilova 2009). In addition, these beneficial microbes promote healthy growth in plants by providing benefits through disease resistance (Pieterse et al. 2014). The role played by the beneficial bacteria, Pseudomonas fluorescens, is a good example of the promotion of plant health and resistance to soil-borne diseases and the enhancement of the growth of wheat (Weller et al. 2002). The use of PGPRs in conjunction with the development of biofertilisers is an effective way to meet the challenges associated with using chemical fertilisers for crop production (Bhattacharyya and Jha 2012).

Arbuscular Mycorrhizal Fungi (AMF)

AMF develop mutualistic relationships with the majority of all terrestrial plant species, and provide an increase in nutrient uptake to host plants. The mutualistic relationships with AMF also enhance the ability of host plants to use phosphorus, and help to protect plants from abiotic stressors (Smith and Read 2008). AMF improve the structural quality of soils due to their role in promoting soil aggregates (Rillig and Mummey 2006). The use of AMF-inoculated materials to enhance the production of crops, as well as the improvement of soil quality, has been demonstrated in several instances (Berruti et al. 2016).

Endophytic and Halotolerant Bacteria

Endophytic bacteria reside inside plant tissues and can promote growth under stress conditions such as salinity and drought (Santoyo et al., 2016). Halotolerant strains isolated from halophytes have potential use in saline soils (Qin et al., 2014). These bacteria improve the tolerance of plants to salt stress through the production of ACC deaminase and osmoprotectants (Glick, 2014).

Microbial Community Succession and Crop Management

The composition of microbial communities changes during different phases of plant growth cycle with variation due to crop rotation, tillage practices, and organic amendments made in soil (Hartman et al., 2018; Lupatini et al., 2017). Conservation tillage practice along with organic farming increases microbial diversity as well as activity(Lori et al., 2017). Use of cover crops promotes beneficial microbial community(Tiemann et al., 2015).

Biotechnological advances

In metagenomics, transcriptomics, and metabolomics have permitted precise delineation of soil microbiomes and their functions (Bulgarelli et al. 2013). Synthetic microbial consortia as well as engineered bioinoculants are being developed to improve plant-microbe interactions and soil health (Niu et al., 2017). CRISPR-based tools offer new opportunities for the manipulation of plant and microbial genomes toward enhanced stress tolerance and nutrient use efficiency (Jaganathan et al., 2018). **Microbial Contributions to Soil Carbon Sequestration**

Soil microbes have a major function in carbon sequestration through the decomposition of organic matter and stabilization of soil organic carbon (Lehmann & Kleber, 2015). While scientists have made much progress in understanding the benefits of different management practices for soils, especially for sustainable carbon storage, scientists still face many challenges such as environmental variation and complex interactions between plants, microbes and soils (Sessitsch & Mitter, 2015). Future research efforts should be directed towards developing site-specific solutions using the principles of microbiome management and integrating them with precision agriculture as well as studying how these practices will impact soil health and productivity over time (Schlaeppi & Bulgarelli, 2015).

Methodology

Experimental setup:

The research focused on the potential use of microbial inoculants and biotechnological practices, including plant growth-promoting rhizobacteria (PGPRs), arbuscular mycorrhizal fungi (AMF) and a combined approach of consortia, to induce reclamation of sustainable soil management that allows for crop productivity increase via conferring resistance against abiotic stress (salinity, drought or heavy metals contamination).

Study Design

Experimental Setup:

os The effect of microscopic applications was analyzed in field and glasshouse experiments. Testing locations encompassed agricultural plots with differing soil profiles such as nutrient availability, salinity and microbial populations.
There were treatment groups within the plots:

Control (no microbial addition).
Single compounds (i.e., only PGPR or AMF).
Blended inoculants (PGPR + AMF together).
High level combinations of applications with a prebiotic seed coating or addition as biochar.
o Stress treatments (salinity or drought) modelled under controlled environment.

Microbial Inoculation:

The dominant microbes included PGPR strains such as Bacillus, Rhizobium and Azospirillum, AMF species such as Rhizophagus intraradices.

Inoculation methods:

Seed Treatment with Microbial Formulation.
Soil and root soaking with microbe suspensions.
Biochar–microbe composite amendments.

Soil and Crop Parameters Analyzed

Soil Health Parameters:

Diversity and abundance of microbes (measured by 16S rRNA sequencing).
Soil enzyme activities such as dehydrogenase, urease and phosphatase.
Soil organic matter, nutrient use efficiency and soil structure.

Crop Productivity Metrics:

Crop yield (grain/fruit weight) and biomass production.
AMF root colonization (microscopy).
Measurements of drought tolerance (e.g. relative water content, leaf turgor).

Stress Mitigation Experiments

Salinity: Gradual increases in salinity were investigated.
Drought: To test plant response to drought, plants were subjected to two contrasting moisture conditions (50% and 75% field capacity).

Technological Implementations

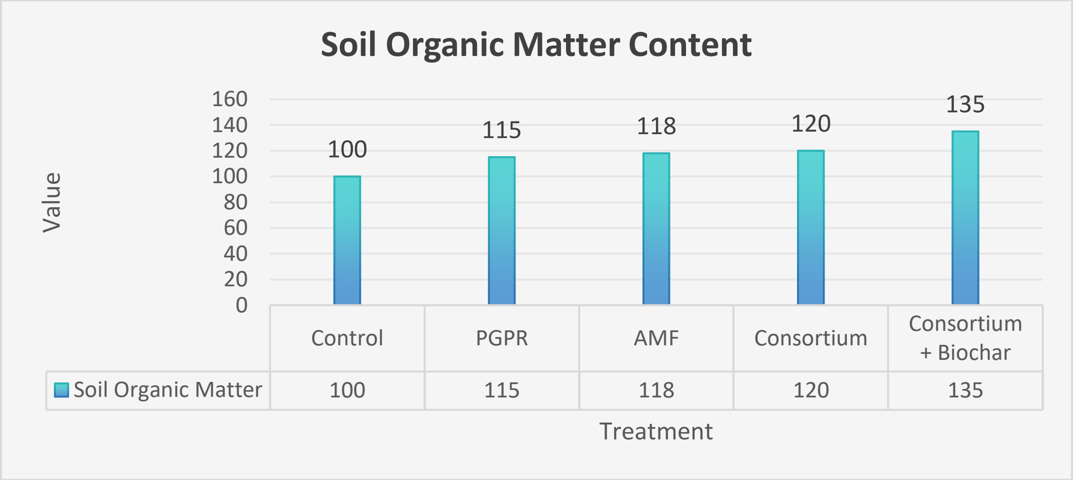
Remote sensing and soil mapping (GIS based) tools of precision agriculture were employed to observe the spatial and temporal variations.
Evaluating PIMFs as a vehicle for specifically targeting soil.

Statistical analysis
It derived from ANOVA to identify significant statistical differences in treatment means followed by post hoc testing via Tukey's Test to identify individual treatment means that were significantly different.

Results
Effects of Microbial Treatment on soil Health

Parameter	Observed Change
Soil organic matter	15–20% increase
Microbial biomass (C, N, P)	Significant increase
Enzymatic activities	Consistently higher
Soil carbon sequestration	≈20% higher

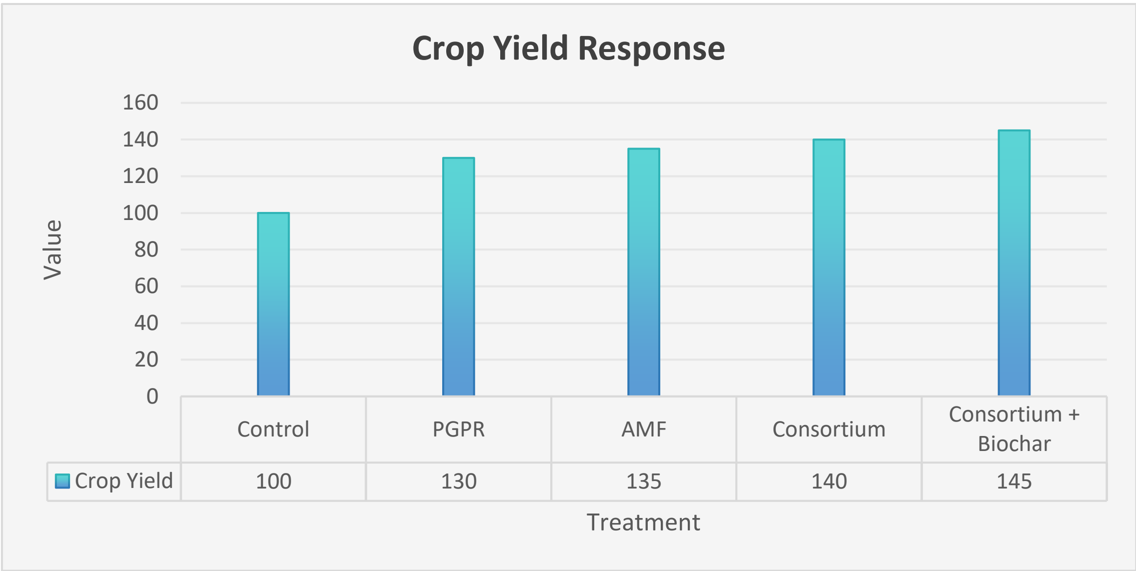
Soil health indicators were significantly increased with the application of microbial inoculants, as compared with untreated control soils. Application of PGPR, AMF, and microbial consortia produced a 15 to 20% increase in soil organic matter, as compared to the untreated control ($p < 0.05$). Combined microbial inoculation and biochar amendments showed the greatest amount of increase in soil organic matter content.



Microbial Biomass - Carbon, Nitrogen And Phosphorus. The results showed that all treatment combinations with AMF and PGPR had significantly high microbial biomass carbon, nitrogen and phosphorus contents as compared to the control ($p < 0.05$). These findings indicate that microbial activity and turnover of nutrients were much more significant in the AMF/PGPR treated soils than in the Control.

Microbial Enzymes Associated With Nutrient Cycling The performance of both AMF and PGPR treated soils was consistently greater than that of the control for all enzymatic activities shown. The highest levels of enzymatic activity were associated with mixed inoculant treatments.
Crop Production And Growth: Crop production responded positively to microbial amendments under field and greenhouse conditions. Increases in above-ground biomass and yield for PGPR treated crops were significant compared to controls. The cereal–legume cropping system had yield increases of 30%–40% relative to the control cropping system ($p < 0.05$).

Parameter	Response
Crop yield	Up to 40% increase
Seed germination	Higher rates
Seedling vigor	Enhanced
AMF root colonization	>45%



3. Under Stressful Environmental Conditions

Salinity Stress Mycorrhizal fungi (AMF)-inoculated sorghum (Zea mays) exhibited better ionic balance when compared to non-inoculated controls when grown under saline conditions. Compared to controls, roots of inoculated plants contained significantly less Na^+ and they had higher K^+:Na^+ ratios ($p < 0.05$), which implies that these plants were able to exclude toxic ions more effectively, and their osmotic potential was better during salt stress. The combination of AMF and plant growth promotor inoculants provided the highest level of salinity tolerance for plant growth metrics when compared to either AMF-only or PGPR-only treatments.

Drought Stress Plant Growth Promotion using PGPRs, in conjunction with AMF colonization, improved physiological parameters such as leaf water content and leaf turgor pressure with regards to drought and moderate soil moisture loss (i.e., depth of soil saturation 50% and 75% field capacity) ($p < 0.05$). Additionally, plant water efficiency was greatest for those plants treated with a combination of microbial consortia and biochar which promoted improved soil moisture retention and water uptake from root

4. Results of Precision Agriculture

Advanced Formulations Crop vigor and soil fertility displayed reduced spatial variability in treated plots utilizing Microbial Consortia as determined by remote sensing and GIS mapping.

5. Indicators of Sustainability

By using microbial consortia, it was possible to lower the amount of synthetic nitrogen and phosphorous fertilisers by 33% while maintaining crop yield levels comparable to the fully fertilised control plot. Some reduced input fertiliser treatments yielded a similar or even higher yield than that obtained from the fully fertilised control plot. Additionally, using microbial treatments has provided further benefits in the form of increased levels of disease suppression. The incidence of soil-borne pathogens decreased by around 30% compared to the untreated control when using the synergistic combination of AMF and PGPR. Using beneficial microorganisms can greatly enhance soil health while providing enhanced disease and abiotic stress tolerance for crop species.

Discussion

The data presented demonstrates that inoculating soils with microbes and applying biotechnology could enhance soil conditioning and productivity of crops, increase the overall crop production capacity of crops, and improve their ability to withstand environmental stresses (abiotic). This supports their role as useful tools to manage soil . The improvements seen across biological, physiological, and agronomic measures confirm that targeted changes to the soil microbiome can cut down on the need for synthetic inputs while keeping or improving crop performance (Bargaz et al., 2018; Nadarajah & Abdul Rahman, 2023).

Microbial Inoculation and Soil Health Enhancement

The rise in soil organic matter microbial biomass, and enzyme activity seen in inoculated treatments highlights how beneficial microbes contribute to soil biochemical processes. Higher activities of dehydrogenase, phosphatase, and urease point to faster nutrient cycling and better soil metabolic activity. These are seen as sensitive signs of soil quality (Das et al. 2022; Li et al. 2024). Similar boosts in enzyme activity after using PGPR and AMF have been reported linked to more root exudation and microbial turnover (Bargaz et al. 2018; O'Callaghan et al. 2022). Wholesome impact on soil's abilities to recover from environmental changes is throught complete sequence of organisms in an ecosystem through biochar application to soils where chemical herbicides applied to control weeds but would not allow for soil microbes and plants or trees that could provide more nitrogen and phosphorus through biological processes in soil systems due to limited dissolved oxygen inside root zone habilitation areas (bio-char and nitrogen in root zone); Studies that used biochar-microbe mixes have shown that they are more effective than putting just bio-char alone in soil for improving carbon sequestration by Soil Type (Das et al. 2022); To put it into perspective, most farmers use chemical fertilizer that is dissolved chemically rather than naturally occurring microbe-to-microbe interactions like those found in biochar mix.

Crop Growth and Root Zone

Plots that were treated with PGPR and AMF achieved large increases in crop yield and plant mass which is a clear indication of the agricultural advantages of using microbes. Such yield enhancements of up to 40% are consistent with recent large-scale experiments. These studies concluded that the application of PGPR may result in a 20-45% increase in crop growth, depending on the type of crop and soil (Schütz et al. 2018; Kumawat et al., 2023).

Significantly better seed germination and early vigor of seeds inoculated with microbes suggest that prebiotic and microbial blends may have a positive effect on the initial root environment which is the main source of nutrients and the key to stress resistance (Mohanty et al., 2021). Several other studies also confirm that microbial seed coatings promote early root development and make seedlings more competitive (Krishnan et al. 2025).

AMF colonization rates of more than 45% were strongly associated with increased phosphorus uptake and water deficit tolerance thus emphasizing the very important role of mycorrhizal symbiosis in plant nutrition. Previous studies have revealed that AMF-supported fungal networks not only increase the total root surface area but also enable plants to get nutrients and water from places that are difficult to reach (Tahiri et al. 2021).

Consortium inoculants performed better than single strains thereby lending support to the mounting assertion that microbial communities provide functional complementation and synergistic interactions (O'Callaghan et al. 2022; Das et al. 2022).

Reducing Salt and Drought Stress

When subjected to saline conditions, plants inoculated with AMF demonstrated an elevated (K^+/Na^+) ratio and reduced sodium accumulation reflected in improved ion homeostasis. Results associated with increased activity of antioxidants and regulation of transport of ions had previously been attributed to PGPR and AMF (Ecological Journal of Research, 2023; Liu et al. 2025). Additional mechanisms of action, such as the osmotic effect of compatible solutes, structural modification of roots, and altered nutrient ratios, likely contribute to the synergism between PGPR and AMF treatments in moderate to high level saline conditions, as indicated by past studies (Li et al., 2020; Lin et al., 2025). Inoculated plants subjected to drought conditions displayed increased relative water content, increased rates of photosynthesis, and increased water use efficiency as compared to non-inoculated plants due to protection provided by microbial inoculants. The enhanced water use by microbial contributions has been confirmed in the literature to be based upon the regulation of plant hormones produced during drought stress (Ferioun et al., 2025; Tahiri et al., 2021). Better performance of biochar-amended microbial treatments in water-deficit conditions can be attributed to higher soil moisture retention and the microbial mediation of root control of water (Das et al., 2022).

Advance formulation and role of Precision Tools

The reduced spatial variability in crop vigor quantified through remote sensing and GIS-based mapping illustrates the contribution of microbial consortia to the stabilization of soil–plant interactions.The same vegetation index applications to evaluate the effectiveness of microbial treatments have been reported in different publications, which shows the worth of combining biological inputs with precision agriculture technologies (Ambaru et al., 2025; Bhamini et al., 2025; Fallah et al., 2025).

The nano-enhanced microbial formulations demonstrated the improved delivery efficiency and early-stage plant responses, thus, they are in line with the recent findings that nano-carriers protect microbial viability and facilitate root colonization (Kumawat et al., 2023). It seems that these formulations are especially advantageous under conditions of stress, when targeted microbial activity can maintain plant growth even if there are environmental constraints.

Sustainability and Reduced Input Dependency

Reducing the use of synthetic fertilizers without sacrificing the yield is probably the most significant result of this research. A cut of nitrogen and phosphorus inputs by up to 33% is in line with the global ambition to lower the negative impacts on the environment caused by the excessive use of fertilizers. Microbial consortia paired with traditional management approaches were reported to reduce the incidence of pathogenic organisms in previous research (e.g., Bargaz et al., 2018; O'Callaghan et al., 2022). Additionally, the elimination of soil-borne pathogens demonstrates that beneficial microorganisms have more than just one function, as such microorganisms have been shown to reduce the necessary incidence of disease by approximately thirty per cent (30%), which supports the findings of other studies that demonstrated that PGPR and AMF stimulate systemic resistance, therefore, preventing pathogenic organisms from competing against the plant (Mohanty et al., 2021; Krishnan et al., 2025). Collectively, these findings support the potential of microbial-based strategies as a means of enhancing productivity, resilience, and ecological sustainability concurrently in agricultural systems.

Conclusion

These are the research results that the application of microbial inoculants and biotechnological techniques might lead to the push towards the green farming methods. The beneficial soil microorganisms, such as the plant growth-promoting rhizobacteria and the arbuscular mycorrhizal fungi, are just a few of the factors that can contribute to the enhancement of soil fertility, the improvement of nutrient availability, and the initiation of vigorous plant growth. Besides being co mechanisms of increased crop yields and better plant health, these biologically-based techniques also play an important role in the building-up of resistance to various abiotic stresses like drought, salinity, and nutrient deficiencies.

The introduction of microbial products in conventional cropping systems as a means to decrease reliance on chemical fertilisers and pesticides, and therefore reduce their impact on the environment. Adoption of microbiome-based strategies for soil health management will result in improvements to soil texture, soil organic content and microbial diversity over time as positive effects of adopting these types of strategies. In addition, utilizing advanced applicators along with precision agriculture technology will not only help with the appropriate application of these biological products, they will also increase their effectiveness, resulting in similar performance of biological products on crops under various environmental conditions.

Utilizing new technologies in agriculture is part of the international efforts to provide food for a growing population and to do so in a way that conserves our planet's natural resources and creates sustainable, environmentally friendly practices. microbiome-based products have demonstrated an improvement in efficiency, productivity, and ecosystem health through improved resource utilization; therefore, it may be reasonable to use microbiome-based practices as a platform for designing future agriculture systems. In order to maximize the benefits of the new agricultural practices through agricultural research, along with applied research, collaboration among scientists, farmers, and policy makers to improve the techniques, and to identify barriers or obstacles to implementation, generalization of these techniques to the whole agriculture sector, support in generalization of these techniques to the whole agriculture sector all require continuing effort. The study reveals the enormous potential for developing new agricultural practices through microbial technologies and biotechnologies for contemporary agriculture industry, and will be a significant milestone in the development of agricultural production systems that are not only resilient and productive but also sustainable.

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