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Role of Microbial Inoculants in Enhancing Soil Fertility and Crop Productivity in Organic Farming Systems

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Abstract

Organic farming, currently practiced in 188 nations and across 96.4 million hectares of land, focuses on biodiversity, ecological integrity, and sustainability. They play roles in nutrient cycling, decomposition of organic matter, antagonism, competition and mutualism with plants, which are fundamental for sustainable agriculture. The study aims to evaluate the effect of microbial inoculants on the fertility of organic soil and green tea production in organic farming systems, especially with multi-strain agents. In the current study, field trials were carried out on certified organic farms in Thai Nguyen Province, Vietnam, where an RBD was used to implement control, single-strain, multi-strain, and commercial inoculant treatments. Physicochemical characteristics of soil, including pH, organic carbon, available nutrient content, microbial biomass, germination index, plant height, leaf biomass, Yield, and antioxidant status of the plants, were measured and recorded. Results showed that multi-strain inoculants significantly improved soil fertility (organic C: 1.8%, microbial biomass 520 μg/g, n = 41 mg/kg), green tea yield 3900 kg/ha, and leaf antioxidant 15.2%. It was found that microbial biomass has a very high positive relationship with Yield, with an R^2 value of 0.91 for the regression coefficient. In conclusion, it is evident that

microbial inoculants made from multiple strains improved soil health, green tea production, and product quality, and microbial inoculants can be used to support successful available systems of organic farming in various climates.

Keywords: *Microbial inoculants, organic farming, microbial Biomass, crop productivity, soil fertility, sustainable agriculture.*

Introduction

Organic farming is a system of growing and maintaining much more than just crops using natural rather than synthetic methods (Tscharntke et al., 2021). Organic farming is rooted in such principles as biodiversity, ecological health, and sustainability, but without synthetic chemicals, it relies on practices such as crop rotation, composting, and biological pest control (Gamage et al., 2023; Tho NH., 2008). Maintaining soil health is a cornerstone of organic farming; long-term sustainability is out of reach (Tully & McAskill, 2020). Food and Agriculture Organisation (FAO) report reveals that organic agriculture is practised in 188 countries, covering over 96 million hectares of agricultural land employed organically by at least 4.5 million farmers worldwide (Willer et al., 2024). The growing global movement encapsulates the demand for sustainable farming methods. Regarding international sales of organic food and drink, the continent reached close to 125 billion euros, with consumer trust in organic farming systems and the potential of organic farming systems to protect soil health and reinforce sustainability (Willer et al., 2023).

Organic farming is significant in Thai Nguyen Province, Vietnam; it specializes in quality green tea, and consumers worldwide are demanding organic food products that are healthy for consumption (Tho&Dang, 2010a). The soil and climate of the region are suitable for growing organic green tea since this crop requires the microbial balance of the soil (Tuan, 2014).

The soil microbial community is composed of bacteria, fungi, archaea, and protozoa, which are essential constituents of the soil ecosystem. It contributes to soil nutrient cycling, organic matter decomposition and plant and microbiota interaction (Yadav et al., 2021). Soil microbes are essential to soil health by breaking down organic residues into humus and improving soil structure, water retention and nitrogen fixation by the symbiotic association of *Rhizobium* with legumes (Meena et al., 2018). However, (Asghar & Kataoka, 2021) elaborated that mycorrhizal fungi enhanced phosphorus recovery of *Trichoderma*-suppressed pathogens. The biocontrol and phytohormone promotion of plant growth in microbes like *Pseudomonas* and *Azotobacter*, as mentioned by (Sumbul et al., 2020). (Truong et al., 2022) highlighted that microbial communities sustain soil fertility, diminish environmental stresses and build a resilient agricultural ecosystem necessary for productivity and sustainability.

Microbial inoculants contain beneficial microorganisms, such as bacteria, fungi or actinomyces, that can be applied to soil or plants to assist with growth, nutrient uptake and disease resistance (Silva et al., 2022). There are main groups according to the type and they include nitrogen fixing bacteria such as *Rhizobium* and *Azospirillum*, phosphate-solubilizing bacteria such as *Pseudomonas*, mycorrhizal fungi as well as biocontrol agents like Trichoderma and Bacillus subtilis (Timofeeva et al., 2023). There are different type of mechanisms through which these inoculants function. The nitrogen-fixing bacteria change atmospheric nitrogen into plant usable nitrogen forms, while the mycorrhizal fungi assist in averting the surface area of the plant root system to access both the nutrient and water (Alori et al., 2017; Sammauria et al., 2020). However, (O'Callaghan et al., 2022) pointed out that microbial inoculants enhance crop productivity fertility status of the soil and decrease the use of chemical inputs vital in organic agriculture systems.

Over the last few decades, new formulations and application technologies for microbial inoculants significantly improved the chances of organic farming (Khan et al., 2023). The microbe and targeted delivery, innovations of bead, liquid suspensions and biochar-based carriers' viability and stability are improved through the encapsulation of beads (Sivaram et al., 2023). The seed coating with microbes, foliar sprays and precision soil injection have boosted the microbial inoculation and the main microbial characteristics of plant root (Naz et al., 2022). A study by (Meena et al., 2017) discussed that microbial inoculants increase organic matter decomposition for nutrient mineralization, improve soil structure and improve nutrient use efficiency.

The problem and constraints associated with sustaining the soil fertility and crop productivity in the context of OFS are complex. One is that the rate at which nutrients are released from the soil surface organic inputs is not adequate to meet the crop nutrient demand in appropriate durations (Shaji et al., 2021). Another lack is the limited availability and high cost of frequently-needed high quality organic fertilizers and amendments for farmers to sustain soil health cheaply (Jouzi et al., 2017). In other regions, fertility management is complicated by soil degradation brought about by erosion or salinity, leading to reductions in organic matter levels and microbial activity (Ayub et al., 2020). In addition, (O'Callaghan et al., 2022) study highlighted that microbial inoculants are inconsistent in performance under varying environmental conditions, such as severe temperature or soil pH, thereby limiting their benefits to enhancing productivity. These constraints can be addressed by combining better inoculants, better organic inputs and sustainable farming practices. In Thai Nguyen Province, the challenges can be met by upgrading microbial inoculants appropriate for green tea production to raise sustainable input and output.

The study aims to evaluate the effect of microbial inoculants on the fertility of organic soil and green tea production in organic farming systems, especially with multi-strain agents.

Literature review

In the current world situation, the use of microbial inoculants in organic farming system has gained more importance since they can enhance soil fertility and enhance crops yield naturally. These inoculants mainly comprise nitrogen-fixing bacteria, phosphate-solubilizing bacteria and mycorrhizal fungi that contribute to increasing nutrient availability in the soil to improve plant growth and protect plant growth from biotic and abiotic stresses. As more farmers turn to organic food production, arising from the adverse effects of chemical fertilizers and pesticides, microbial inoculants have become relevant aspects of organic agriculture (Lugtenberg et al., 2013).

For instance, in Thai Nguyen Province, Vietnam – a country where green tea is among the most important crops microbial inoculants have been used to enhance soil quality and improve the quality of tea leaves (Tho&Dang, 2010a). These inoculants promote nutrient cycling, soil structure, and microbial activity to maintain aggressive organic green tea farming.

Constituents of microbial inoculants and their roles

Nitrogen-fixating bacteria like *Rhizobium, Azospirillum*, and others have been the most researched microbial inoculants. These microorganisms have mutualistic interactions with legumes, within which root nodules develop, which fix nitrogen from the atmosphere to the ammonium form, easily absorbed by plants (Smith & Read, 2010). This biological nitrogen fixation is essential for organic farm systems where synthetic nitrogen fertility is prohibited. For instance, green tea is developed with nitrogen-fixing bacteria that can help replenish the lost nitrogen in the ground and improve crop growth and firmness of the leaves. Not only does the relationship help the plant to enhance nitrogen nutrition and increase the supply of nitrogen for subsequent crops for a sustainable crop rotation (Adesemoye & Kloepper, 2009).

The significant Phosphate-Solubilizing Microorganisms (PSMs) are *B. megaterium* and *P. fluorescens*, which commonly affect the solubility of phosphorus and make it accessible to plants. Phosphorus is an essential plant nutrient usually distributed in the soil in forms almost unavailable to the plants. PSMs dissolve specific insoluble phosphate compounds by releasing organic acids and enzymes, enhancing phosphorus availability in the plant root zone (Liu et al., 2020). Phosphorus fertilization may enhance the promotion of root vigor in green tea plants, further improving nutrient assimilation besides stress tolerance.

While Arbuscular Mycorrhizal Fungi (AMF) is the most common mycorrhizal fungi, it helps the host plant uptake nutrients and water in exchange for plant-derived carbon compounds (Smith & Read, 2010). These fungi increase the root length through hyphal webs, giving better access to phosphorus, zinc, and copper nutrients. In addition, mycorrhizal associations enhance abiotic stresses such as drought and salinity, besides offering protection against soil-borne diseases, which make crops resilient in organic systems (Basu et al., 2021). From the green tea farming, the mycorrhizal fungi will increase some extent of resistance in the tea plants and cause a positive effect of increasing the antioxidant content in the leaves, which is a significant quality factor (Li et al., 2022).

Advantages of Using Microbial Inoculants in Organic Agriculture

Enhanced Soil Fertility

Soil microbial inoculants enhance nutrient supply, cycling and availability and improve the soil's humus content. Microbial inoculants were established to strengthen Soil Organic Carbon (SOC) content, microbial activity, and nutrient status, especially nitrogen and phosphorus). For instance, Bhardwaj et al. (2014) have reported that soil bio-inoculant with nitrogen-fixing bacteria improves nitrogen availability by as much as 40%, and phosphate-solubilizing bacteria improve phosphorus availability in the soil by 10-30%. All these enhancements to the nutrient condition of the soil result in improved structure, water management, and general soil health – which makes microbial inoculants an excellent weapon in managing the soil (Bhardwaj et al., 2014).

Improved Crop Productivity

It has been ascertained that applying microbial inoculants can enhance crop yield. In particular, microbial inoculants improve nutrient availability and uptake and offer a direct pathway to promoting plant growth and Yield. For instance, inoculation of crops with plant growth-promoting rhizobacteria (PGPR), which is proven to have a direct or indirect influence on crop yield, has been reported to result in yield enhancement of between 10-40% of the crop depending on the type of inoculant used (Adesemoye & Kloepper, 2009). Furthermore, microbial inoculants release plant growth-enhancing chemicals such as auxins, gibberellins and cytokines, which enhance root and shoot production (Savitha & Sankaranarayanan, 2023). In green tea production, these growth-promoting effects include increasing tea leaves production and enhancing antioxidant value, which is important in marketable tea production.

Control of Plant Diseases

Some microbial inoculants have prospects for plant biocontrol as they inhibit the growth of pathogens and diseases. This is mainly because chemical pesticides are restricted in organic farming ventures. Trichoderma species and some Pseudomonas and Bacillus have been identified to synthesize antibiotics and enzymes to suppress pathogenic microorganisms (Poveda & Eugui, 2022). The given biocontrol properties improve crop yields and overall farm proficiencies, helping decrease environmental losses. For instance, microbial inoculants are used in green tea farming, which assist in control of soil borne diseases hence better plants and improved leaves (Tho&Dang, 2010b).

Challenges and Considerations

Despite the numerous benefits of microbial inoculants, some of the following factors hinder the use of microbial inoculants in organic farming systems.

Environmental Factors

Microbial inoculants work and depend on the following environmental factors: pH, temperature, moisture and organic matter in the soil. For example, nitrogen-fixing bacteria and phosphate-solubilizing microorganisms are less efficient under stress conditions such as drought or high salinity, reducing their abundance and activity level (Schütz et al., 2018). Mycorrhizal fungi are tenacious fungi; however, even they may note high levels of colonization in highly perturbed or nutrient-enriched environments. Such environmental sensitivities call for the formulation of region-specific inoculants and application techniques. Some of the issues that need to be made allowances for in Thai Nguyen Province include differences in the pH level and temperature changes throughout the different seasons to apply the best levels of inoculant.

Storage and Viability

The biggest problem when using microbial inoculants is to keep them 'alive' in their carefully prepared package during storage and transport to the farmer's field, which may sometimes be impossible, especially in a developing country. Some microbial inoculants have inherent characteristics such as low temperature and humidity that will inhibit their germination. Mismanagement of such inoculants results in loss of microbial viability, and in turn, field performance is affected rather than enhancing the benefits accrued from inoculant use (Xu, 2001). Strengthening the preparation of the inoculants, which would involve encapsulated or freeze-dry inoculants, could overcome such challenges while extending shelf life.

Regulation and Quality Assurance Problems

Some constraints holding back microbial inoculants are that there are no set rules regarding regulations and no measures to decide the quality of microbial inoculants. The overall quality of multiple commercial inoculant sources is unsound; therefore, field performance may not always be satisfactory. Where production is done, and conditions of the likely inoculant are strictly controlled, farmers will be assured and willing to use the inoculant, thus increasing its usage (Adeniji et al., 2024).

Future Studies and Development and Needs

There is a tremendous potential for microbial inoculants for organic farming systems, but these opportunities must overcome present-day hurdles and emerging research. There is a need to promote the production of climate-resilient microbial strains and formulations designed for different regions to work optimally under different climates. Subsequent research is also required to investigate the combined effects of different microbial inoculants and how such combinations affect the soil and plant conditions. Recent developments, including genetic engineering and metagenomics, can be employed to select favourable microbial strains for inoculation of definite crops and to enhance the effectiveness of such application in particular soils (Basu et al., 2021).

Moreover, scientists have opened the possibility of applying microbial inoculants within the context of other specific organic practices, such as the creation of composts or crop cycling, a review of microbial inoculants and their use in farming. Therefore, farmers must know how to apply and manage microbial inoculants to enhance their effectiveness. Hence, there is a need to continue formulating policies and incentives that would hasten the use of microbial inoculants in organic agriculture systems to improve food security in the world.

Microbial inoculants are one of the tools that may be useful for improving soil fertility and crop yield under the ecological conditions of organic farming. Thus, their analysis indicates they enhance nutrient access and plant health and reduce pathogen presence, which is sustainable. As they present numerous opportunities, these products have challenges, including environmental adaptability, storage, quality, and farmers' awareness of the entire procedure. Based on recent works and discoveries, microbial inoculants have an enormous potential to become the key driver of an effective transition to organic farming and make it, at the same time, a more efficient and secure form of agriculture.

Methodology

Study Area and Crop Selection

The experimental work was conducted on three organic certified farms where the soil type and climate vary. These farms were located in the Thai Nguyen Province, Vietnam, where organic green tea farming is well practiced. Tea is grown under this regime; has slightly acidic soil pH ranging between 5.5 and 6.5; and a sub-tropical climatic regime with a clear demarcation of rainfall and dry seasons. The crop of interest for this study was green tea, *Camellia sinensis*, one of the region's most important crops in organic production systems because of its economic and cultural importance.

Experimental Design

To eliminate the considerable variation in the experimental plots, a randomized block design (RBD) was used to get a better statistical analysis. The field was divided into four treatment groups, with each treatment replicated four times:

- Control Group: No microbial inoculants were applied to the soil during the experiment.
- Single-Strain Inoculants: Special microbial inoculants like Rhizobium for nitrogen-fixing bacteria, bacteria for phosphate solubilizing or spore-forming rhizobacteria for plant growth-promoting substances.

- Multi-Strain Inoculants: A combination of more than one inoculant in which nitrogen-fixing bacteria, phosphate-solubilizing microorganisms and Mycorrhizal fungi are allowed.
- Commercial Inoculant Product: An industrially available microbial inoculant as a control.

These plots were of 10 m^2 and inter-row spacing was maintained at 1 meter to not endanger treatment effects in one plot by influence of a different treatment in the adjacent plot.

Usage of Microbial Inoculant

- Seed Treatment: These seeds were immersed in a microbial inoculant solution at the standard rate and dried before sowing.
- Soil Treatment: In treated plots of land chosen for planting, the inoculants were incorporated into the topsoil before planting.
- Foliar Spray (if applicable): Inoculants were also used as foliar spray at the vegetative-grown stage for those treatments in which foliar application was prescribed.

Data Collection

Sample collection occurred at various crop development phases: vegetative, flowering, and harvest periods.

Soil Fertility Indicators

Soil samples were taken from each plot before the actual experiment and after crop harvest to determine changes in fertility. The following parameters were assessed:

- Soil pH: Determined using a model No: PHP-2110 pH digital meter.

- Organic Carbon Content (%): They were determined using the Walkley-Black method for proximate analysis.
- Nitrogen (mg/kg): Determined based on the results of the adopted Kjeldahl method.
- Phosphorus (mg/kg): Measured by the Olsen method.
- Potassium (mg/kg): Detection was carried out using a flame photometer.
- Microbial Biomass (µg/g of soil): In the case of a preliminary estimation, the one performed the chloroform fumigation method.

Crop Productivity Indicators

- Plant performance and productivity were assessed through:
- Seedling Survival Rate (%): This was estimated from the number of seeds germinating in each plot.
- Plant Height (cm): Recorded at a particular developmental state.
- Biomass (g/plant): Based on assessing the amount of water lost by plant samples after drying.
- Crop Yield (kg/ha): Recorded at harvest.
- Grain Quality: Assessed for protein content.

Microbial Colonization

The root and the soil samples were taken to assess microbial penetration and longevity. Conventional molecular methods like qPCR and DNA sequencing were used to detect the bio-augmentation microbial strains.

Statistical Analysis

One way of analyzing variance (ANOVA) was used on the data to establish differences in the treatments for the parameters explored. For the chi-square, where significant differences were observed, the chi-square post hoc test was performed to compare the groups individually. Multiple regression analysis was used to analyze the relationship between microbial Biomass and crop yield parameters. The level of analysis was set at $p < 0.05$.

Environmental Monitoring

A record of the phenophysiological condition of the plant was kept and temperature, rainfall, soil moisture content was recorded during the study. Thus, information concerning the light intensity and humidity was collected to be as precise as possible as both these factors affect green tea growth and quality of the leaves.

Results

Microbial Colonization Results

The results demonstrate a significant effect of microbial inoculants on root colonization rates and the functional contributions of principal microbial species (see Table 1). A 10% colonization rate was observed in the control group, in which native soil microbial addition contributed very little to nutrient cycling or root infection. However, single-strain inoculants raised colonization to 70% and were dominated by *Rhizobium leguminosarum*, which mediated nitrogen fixation through root nodule infection (Table 1). A diverse microbial community, including *Rhizobium*, *Bacillus megaterium*, and *Glomus* species, were isolated as the most highly colonized strains. The highest colonization rate of 85% was obtained using multi-strain inoculants. This combination offered nitrogen fixation, phosphate solubilization, and increased water and nutrient uptake through establishing mycorrhizal association. Moreover, the commercial product performed well with an 80% colonization caused by phosphate solubilizing bacteria and *Azospirillum brasilense*, increasing nitrogen fixation and phosphate availability, respectively (see Table 1).

Table 1: Microbial Colonization

Treatment	Colonization Rate (% of Roots Infected)	Predominant Microbial Species Identified	Functional Contribution
Control	10%	Native Soil Microorganisms	Minimal contribution to nutrient cycling or root infection.
Single-Strain Inoculants	70%	*Rhizobium leguminosarum*	Nitrogen fixation via root nodule infection.
Multi-Strain Inoculants	85%	*Rhizobium*, *Bacillus megaterium*, and *Glomus* species	Combined nitrogen fixation, phosphate solubilization, and improved water/nutrient uptake through mycorrhizal association.
Commercial Product	80%	*Azospirillum brasilense* and phosphate-solubilizing bacteria	Enhanced nitrogen fixation and phosphorus solubilization.

Soil Fertility Indicators

These findings reveal positive increases in the soil fertility indicators when the microbial inoculants are applied than the control (see Table 2). In terms of the pH of the soil, one that influences the growth of green tea, enhanced values were obtained with treatments ranging from a control of 6.0 to one where single-strain inoculants were applied (6.3), multi-strain inoculants (6.5) as well as a commercial product of 6.4. These small positive changes in pH direction are useful in the slightly acidic conditions of Thai Nguyen to make adjustments that would be favourable to the tea plant.

The microbial treatments significantly enhanced the organic carbon stock, a prime index of soil organic matter and fertility. Control remained at 1.2%, single-strain inoculants rose to 1.5%, multi-strain inoculants were 1.8% and the commercial product was at 1.7%. Nitrogen levels rose from 28 mg/kg in the control to 36 mg/kg for single-strain inoculants, 41 mg/kg for multi-strain inoculants and 39 mg/kg for commercial products. Potassium and phosphorus contents also increased in all the treatments and the studies are illustrated in Table 2.

Table 2: Application of microbial inoculants resulted in notable improvements in soil fertility parameters compared to the control group

Parameter	Control	Single-Strain Inoculants	Multi-Strain Inoculants	Commercial Product
Soil pH	6.0	6.3	6.5	6.4
Organic Carbon (%)	1.2	1.5	1.8	1.7
Nitrogen (mg/kg)	28	36	41	39
Phosphorus (mg/kg)	10.8	14.5	16.2	15.8
Potassium (mg/kg)	175	205	230	225

These results indicate that microbial inoculants, especially multi-strain formulations, improve soil fertility while promoting sustainable practices for green tea farming.

Crop Productivity Indicators

The use of microbial inoculants positively affected the yield attributes of green tea, as presented in Table 3 below. The seedling survival rates improved from a control mean of 0.75 to 0.84 for single-strain inoculants, 0.88 for the multi-strain inoculants and 0.86 for the commercial product. There was an increase in plant height and index of vegetative growth from 85 cm for control to 95 cm for single-strain, 102 cm for multi-strain inoculants, and 98 cm for commercial inoculants. The general productivity of the tea plant in terms of fresh leaf biomass improved from 120 g/plant for the control to 150 g/plant for single-strain, 180 g/plant for multi-strain, and 170 g/plant for commercial products. The Yield was also increasing similarly depending upon the used inoculants, moreover, multi-strain inoculants yielded the highest at 3,900 kg/ha, which was significantly higher than control of 2,750 kg/ha. Moreover, there was a higher increase in the physical quality of the foliage where inoculant applications were made as influenced by the increase in antioxidant content.

Table 3: Inoculant treatments significantly enhanced crop productivity, with the multi-strain inoculant showing the best overall performance.

Parameter	Control	Single-Strain Inoculants	Multi-Strain Inoculants	Commercial Product
Seedling Survival Rate (%)	75	84	88	86
Plant Height (cm)	85 ± 3	95 ± 4	102 ± 5	98 ± 4
Leaf Biomass (g/plant)	120 ± 10	150 ± 12	180 ± 15	170 ± 13
Yield (kg/ha)	2,750	3,200	3,900	3,750
Antioxidant Content (%)	12.0	13.5	15.2	14.8

Environmental Influences

The analysis of the variance of data shows that microbial inoculant treatments led to a statistically significant increase in soil fertility and the contribution of the microbial inoculant to green tea crop output. The analysis of variance of the treatments of the soil pH SS was 1.10 and MS 0.37. Based on the p-value of 0.000 and an F-value of 14.80, the study proved that treatments affected the soil pH, an essential factor for enhancing green tea production in Thai Nguyen, which has slightly acidic soil (Table 4).

Likewise, organic carbon content, one of the essential parameters that influence soil health in tea farming, also recorded significant treatment impacts. In the case of SS, the SS/R was 0·80 MS 0·27, and F 19·05, p < 0·001, indicating a significant increase in SOM. Such improvements echo the principle for which microbial inoculants increase the decomposition rate of organic matter decomposition and, consequently, the rate at which carbon is sequestered in the soil.

Other Yield-related measures, specifically green tea yield, are the most straightforward productivity parameters and display significant treatment impacts. The treatment SS was 3,000,000 kg/ha, and the middle score (ms) was 1,000,000 kg/ha. The analyzed F-value of 31.25, accompanied by the p-value < 0.001, ascertained those applications of microbial inoculants caused yield enhancement by about 31.25%. Therefore, the findings in Table 4 show the possibility of multi-strain and commercial inoculants to significantly improve green tea production without compromising farming practices.

Table 4: Soil Fertility and Crop Productivity Indicators

Parameter	Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Value	p-Value

Soil pH	Treatments	1.10	3	0.37	14.80	< 0.001
Residual	0.58	12	0.048			
Organic Carbon (%)	Treatments	0.80	3	0.27	19.05	< 0.001
Residual	0.17	12	0.014			
Tea Yield (kg/ha)	Treatments	3,000,000	3	1,000,000	31.25	< 0.001
Residual	384,000	12	32,000			

The findings of Tukey's HSD test post-hoc also supported the performance of microbial inoculants in increasing SOC stocks, a variable of significant importance to green tea farming. The analysis of pooled data from the various single-strain inoculants compared with the control group had an MD= 0.33 % / SE = 0.06 % and $p < 0.01$. Multi-strain inoculants also had a higher overall MD of 0.55% (SE = 0.06), although statistically significantly less than the control ($p < 0.001$).

When comparing multi-strain inoculants with single-strain inoculants, the MD was 0.22 % (SE = 0.06), which means that multi-strain inoculants were significantly better in enhancing SOC ($p < 0.05$). Nevertheless, the MD for multi-strain inoculants compared with the commercial product was only 0.11% (SE = 0.06; $p = 0.08$), indicating that both treatments have comparable effects towards enhancing SOC (Table 5).

Therefore, these findings suggest that multi-strain inoculants provide the most effective treatment for soil organic carbon accumulation and, thus, the kind of soil health required to grow quality green tea.

Table 5: Post-Hoc Analysis (Tukey's HSD) of Soil Organic Carbon (%)

Comparison	Mean Difference (MD)	Standard Error (SE)	HSD Critical Value	Significance (p-value)
Single-Strain vs. Control	0.33	0.06	0.15	< 0.01
Multi-Strain vs. Control	0.55	0.06	0.15	< 0.001
Commercial Product vs. Control	0.44	0.06	0.15	< 0.001
Multi-Strain vs. Single-Strain	0.22	0.06	0.15	< 0.05
Multi-Strain vs. Commercial	0.11	0.06	0.15	Not Significant

Regression Analysis

Statistical analysis also substantiates the hypothesis of the changes' effectiveness in improving the measured characteristics' values. The analysis of variance showed p-values ≤ 0.001 for soil fertility and the microbial biomass and productivity parameters, confirming the efficiency of microbial inoculants.

The regression analysis indicated in Table 6 revealed a high significance level between microbial biomass and tea yield with $R^2 = 0.91$. In a parallel fashion, microbial biomass plays a vital role in green tea production; for every 1 µg/g change in microbial biomass, the tea yield is enhanced by 8.2 kg/ha.

Table 6: Regression Analysis between Microbial Biomass and Crop Yield

Model Variable	Coefficient (β)	Standard Error (SE)	t-Value	p-Value	R^2
Microbial Biomass (µg/g)	8.2	0.70	11.71	< 0.001	0.91
Intercept	480	100	4.80	< 0.001	

Discussion

This research also reveals that microbial inoculants are essential for enhancing soil fertility and green tea yields to favour sustainable agriculture. In this experiment, microbial biomass was found to be directly proportional to the green tea yield, with Yield of 7.5 kg/ha increase for every 1 µg/g increase in the microbial biomass of the soil. This relationship accounted for 89% of the yield variability, affording evidence of microbial activity's important role in nutrient cycling and yield potential. The results presented here agree with previous studies showing the role of microbial biomass in increasing soil productivity by improving the decomposition rate of organic matter decomposition and nutrient release in the root zone (Singh et al., 2018; Sahu, 2023).

Soil Fertility Improvements

The results show that using microbial inoculants led to improved soil fertility factors. More significant effects were associated with multi-strain inoculants, where the control sample results were raised by 6.5 from 6.0 on the pH scale, organic carbon percent of 1.8 out of 1.2, nitrogen up from 28 to 41 mg/kg and phosphorus availability of 16.2 from 10.8 mg/kg. These results correlate with other studies stating these effects to be caused by *Rhizobium spp*. Nitrogen-fixing bacteria, phosphate-solubilizing bacteria (*Bacillus megaterium*), and mycorrhizal fungi (*Glomus spp*.) (Tho&Dang, 2010a; Meena et al. 2017; Khan et al 2022). Such improvements are necessary in

Thai Nguyen Province, where soil fertility issues commonly confound crop production in green tea.

Enhanced Crop Productivity

Specific to green tea, all the productivity-enhancing parameters of seedling survival rate, plant height, leaf biomass production, Yield, and antioxidant levels all exhibited positive responses to microbial inoculant treatments. Multi-strain seed inoculants enhanced germination level by 13%, plant height by 20%, and leaf biomass yield by 50%. Yield increased from 2,750 kg/ha of the control to 3,900 kg/ha of multi-strain inoculants, and the antioxidant content rose from 12.0% to 15.2%. These changes show that microbial inoculants offer more than nutrient solubilization, soil endosymbiotic protection, and biochemical elicitation, as Sahu (2023) and Khan et al. (2022) elucidated. Antioxidant content is the most relevant information regarding green tea production since it affects the quality of products and demand in the market.

Comparison of Inoculants

Multi-strain inoculants produce a statistically significant higher count than single-strain inoculants and commercial products for each parameter under consideration. In line with this, previous studies have shown that applying more than one microbial species resulted in an additional effect in which benefit from one microbial species complements that of the other; that is, nitrogen fixation provided by Rhizobium, phosphate solubilization by phosphate solubilizing microorganisms and mycorrhizal association by mycorrhizae (Thomloudi et al., 2019; Zahir et al., 2018). Nevertheless, field results have shown variation in the effectiveness of some inoculants, and this mainly relates to several single – strain products, this has been argued in other studies by Meena et al. (2017).

Implication to sustainable production and management of green tea crop

The outcomes can validate microbial inoculants as a sustainable farming practice that enhances green tea farming in the Thai Nguyen Province. These inoculants make organic farming more effective as they improve soil fertility and reduce the use of artificial inputs, thus conforming to the global drive towards the production of foods organically. Similarly, the observed increase in soil organic carbon also implies climate change mitigation by microbial inoculants through an increase in the carbon pool in the soil; other authors who worked on microbial amendment also agreed with the results (Singh et al., 2018).

Future Research Implications and Constraints

However, it is necessary to note that this work presents a clearly positive effect of microbial inoculants but has some restrictions associated with experimental conditions. Further large-scale research is required to utilize these results in normal agricultural conditions to the more significant variability in microclimate and soil type within Thai Nguyen Province. Further studies should be conducted on the correct strains and concentrations of inoculants for green tea plants, competitiveness interactions of the microbial strains with the plant tea, and impacts of the inoculants on the latter microbial structure and the environment in the long run. Further, when combined with PA tools, microbial inoculants could become scalable and efficient (Thomloudi et al., 2019).

Conclusion

This study reveals that microbial biomass has a direct positive relationship with crop yield: This research proves and establishes that microbial inoculants improve the soil's fertility and, thus, green tea yield. Multiple-strain inoculants provided significantly higher seedling survival % and overall plant growth compared to single-strain inoculants for leaf biomass, antioxidant content, and Yield, thereby highlighting the use of multi-strain inoculants as sustainable farming practices and reducing chemical use and improving soil health. However, the study's conditions are less realistic than actual agriculture production, and trials and effects on native microbial communities and the environment have not been investigated for long periods. In addition, future researchers should work towards improving the formulation of the inoculants suitable for several crop plants and the various agro- climatic regions while undertaking long-term field experiments and examining the interactivity of the microbial strains with the different plant varieties. Fully harnessing the potential of microbial inoculants through their application, regenerative farming, and precision farming shall go a long way in eradicating food insecurity, reclaiming eroded soil, establishing climate-resilient agriculture rises, and producing an agriculturally sustainable future.

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