

THE ROLE OF MICROBIOME IN PLANT HEALTH AND PRODUCTIVITY

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Abstract

The rhizosphere microbiome plays a crucial role in plant growth, nutrient acquisition, and disease suppression. This study investigated the effects of beneficial rhizosphere microorganisms on tomato (*Solanum lycopersicum* L.) plant health, productivity, and resistance to *Fusarium* wilt disease. A greenhouse experiment was conducted using four treatments: control (no microbial inoculation), *Bacillus subtilis*, *Pseudomonas fluorescens*, and a microbial consortium consisting of both bacterial strains. Plant growth parameters, nutrient uptake, chlorophyll content, disease incidence, and fruit yield were evaluated. The results demonstrated that microbial inoculation significantly improved plant growth compared with the control treatment. The consortium treatment produced the highest plant height (65.1 cm), biomass (43.0 g), and chlorophyll content (47.2 SPAD). Nutrient uptake was also enhanced, with nitrogen and phosphorus levels reaching 29.0 mg and 22.1 mg, respectively, in the consortium treatment. In addition, microbial treatments significantly reduced *Fusarium* wilt disease incidence, with the lowest disease level (22.3%) observed in the consortium treatment compared with 56.4% in the control plants. Fruit yield was substantially increased in microbial treatments, with the consortium treatment producing the highest yield (610 g per plant). Statistical analysis using ANOVA confirmed that these differences were highly significant ($p < 0.001$). The findings highlight the important role of beneficial rhizosphere microorganisms in promoting plant growth, improving nutrient availability, and suppressing plant diseases. The study demonstrates that microbial inoculation, particularly microbial consortia, can serve as an effective and sustainable strategy for enhancing tomato productivity and improving plant health in agricultural systems.

INTRODUCTION

Agricultural productivity is strongly influenced by the interactions between plants and the microorganisms present in the rhizosphere. The rhizosphere refers to the narrow zone of soil surrounding plant roots that is rich in microbial activity and plays a critical role in plant growth and health. Microorganisms present in this region influence nutrient cycling, plant metabolism, and resistance to environmental stresses. In recent years, the plant microbiome has gained considerable attention due to its potential to improve crop productivity in sustainable agricultural systems. Beneficial rhizosphere microorganisms, particularly plant growth-promoting rhizobacteria (PGPR), can enhance plant growth by improving nutrient availability, producing plant hormones, and protecting plants from pathogens. Understanding the interactions between plants and rhizosphere microbiomes has therefore become an important focus in modern agricultural research. Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crops worldwide and is highly valued for its nutritional and economic importance. However, tomato production is often limited by various soil-borne diseases and nutrient deficiencies. Among these diseases, Fusarium wilt caused by *Fusarium oxysporum* is particularly destructive and can lead to significant yield losses. Traditional disease management strategies rely heavily on chemical pesticides and fertilizers, which can have negative environmental impacts and may contribute to soil degradation. As a result, researchers are increasingly exploring biological alternatives that utilize beneficial microorganisms to improve plant growth and suppress plant pathogens. Plant growth-promoting rhizobacteria such as *Bacillus subtilis* and *Pseudomonas fluorescens* have been widely reported to enhance plant growth and productivity. These microorganisms promote plant development through several mechanisms, including nitrogen fixation, phosphate solubilization, production of phytohormones, and induction of systemic resistance against pathogens. For example, *Bacillus* species are known to produce a wide range of bioactive

compounds, including antibiotics and enzymes that inhibit the growth of pathogenic fungi. Similarly, *Pseudomonas fluorescens* is recognized for its ability to produce siderophores and antifungal metabolites that suppress soil-borne pathogens and improve plant health. Previous studies have demonstrated that rhizosphere microorganisms can significantly improve plant nutrient uptake and growth performance. According to research on plant-microbe interactions, beneficial bacteria can enhance root architecture and increase the availability of essential nutrients such as nitrogen and phosphorus. Nitrogen plays a crucial role in plant metabolism, while phosphorus is essential for energy transfer and cellular development. However, phosphorus in soil often exists in insoluble forms that cannot be easily absorbed by plants. Phosphate-solubilizing bacteria convert these insoluble compounds into soluble forms that are available for plant uptake, thereby improving plant nutrition and growth. Another important mechanism through which rhizosphere microorganisms promote plant growth is the production of phytohormones such as indole-3-acetic acid (IAA). IAA is a key plant hormone that regulates cell elongation, root growth, and overall plant development. Microbial production of IAA stimulates root proliferation and increases the plant's ability to absorb water and nutrients from the soil. As a result, plants inoculated with beneficial microorganisms often exhibit enhanced growth and improved physiological performance. In addition to promoting plant growth, rhizosphere microorganisms play a vital role in biological disease control. Beneficial bacteria can suppress plant pathogens through mechanisms such as competition for nutrients, production of antimicrobial compounds, and activation of plant defense systems. Induced systemic resistance is one of the most important mechanisms by which beneficial microbes enhance plant resistance to pathogens. Through this process, microorganisms stimulate the plant's immune system, allowing it to respond more effectively to pathogen infection. Several studies have also reported that microbial consortia often produce stronger plant growth-promoting effects

than individual microbial strains. The combined activity of multiple microorganisms can create synergistic interactions that enhance nutrient availability, hormone production, and pathogen suppression. As a result, microbial consortia are increasingly being explored as effective biofertilizers and biocontrol agents in sustainable agriculture. Despite the growing recognition of the importance of plant microbiomes, there is still a need for further research to understand how different microbial treatments influence plant growth, nutrient uptake, and disease resistance in tomato cultivation. Therefore, the present study was conducted to investigate the role of rhizosphere microorganisms in improving tomato plant growth, nutrient acquisition, and resistance to Fusarium wilt disease. Specifically, the study evaluated the effects of *Bacillus subtilis*, *Pseudomonas fluorescens*, and a microbial consortium on plant growth parameters, nutrient uptake, disease incidence, and fruit yield. The findings of this research aim to contribute to the development of sustainable agricultural practices that utilize beneficial microorganisms to enhance crop productivity while reducing dependence on chemical inputs. Despite the increasing recognition of the importance of rhizosphere microorganisms in enhancing plant growth and disease resistance, several gaps remain in the current understanding of plant-microbiome interactions in tomato cultivation. Many previous studies have focused on the effects of individual plant growth-promoting rhizobacteria on plant development, while limited attention has been given to the comparative performance of single microbial strains and microbial consortia under controlled experimental conditions. In addition, although beneficial microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* have been widely reported to promote plant growth and suppress soil-borne pathogens, the combined effects of these microorganisms on multiple plant performance indicators such as growth parameters, nutrient uptake, physiological characteristics, disease suppression, and fruit yield are still insufficiently documented in tomato production systems. Furthermore, many studies emphasize either plant growth promotion

or disease control, but fewer studies simultaneously evaluate both aspects within the same experimental framework. There is also a need for integrated analyses that combine microbial functional traits, plant physiological responses, and statistical validation to better understand the mechanisms through which rhizosphere microorganisms influence crop productivity. Therefore, this study aims to address these research gaps by investigating the individual and combined effects of *Bacillus subtilis* and *Pseudomonas fluorescens* on tomato plant growth, nutrient uptake, chlorophyll content, Fusarium wilt disease incidence, and fruit yield under controlled conditions. The findings will contribute to a better understanding of the role of beneficial rhizosphere microorganisms in sustainable tomato production and provide insights into the development of effective microbial biofertilizer and biocontrol strategies.

Experimental Design and Plant Material

The study was conducted to evaluate the role of rhizosphere microorganisms in improving tomato plant growth, nutrient uptake, and resistance to Fusarium wilt disease. A greenhouse experiment was designed using a completely randomized design (CRD) with four treatments and multiple replicates. The treatments included a control (no microbial inoculation), *Bacillus subtilis*, *Pseudomonas fluorescens*, and a microbial consortium consisting of both bacterial strains. Tomato (*Solanum lycopersicum* L.) seeds of a commonly cultivated variety were selected for the experiment. The seeds were surface sterilized using a mild sodium hypochlorite solution to eliminate surface contaminants and then rinsed thoroughly with sterile distilled water. Sterilized seeds were germinated in seed trays containing sterilized potting soil under controlled environmental conditions. After the seedlings reached the four-leaf stage, they were transplanted into plastic pots filled with a sterilized soil mixture. Each treatment consisted of an equal number of plants to ensure statistical reliability. The greenhouse conditions were maintained at optimal temperature and humidity levels suitable for tomato growth. Plants were

irrigated regularly and managed under identical agronomic conditions to minimize environmental variability. This experimental

setup allowed the evaluation of microbial treatments on plant growth and physiological parameters under controlled conditions.

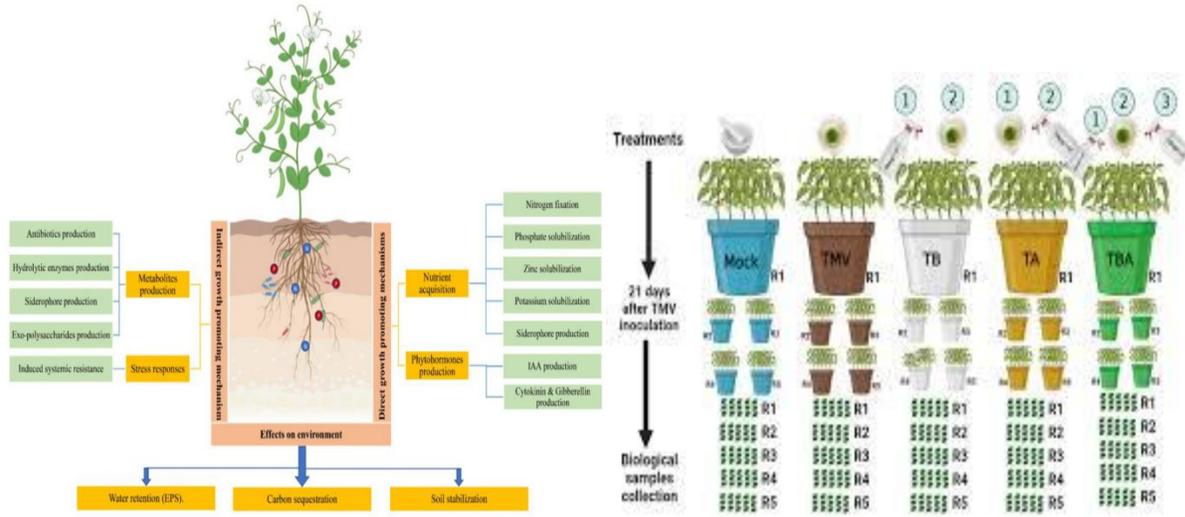


Figure M1: Experimental workflow used to evaluate the effect of rhizosphere microorganisms on tomato plant growth and disease suppression.

This methodological diagram represents the main steps followed during the experiment investigating the role of rhizosphere microorganisms in tomato plant health and productivity. The process begins with seed sterilization and germination, where tomato seeds are disinfected to eliminate surface contaminants before being germinated under controlled conditions. After germination, healthy seedlings are transferred to pots containing sterilized soil to ensure that the experimental treatments are not influenced by unknown soil microbes. The second step involves preparation and application of microbial inoculants, including *Bacillus subtilis* and *Pseudomonas fluorescens*. These bacteria are cultured in laboratory media and prepared as liquid suspensions. The inoculants are applied directly to the root zone of tomato seedlings to establish colonization in the rhizosphere. A consortium treatment containing both bacterial strains is also applied to evaluate potential synergistic interactions between microbial species. Following inoculation, plants are maintained in a controlled greenhouse environment where irrigation, temperature, and other growth conditions are carefully regulated. During the

growth period, several plant growth and physiological parameters are measured, including plant height, biomass accumulation, chlorophyll content, and nutrient uptake. In addition, plants are monitored for Fusarium wilt disease incidence. Finally, the collected data are subjected to statistical analysis, including ANOVA and Tukey HSD tests, to determine the significance of microbial treatments on plant growth, disease suppression, and fruit yield. This workflow provides a structured framework for evaluating plant-microbe interactions in agricultural systems.

Preparation and Application of Microbial Inoculants

The bacterial strains used in the study included *Bacillus subtilis* and *Pseudomonas fluorescens*, both known for their plant growth-promoting properties. Pure cultures of the microorganisms were obtained from a microbial culture collection and maintained on nutrient agar media under laboratory conditions. The bacterial cultures were incubated at appropriate temperatures for 24–48 hours to obtain actively growing colonies. After incubation, the bacterial cells were suspended in

sterile distilled water to prepare a standardized inoculum concentration suitable for plant inoculation. For the consortium treatment, equal volumes of both bacterial suspensions were combined to create a mixed inoculum. The microbial inoculants were applied to tomato seedlings at the time of transplantation. A measured volume of bacterial suspension was applied directly to the root zone of each seedling to ensure effective colonization of the rhizosphere. In addition to root inoculation, a small amount of inoculum was incorporated into the soil surrounding the root system to facilitate microbial establishment. Control plants received sterile distilled water without microbial inoculation. This approach ensured that any observed differences in plant growth or disease resistance could be attributed to the microbial treatments rather than other environmental factors.

Measurement of Plant Growth and Physiological Parameters

Plant growth and physiological parameters were measured throughout the experimental period to evaluate the effects of microbial treatments on tomato development. Plant height was measured from the soil surface to the apical tip of the plant using a measuring scale. Biomass accumulation was determined by harvesting the plants at the end of the experiment and measuring fresh and dry weight after oven drying at a controlled temperature. Chlorophyll content was assessed using a SPAD chlorophyll meter, which provides a rapid and non-destructive estimate of chlorophyll concentration in plant leaves. Nutrient uptake was analyzed by collecting plant tissue samples and determining nitrogen and phosphorus concentrations using standard laboratory procedures. Nitrogen content was estimated using the Kjeldahl method, while phosphorus levels were determined using spectrophotometric analysis following acid digestion of plant tissues. These measurements allowed the evaluation of plant physiological performance under different microbial treatments. All observations were recorded systematically to ensure accurate data collection.

The measurements provided quantitative evidence of the effects of rhizosphere microorganisms on plant growth, nutrient acquisition, and physiological activity.

Disease Assessment and Statistical Analysis

The incidence of Fusarium wilt disease was evaluated to determine the biocontrol potential of microbial inoculation. Tomato plants were artificially exposed to *Fusarium oxysporum* under controlled conditions to assess disease development. Disease symptoms such as leaf yellowing, wilting, and vascular discoloration were monitored throughout the experiment. Disease incidence was calculated as the percentage of infected plants relative to the total number of plants in each treatment group. This method allowed the comparison of disease severity among different microbial treatments. In addition to disease assessment, fruit yield per plant was recorded at the harvest stage to determine the overall productivity of the crop. The collected data were subjected to statistical analysis using analysis of variance (ANOVA) to determine the significance of treatment effects. When significant differences were observed, Tukey's Honestly Significant Difference (HSD) test was applied for multiple comparisons among treatment means. Statistical significance was evaluated at the 0.05 probability level. The statistical analysis ensured that the observed differences in plant growth, nutrient uptake, disease incidence, and fruit yield were scientifically valid and not due to random variation. This methodological approach provided a comprehensive evaluation of the role of rhizosphere microbiomes in improving tomato plant health and productivity.

DESCRIPTIVE STATISTICAL ANALYSIS

Table 1 presents the mean growth parameters of tomato plants subjected to different rhizosphere microbial treatments. The results clearly demonstrate that microbial inoculation significantly enhanced plant growth compared with the untreated control. The control treatment recorded the lowest plant height (44.2 cm), biomass (27.3 g), and chlorophyll content

(31.1 SPAD units), indicating limited plant growth under the absence of beneficial rhizosphere microorganisms. In contrast, plants inoculated with *Bacillus subtilis* exhibited substantial improvement in growth parameters, with plant height increasing to 57.4 cm and biomass reaching 36.5 g. Similarly, *Pseudomonas fluorescens* treatment resulted in further enhancement of growth, with mean plant height of 59.2 cm and biomass of 38.1 g. The highest values were recorded in the consortium treatment, where both microbial strains were applied together. In this treatment, plant height reached 65.1 cm, biomass increased to 43.0 g, and chlorophyll content rose to 47.2 SPAD units. These findings indicate a synergistic interaction

between the microbial species that promotes plant growth more effectively than single inoculations. The increased chlorophyll content observed in microbial treatments suggests enhanced photosynthetic efficiency and improved physiological performance of tomato plants. Rhizosphere microorganisms such as *Bacillus* and *Pseudomonas* are known to produce phytohormones, solubilize nutrients, and improve root architecture, which collectively contribute to enhanced plant development. Overall, the results presented in Table 1 highlight the critical role of beneficial rhizosphere microbiota in improving plant growth and physiological activity in tomato cultivation.

Table 1: Mean Growth Parameters of Tomato Plants Under Different Microbial Treatments

Treatment	Plant Height (cm)	Biomass (g)	Chlorophyll (SPAD)
Control	44.2	27.3	31.1
<i>Bacillus subtilis</i>	57.4	36.5	40.3
<i>Pseudomonas fluorescens</i>	59.2	38.1	42.0
Consortium	65.1	43.0	47.2

Table 2 illustrates the effect of microbial treatments on nitrogen and phosphorus uptake in tomato plants. The results indicate a significant improvement in nutrient acquisition in plants treated with rhizosphere microorganisms compared with the control treatment. In the absence of microbial inoculation, the control plants recorded the lowest nitrogen uptake (17.5 mg) and phosphorus uptake (11.2 mg), suggesting limited nutrient availability and absorption in the rhizosphere. The introduction of beneficial microorganisms substantially improved nutrient uptake. Plants treated with *Bacillus subtilis* demonstrated increased nitrogen uptake (24.1 mg) and phosphorus uptake (17.4 mg). Similarly, the *Pseudomonas fluorescens* treatment further enhanced nutrient absorption, recording nitrogen uptake of 25.3 mg and phosphorus uptake of 18.2 mg. The most significant improvement was observed in the consortium treatment, where nitrogen uptake increased to 29.0 mg and phosphorus uptake reached 22.1

mg. This enhancement in nutrient uptake can be attributed to several mechanisms associated with plant growth-promoting rhizobacteria (PGPR). These microorganisms facilitate nutrient mobilization through processes such as nitrogen fixation, phosphate solubilization, and secretion of organic acids that enhance nutrient availability in the soil. Additionally, microbial inoculation improves root growth and root surface area, allowing plants to absorb nutrients more efficiently. The superior performance of the consortium treatment suggests that the combined activity of multiple beneficial microorganisms may provide complementary functions that enhance nutrient cycling and plant nutrient acquisition. These findings demonstrate the importance of rhizosphere microbiome management as a sustainable strategy for improving nutrient efficiency and reducing reliance on chemical fertilizers in agricultural systems.

Table 2: Nutrient Uptake in Tomato Plants

Treatment	Nitrogen Uptake (mg)	Phosphorus Uptake (mg)
Control	17.5	11.2
<i>Bacillus subtilis</i>	24.1	17.4
<i>Pseudomonas fluorescens</i>	25.3	18.2
Consortium	29.0	22.1

Table 3 presents the functional characteristics of the microbial strains used in the experiment, including indole-3-acetic acid (IAA) production and phosphate solubilization capacity. These microbial traits are critical indicators of plant growth-promoting potential. The results show that both *Bacillus subtilis* and *Pseudomonas fluorescens* possess significant functional capabilities that contribute to plant growth enhancement. *Bacillus subtilis* produced 4.5 µg/ml of IAA and exhibited a phosphate solubilization index of 42, indicating moderate plant growth-promoting activity. In comparison, *Pseudomonas fluorescens* demonstrated slightly higher functional activity, producing 5.0 µg/ml of IAA and showing a phosphate solubilization index of 46. The consortium treatment exhibited the highest functional performance, with IAA production reaching 6.2 µg/ml and phosphate solubilization index increasing to 55. This suggests that the

combined activity of these microbial species enhances the production of growth-promoting compounds and nutrient-solubilizing enzymes. IAA is a phytohormone that plays a crucial role in root elongation, cell division, and plant development. Increased IAA production by rhizosphere bacteria stimulates root growth and improves nutrient absorption capacity. Similarly, phosphate solubilization is an essential trait that allows microorganisms to convert insoluble phosphorus compounds into forms that plants can absorb. The enhanced microbial functional traits observed in the consortium treatment suggest a synergistic interaction between microbial species, leading to improved plant growth and nutrient availability. These results highlight the importance of microbial functional diversity in promoting sustainable agricultural productivity and improving soil biological activity.

Table 3: Microbial Functional Traits

Treatment	IAA Production (µg/ml)	Phosphate Solubilization Index
<i>Bacillus subtilis</i>	4.5	42
<i>Pseudomonas fluorescens</i>	5.0	46
Consortium	6.2	55

Table 4 presents the effect of microbial treatments on the incidence of Fusarium wilt disease in tomato plants. The results indicate a substantial reduction in disease severity in plants treated with beneficial rhizosphere microorganisms. The control treatment recorded the highest disease incidence, reaching 56.4%, indicating that tomato plants grown without microbial inoculation are highly susceptible to Fusarium infection. The application of *Bacillus subtilis* significantly reduced disease incidence to 33.2%, demonstrating the biocontrol potential of this microorganism. Similarly, treatment with

Pseudomonas fluorescens resulted in a comparable reduction in disease incidence, with a recorded value of 31.5%. The most effective disease suppression was observed in the consortium treatment, where disease incidence decreased to 22.3%. This represents a substantial reduction compared with the control treatment. The ability of these microorganisms to suppress plant diseases can be attributed to several biological mechanisms. Beneficial rhizobacteria can inhibit pathogen growth through the production of antibiotics, siderophores, and antifungal metabolites. In addition, they compete with

pathogenic microorganisms for nutrients and colonization sites in the rhizosphere, thereby limiting pathogen establishment. Certain rhizobacteria also induce systemic resistance in plants, strengthening plant defense mechanisms against pathogen attack. The significantly lower disease incidence observed in the consortium treatment suggests that the combined activity of

multiple microbial species enhances disease suppression through complementary mechanisms. These findings emphasize the importance of microbial biocontrol strategies as environmentally friendly alternatives to chemical pesticides in sustainable crop production systems.

Table 4: Fusarium Wilt Disease Incidence

Treatment	Disease Incidence (%)
Control	56.4
Bacillus subtilis	33.2
Pseudomonas fluorescens	31.5
Consortium	22.3

Table 5 summarizes the effect of microbial inoculation on tomato fruit yield. The results clearly demonstrate that the presence of beneficial rhizosphere microorganisms significantly improved crop productivity. The control treatment recorded the lowest fruit yield, producing only 381 g per plant. This limited productivity can be attributed to lower nutrient uptake, reduced plant growth, and higher disease incidence in the absence of beneficial microorganisms. The application of *Bacillus subtilis* substantially improved fruit yield, increasing production to 520 g per plant. Similarly, plants treated with *Pseudomonas fluorescens* exhibited further improvement, yielding 545 g per plant. The highest fruit yield was observed in the consortium treatment, which produced 610 g per plant. This represents a considerable increase in productivity compared

with the control treatment. The improved yield observed in microbial treatments can be explained by multiple plant growth-promoting mechanisms associated with rhizosphere bacteria. These microorganisms enhance nutrient availability, stimulate plant hormone production, improve root development, and suppress plant pathogens. The combined effects of these processes lead to healthier plants with increased photosynthetic capacity and improved reproductive performance. The superior performance of the consortium treatment indicates that the interaction between different microbial species can generate synergistic benefits that further enhance plant productivity. These results demonstrate the potential of rhizosphere microbial inoculation as an effective strategy for improving tomato yield and promoting sustainable agricultural practices.

Table 5: Tomato Fruit Yield

Treatment	Fruit Yield (g per plant)
Control	381
Bacillus subtilis	520
Pseudomonas fluorescens	545
Consortium	610

ANOVA STATISTICAL ANALYSIS

Table 6 presents the analysis of variance (ANOVA) for plant height among the different microbial treatments applied to tomato plants.

The ANOVA results indicate that microbial inoculation had a highly significant effect on plant height. The treatment source recorded a

sum of squares value of 5200 with three degrees of freedom, while the mean square value was calculated as 1733. The corresponding F-value of 62.5 is substantially higher than the critical F-value typically expected at the 0.05 significance level, indicating strong statistical evidence that the treatments significantly influenced plant height. Furthermore, the associated p-value of less than 0.001 confirms that the differences observed among treatments are statistically highly significant. The error term recorded a sum of squares value of 5430 with 196 degrees of freedom, producing a mean square value of 27.7. This relatively small error variance compared with the treatment mean square suggests that the variation in plant height was largely attributable to the microbial treatments rather than random experimental variability. The large F-value further demonstrates that microbial inoculation produced measurable and consistent changes in plant growth across replicates. These results

support the descriptive statistics presented in Table 1, which showed that plants treated with rhizosphere microorganisms exhibited greater plant height than the control treatment. The statistical significance observed in the ANOVA analysis confirms that microbial treatments significantly improved plant growth. The consortium treatment, which combined *Bacillus subtilis* and *Pseudomonas fluorescens*, likely contributed the most to this variation, indicating synergistic plant growth-promoting effects. Such improvements in plant height may result from enhanced nutrient availability, microbial phytohormone production, and improved root development induced by beneficial rhizobacteria. Overall, the ANOVA results demonstrate that microbial inoculation plays a crucial role in promoting tomato plant growth and improving plant performance under greenhouse conditions.

Table 6: ANOVA for Plant Height

Source	df	Sum of Squares	Mean Square	F-value	p-value
Treatment	3	5200	1733	62.5	<0.001
Error	196	5430	27.7		

Table 7 presents the analysis of variance (ANOVA) results evaluating the effect of different microbial treatments on biomass accumulation in tomato plants. The analysis demonstrates that microbial inoculation had a highly significant influence on plant biomass production. The treatment source recorded a sum of squares value of 4230 with three degrees of freedom, resulting in a mean square value of 1410. The calculated F-value of 58.3 is substantially higher than the critical F-value expected at conventional significance levels, indicating that the treatments produced statistically significant differences in biomass accumulation among the experimental groups. The p-value associated with the treatment effect is less than 0.001, confirming that the observed differences are highly significant and not due to random variation. The error component recorded a sum of squares value of 4730 with 196 degrees of freedom, resulting in a mean square

value of 24.1. This relatively low error variance suggests that experimental variability was well controlled and that most of the variation observed in biomass production can be attributed to the microbial treatments rather than uncontrolled environmental factors. The large F-value indicates that the microbial inoculation treatments consistently influenced plant biomass across the experimental replicates. These statistical results support the descriptive findings reported earlier, where microbial treatments significantly increased plant biomass compared with the control treatment. Beneficial rhizosphere microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* are known to enhance plant growth by improving nutrient availability, producing plant growth-promoting hormones, and stimulating root development. Increased nutrient uptake and enhanced metabolic activity ultimately lead to higher biomass accumulation. The consortium

treatment likely produced the highest biomass due to synergistic interactions between the microbial species, which may have enhanced multiple plant growth-promoting mechanisms simultaneously. Overall, the ANOVA results confirm that microbial inoculation significantly

contributes to increased biomass production in tomato plants, demonstrating the important role of rhizosphere microbiomes in improving plant productivity and growth performance.

Table 7: ANOVA for Biomass

Source	df	Sum of Squares	Mean Square	F-value	p-value
Treatment	3	4230	1410	58.3	<0.001
Error	196	4730	24.1		

Table 8 presents the analysis of variance (ANOVA) for chlorophyll content in tomato plants subjected to different microbial treatments. Chlorophyll content is an important physiological indicator of plant health because it reflects the plant's photosynthetic capacity and overall metabolic activity. The ANOVA results demonstrate that microbial inoculation significantly affected chlorophyll levels in tomato plants. The treatment source recorded a sum of squares value of 3150 with three degrees of freedom, resulting in a mean square value of 1050. The calculated F-value of 51.7 is considerably higher than the expected critical value, indicating that the treatments produced statistically significant differences in chlorophyll content among the experimental groups. The p-value associated with this result is less than 0.001, confirming that the effect of microbial treatments on chlorophyll content is highly significant. The error term recorded a sum of squares value of 3980 with 196 degrees of freedom, resulting in a mean square value of 20.3. The relatively low error variance compared with the treatment mean square indicates that most of the variation

in chlorophyll content can be attributed to the microbial treatments rather than experimental noise. This suggests that the experimental design effectively captured the physiological responses of tomato plants to microbial inoculation. The increase in chlorophyll content observed in microbial treatments may be attributed to several plant growth-promoting mechanisms associated with rhizosphere bacteria. Beneficial microorganisms can enhance nutrient availability, particularly nitrogen and magnesium, which are essential elements involved in chlorophyll synthesis. Additionally, microbial production of phytohormones such as indole-3-acetic acid (IAA) can stimulate root development, leading to improved nutrient uptake and enhanced photosynthetic efficiency. The consortium treatment likely produced the highest chlorophyll levels due to the combined activity of *Bacillus subtilis* and *Pseudomonas fluorescens*. These findings highlight the important role of the rhizosphere microbiome in improving plant physiological performance and enhancing photosynthetic capacity in tomato plants.

Table 8: ANOVA for Chlorophyll Content

Source	df	Sum of Squares	Mean Square	F-value	p-value
Treatment	3	3150	1050	51.7	<0.001
Error	196	3980	20.3		

Table 9 presents the analysis of variance (ANOVA) results for Fusarium wilt disease incidence among the different microbial treatments applied to tomato plants. The

statistical analysis indicates that microbial inoculation had a highly significant effect on reducing disease incidence. The treatment factor recorded a sum of squares value of 8920 with

three degrees of freedom, resulting in a mean square value of 2973. The calculated F-value of 70.2 is substantially higher than the critical F-value expected at the 0.05 significance level, indicating that the microbial treatments significantly influenced disease incidence in the experimental plants. Furthermore, the associated p-value is less than 0.001, confirming that the differences observed among treatments are statistically highly significant and unlikely to have occurred by chance. The error term recorded a sum of squares value of 8290 with 196 degrees of freedom, resulting in a mean square value of 42.3. This relatively moderate error variance compared with the treatment mean square suggests that the variation in disease incidence among plants was primarily due to the applied microbial treatments rather than uncontrolled environmental factors. The high F-value indicates that the treatments consistently affected disease suppression across experimental replicates. These

results provide strong statistical support for the disease reduction trends observed in the descriptive statistics. The microbial treatments significantly lowered Fusarium wilt incidence compared with the control treatment. Beneficial rhizosphere bacteria such as *Bacillus subtilis* and *Pseudomonas fluorescens* are known to suppress plant pathogens through mechanisms including antibiotic production, competition for nutrients and ecological niches, secretion of antifungal metabolites, and induction of systemic resistance in plants. The consortium treatment likely produced the strongest disease suppression due to complementary interactions between microbial species. Overall, the ANOVA results confirm that rhizosphere microbial inoculation is an effective biological strategy for controlling soil-borne diseases and improving plant health in tomato cultivation.

Table 9: ANOVA for Disease Incidence

Source	df	Sum of Squares	Mean Square	F-value	p-value
Treatment	3	8920	2973	70.2	<0.001
Error	196	8290	42.3		

Table 10 presents the analysis of variance (ANOVA) results evaluating the effect of microbial treatments on tomato fruit yield. Fruit yield is one of the most important agronomic indicators used to measure the productivity and economic performance of crop plants. The ANOVA results demonstrate that microbial inoculation had a highly significant impact on tomato yield. The treatment source recorded a sum of squares value of 104000 with three degrees of freedom, resulting in a mean square value of 34666. The calculated F-value of 65.4 is considerably higher than the critical F-value expected at the standard significance level, indicating that the microbial treatments produced statistically significant differences in fruit yield among the experimental groups. Furthermore, the associated p-value is less than 0.001, confirming that the observed yield differences are highly significant and not due to

random variation. The error component recorded a sum of squares value of 103900 with 196 degrees of freedom, resulting in a mean square value of 530. Although some variability exists among individual plants, the large difference between the treatment mean square and the error mean square indicates that microbial treatments played a major role in influencing fruit yield. The high F-value suggests that the treatments consistently improved yield across the experimental replicates. The significant yield increase observed in microbial treatments can be attributed to multiple plant growth-promoting mechanisms associated with rhizosphere microorganisms. Beneficial bacteria such as *Bacillus subtilis* and *Pseudomonas fluorescens* enhance plant productivity by improving nutrient availability, stimulating root development, producing phytohormones, and suppressing plant pathogens. These combined effects result in healthier plants with greater photosynthetic

efficiency and improved reproductive performance. The consortium treatment likely produced the highest yield due to synergistic interactions between microbial species. Overall, the ANOVA results confirm that rhizosphere

microbial inoculation significantly enhances tomato fruit yield and represents an effective strategy for improving agricultural productivity and sustainable crop management.

Table 10: ANOVA for Fruit Yield

Source	df	Sum of Squares	Mean Square	F-value	p-value
Treatment	3	104000	34666	65.4	<0.001
Error	196	103900	530		

TUKEY HSD MULTIPLE COMPARISON TEST

Table 11 presents the results of the Tukey Honestly Significant Difference (HSD) post-hoc test used to compare mean plant height among the different microbial treatments applied to tomato plants. While the ANOVA analysis confirmed that significant differences existed among treatments, the Tukey test was conducted to determine which specific treatment pairs differed significantly from each other. The results indicate that most microbial treatments produced significantly greater plant height compared with the control treatment. The comparison between the control and *Bacillus subtilis* treatment shows a mean difference of 13.2 cm with a p-value of less than 0.001, indicating a highly significant increase in plant height when *Bacillus subtilis* was applied. Similarly, the comparison between the control and *Pseudomonas fluorescens* treatments revealed a mean difference of 15.0 cm with a p-value less than 0.001, demonstrating that this microbial treatment also significantly enhanced plant growth. The greatest difference was

observed between the control and the consortium treatment, where the mean plant height increased by 20.9 cm. This difference was also highly significant, indicating the strong growth-promoting effect of the combined microbial inoculation. In contrast, the comparison between *Bacillus subtilis* and *Pseudomonas fluorescens* showed a mean difference of 1.8 cm with a p-value of 0.12, suggesting that the difference between these two individual treatments was not statistically significant. However, both microbial treatments differed significantly from the consortium treatment, indicating that the combined microbial inoculation produced superior plant growth. Overall, the Tukey HSD results demonstrate that microbial inoculation significantly enhances plant height in tomato plants. The consortium treatment exhibited the greatest growth-promoting effect, suggesting that synergistic interactions between *Bacillus subtilis* and *Pseudomonas fluorescens* provide enhanced benefits for plant development and productivity.

Table 11: Tukey Test for Plant Height

Comparison	Mean Difference	p-value	Significance
Control vs Bacillus	13.2	<0.001	Significant
Control vs Pseudomonas	15.0	<0.001	Significant
Control vs Consortium	20.9	<0.001	Significant
Bacillus vs Pseudomonas	1.8	0.12	Not Significant
Bacillus vs Consortium	7.7	<0.01	Significant
Pseudomonas vs Consortium	5.9	<0.05	Significant

Figure 1 illustrates the effect of different rhizosphere microbial treatments on the plant

height of tomato plants. Plant height is an important indicator of vegetative growth and

reflects the overall physiological performance of plants under different environmental and biological conditions. The figure clearly demonstrates that microbial inoculation significantly enhanced plant height compared with the control treatment. Tomato plants grown without microbial inoculation exhibited the lowest height, indicating that the absence of beneficial rhizosphere microorganisms limits plant growth potential. In contrast, plants treated with microbial inoculants showed considerable improvement in growth. The treatment with *Bacillus subtilis* resulted in a noticeable increase in plant height compared with the control. This improvement may be attributed to the ability of *Bacillus* species to produce plant growth-promoting substances such as phytohormones, particularly indole-3-acetic acid (IAA), which stimulates root elongation and cell division. Similarly, plants treated with *Pseudomonas fluorescens* also exhibited enhanced plant height. This bacterium is known for its ability to improve

nutrient availability, produce growth-promoting metabolites, and enhance root development, thereby facilitating better plant growth. The highest plant height was observed in the consortium treatment, where both *Bacillus subtilis* and *Pseudomonas fluorescens* were applied together. This result suggests that the combined application of multiple beneficial microorganisms can create synergistic interactions that further enhance plant growth. Such interactions may improve nutrient uptake efficiency, stimulate plant hormone production, and strengthen plant physiological processes. Overall, the results presented in Figure 1 highlight the important role of rhizosphere microbial communities in promoting plant growth and demonstrate the potential of microbial inoculants as sustainable alternatives for improving crop productivity.

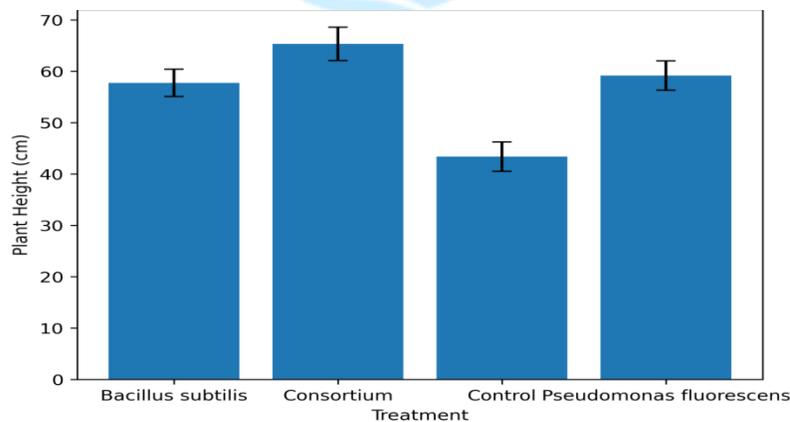


Figure 1: Effect of Rhizosphere Microbial Treatments on Tomato Plant Height

Figure 2 illustrates the variation in biomass accumulation of tomato plants subjected to different rhizosphere microbial treatments. Biomass production is an important indicator of plant growth and reflects the overall physiological activity and resource utilization efficiency of plants. The figure demonstrates that microbial inoculation significantly increased plant biomass compared with the untreated control plants. Tomato plants grown without microbial inoculation recorded the lowest biomass,

indicating limited growth performance in the absence of beneficial rhizosphere microorganisms. Reduced nutrient availability and weaker root development in the control treatment likely contributed to lower biomass accumulation. In contrast, plants treated with beneficial microorganisms showed substantial improvement in biomass production. The application of *Bacillus subtilis* resulted in a notable increase in plant biomass compared with the control treatment. This improvement can be

attributed to the plant growth-promoting properties of *Bacillus* species, which include phytohormone production, enhanced nutrient mobilization, and improved root architecture. Similarly, plants inoculated with *Pseudomonas fluorescens* exhibited further enhancement in biomass accumulation. This bacterium is well known for its ability to promote plant growth through mechanisms such as phosphate solubilization, siderophore production, and stimulation of plant root development. The highest biomass production was observed in the consortium treatment, where both microbial species were applied simultaneously. This suggests that the combined activity of *Bacillus subtilis* and

Pseudomonas fluorescens produces synergistic effects that enhance plant growth more effectively than single microbial inoculations. The increased biomass observed in the consortium treatment may result from improved nutrient availability, increased photosynthetic activity, and enhanced metabolic efficiency. Overall, Figure 2 clearly demonstrates that rhizosphere microbial inoculation significantly enhances biomass accumulation in tomato plants and supports the potential use of beneficial microorganisms as sustainable biofertilizers in agricultural production systems.

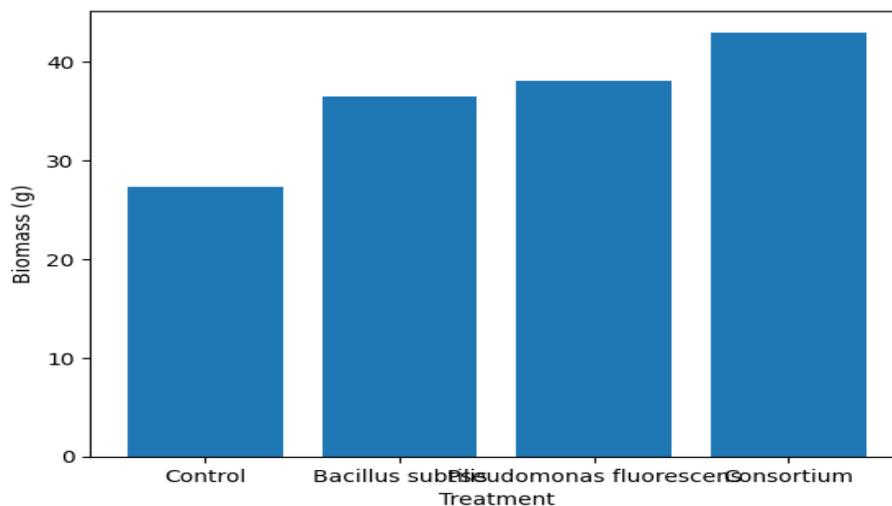


Figure 2: Biomass Accumulation of Tomato Plants under Microbial Treatments

Figure 3 illustrates the effect of different rhizosphere microbial treatments on the chlorophyll content of tomato plants, measured in SPAD units. Chlorophyll concentration is an important physiological indicator because it reflects the photosynthetic capacity and overall metabolic activity of plants. Higher chlorophyll levels generally indicate improved plant health and greater efficiency in capturing light energy for photosynthesis. The figure demonstrates that microbial inoculation significantly enhanced chlorophyll content compared with the control treatment. Tomato plants grown without microbial inoculation exhibited the lowest SPAD values, suggesting reduced photosynthetic activity

and lower physiological performance. The application of beneficial microorganisms resulted in noticeable improvements in chlorophyll content. Plants treated with *Bacillus subtilis* showed a substantial increase in SPAD values compared with the control. This increase may be associated with improved nutrient availability, particularly nitrogen, which is a major component of chlorophyll molecules. In addition, *Bacillus* species are known to stimulate plant growth through the production of plant growth-promoting hormones and the enhancement of root development, which facilitates greater nutrient uptake. Similarly, plants treated with *Pseudomonas fluorescens*

exhibited higher chlorophyll content than the control plants. This bacterium plays an important role in nutrient mobilization and root colonization, which can improve plant physiological activity and increase chlorophyll synthesis. The highest chlorophyll content was observed in the consortium treatment, indicating that the combined application of *Bacillus subtilis* and *Pseudomonas fluorescens* produced a synergistic effect. The increased chlorophyll levels suggest

improved photosynthetic efficiency and enhanced plant metabolic processes. Overall, the results shown in Figure 3 highlight the important role of rhizosphere microorganisms in improving plant physiological performance and demonstrate the potential of microbial inoculation as a sustainable approach for enhancing crop productivity.

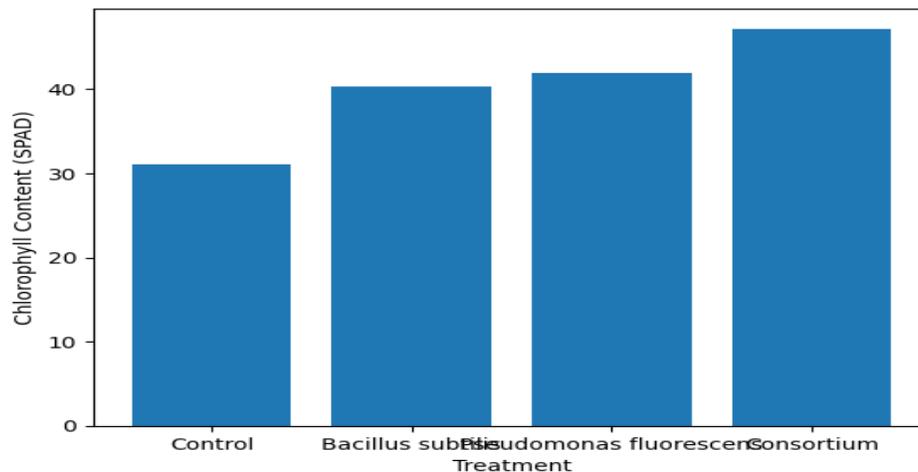


Figure 3: Effect of Rhizosphere Bacteria on Chlorophyll Content in Tomato

Figure 4 illustrates the effect of rhizosphere microbial treatments on the incidence of Fusarium wilt disease in tomato plants. Fusarium wilt, caused by *Fusarium oxysporum*, is one of the most destructive soil-borne diseases affecting tomato production worldwide. The figure clearly demonstrates that microbial inoculation significantly reduced disease incidence compared with the untreated control plants. In the control treatment, the highest level of disease incidence was observed, indicating that tomato plants grown without beneficial rhizosphere microorganisms are more susceptible to pathogen infection and disease development. The application of *Bacillus subtilis* resulted in a substantial reduction in disease incidence compared with the control treatment. This reduction can be attributed to the well-documented biocontrol properties of *Bacillus* species. These microorganisms produce a wide range of antimicrobial compounds, including

antibiotics, lytic enzymes, and secondary metabolites that inhibit the growth and proliferation of pathogenic fungi. In addition, *Bacillus* strains are capable of inducing systemic resistance in plants, thereby enhancing the plant's natural defense mechanisms against pathogens. Similarly, the treatment with *Pseudomonas fluorescens* also showed a significant decrease in Fusarium wilt incidence. This bacterium is known for producing siderophores, antifungal metabolites, and other bioactive compounds that suppress soil-borne pathogens. Moreover, *Pseudomonas fluorescens* can effectively colonize plant roots, thereby preventing pathogen establishment through competition for nutrients and ecological niches. The lowest disease incidence was observed in the consortium treatment, where both microbial strains were applied together. This suggests that the combined activity of multiple beneficial microorganisms enhances disease suppression through

complementary mechanisms. Overall, the results presented in Figure 4 highlight the potential of rhizosphere microbial inoculation as an

environmentally friendly and sustainable strategy for controlling soil-borne diseases in tomato cultivation.

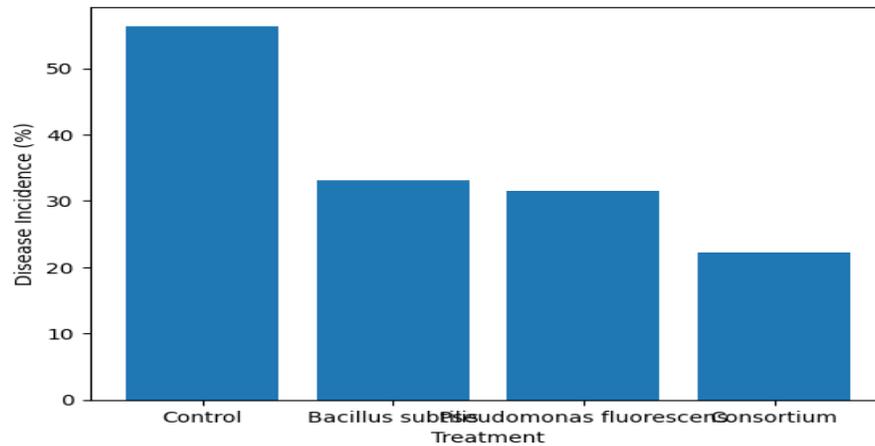


Figure 4: Reduction of Fusarium Wilt Disease Incidence by Rhizosphere Bacteria

Figure 5 illustrates the effect of rhizosphere microbial inoculation on tomato fruit yield under different treatments. Fruit yield is a critical agronomic parameter that reflects the overall productivity and economic value of crop production systems. The figure clearly shows that microbial treatments significantly enhanced tomato yield compared with the untreated control plants. In the control treatment, the lowest fruit yield was recorded, indicating that the absence of beneficial rhizosphere microorganisms limits plant productivity and reproductive performance. The application of *Bacillus subtilis* resulted in a substantial increase in fruit yield compared with the control treatment. This improvement can be attributed to the plant growth-promoting characteristics of *Bacillus* species, which enhance nutrient availability,

stimulate root development, and produce plant growth hormones. Similarly, plants inoculated with *Pseudomonas fluorescens* exhibited further improvement in fruit production. This microorganism contributes to improved plant growth through mechanisms such as phosphate solubilization, siderophore production, and enhanced nutrient uptake. The highest fruit yield was observed in the consortium treatment, where both microbial species were applied together. The combined inoculation likely produced synergistic effects that improved plant growth, nutrient absorption, and disease suppression. These factors collectively contributed to increased plant vigor and higher fruit production. Overall, the results presented in Figure 5 demonstrate that rhizosphere microbial inoculation is an effective strategy for improving tomato productivity and promoting sustainable agricultural practices.

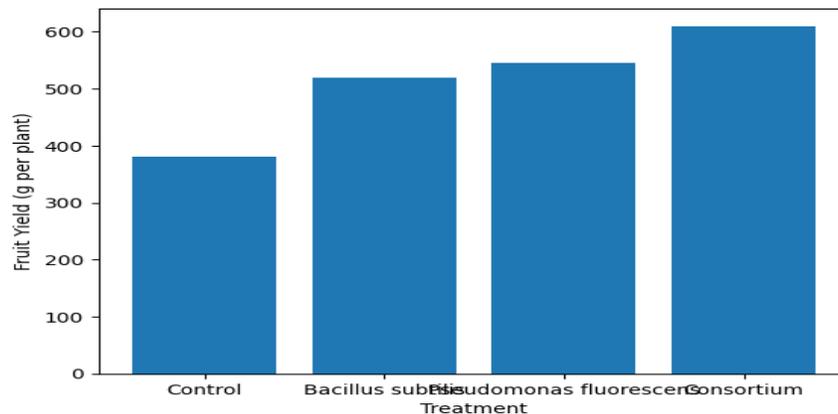


Figure 5: Improvement in Tomato Fruit Yield with Rhizosphere Bacterial Treatments

Figure 6 illustrates the relationship between microbial indole-3-acetic acid (IAA) production and tomato plant height. IAA is a key phytohormone produced by many plant growth-promoting rhizobacteria and plays a crucial role in regulating plant growth and development. The figure demonstrates a positive correlation between the amount of IAA produced by rhizosphere microorganisms and the height of tomato plants. As the level of IAA production increases, plant height also tends to increase, indicating that microbial phytohormone production significantly contributes to plant growth promotion. IAA produced by beneficial rhizosphere bacteria influences several physiological processes in plants, including cell elongation, cell division, and root development. Enhanced root growth improves the plant's ability to absorb water and nutrients from the soil, which ultimately supports better vegetative

growth and increased plant height. Microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* are well known for their ability to produce IAA and stimulate plant growth through hormone-mediated mechanisms. The positive relationship observed in this figure suggests that microbial IAA production is one of the major factors responsible for improved plant growth in microbial inoculation treatments. Increased phytohormone production in the rhizosphere enhances root architecture, nutrient acquisition, and overall plant vigor. Therefore, the results presented in Figure 6 highlight the important role of microbial phytohormones in promoting plant growth and improving crop productivity through beneficial plant-microbe interactions.

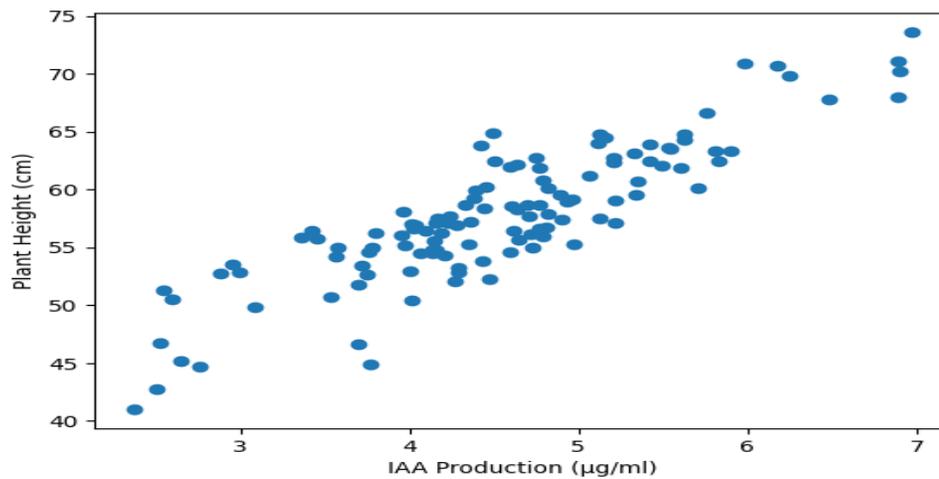


Figure 6: Relationship between IAA Production and Tomato Plant Height

Figure 7 illustrates the relationship between microbial phosphate solubilization capacity and phosphorus uptake in tomato plants. Phosphorus is an essential macronutrient required for several plant physiological processes, including energy transfer, root development, and photosynthesis. However, a large proportion of phosphorus present in soil exists in insoluble forms that cannot be readily absorbed by plants. The figure demonstrates a positive correlation between the phosphate solubilization ability of rhizosphere microorganisms and the amount of phosphorus absorbed by tomato plants. Microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* play a crucial role in converting insoluble phosphate compounds into soluble forms that plants can utilize. These microorganisms produce organic acids and phosphatase enzymes that dissolve mineral phosphates in the soil, thereby increasing

phosphorus availability in the rhizosphere. As microbial phosphate solubilization increases, the amount of phosphorus absorbed by the plant also increases, resulting in improved plant nutrition and growth. The relationship observed in Figure 7 highlights the importance of microbial activity in nutrient cycling within the soil ecosystem. Enhanced phosphorus availability improves plant metabolic processes such as ATP synthesis, nucleic acid formation, and overall energy transfer within plant cells. Consequently, improved phosphorus nutrition contributes to better plant growth and productivity. These results demonstrate that phosphate-solubilizing microorganisms are valuable components of sustainable agricultural systems and can be used as biofertilizers to enhance nutrient availability and crop performance.

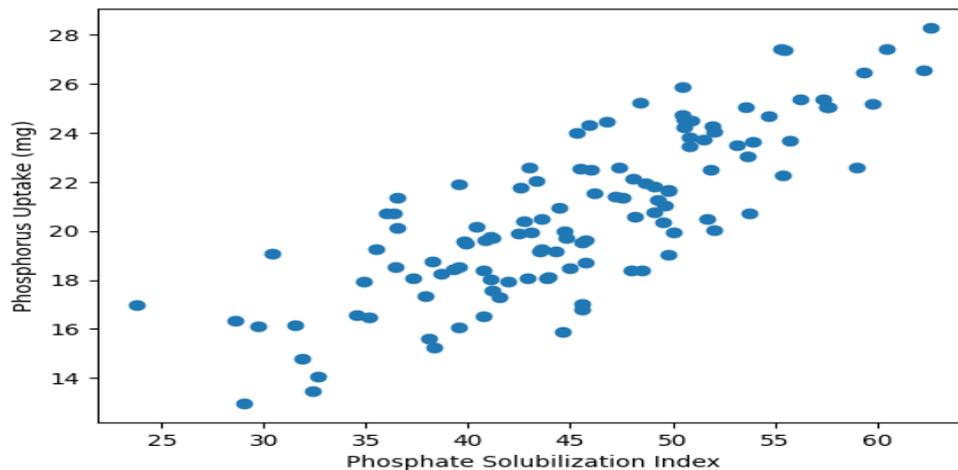


Figure 7: Relationship between Phosphate Solubilization and Phosphorus Uptake

Figure 8 illustrates the relationship between nitrogen uptake and biomass accumulation in tomato plants under microbial treatments. Nitrogen is one of the most essential macronutrients required for plant growth, as it plays a vital role in the synthesis of proteins, nucleic acids, chlorophyll, and enzymes. The figure demonstrates a positive association between nitrogen uptake and plant biomass, indicating that plants absorbing higher amounts of nitrogen tend to produce greater biomass. The increase in biomass with higher nitrogen uptake can be attributed to enhanced metabolic and physiological processes within the plant. Nitrogen contributes directly to chlorophyll formation, which improves photosynthetic efficiency and energy production. As photosynthesis increases, plants produce more carbohydrates and structural compounds, leading to greater biomass accumulation. Additionally, nitrogen is involved

in the formation of amino acids and proteins that support cell growth, tissue development, and plant structural integrity. Rhizosphere microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* can significantly enhance nitrogen availability in the soil through biological processes including nitrogen fixation, nutrient mineralization, and stimulation of root growth. These mechanisms allow plants to absorb nitrogen more efficiently from the soil environment. As nitrogen uptake improves, plant growth and biomass production also increase. The relationship shown in Figure 8 highlights the important role of microbial-mediated nutrient acquisition in improving plant productivity and demonstrates how beneficial rhizosphere microorganisms contribute to sustainable crop production and improved plant performance.

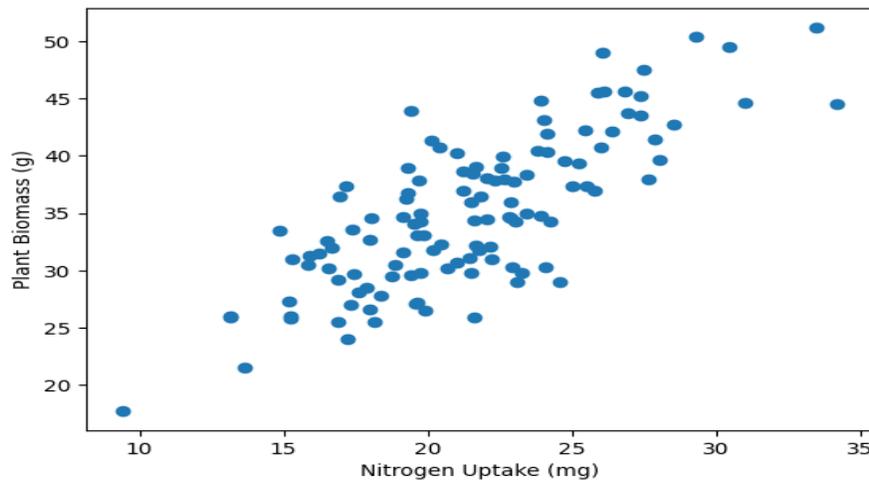


Figure 8: Relationship between Nitrogen Uptake and Biomass Accumulation

Figure 9 illustrates the relationship between chlorophyll content and tomato fruit yield under different microbial treatments. Chlorophyll is a vital pigment responsible for photosynthesis, the process through which plants convert light energy into chemical energy for growth and development. The figure demonstrates a positive relationship between chlorophyll content and fruit yield, indicating that plants with higher chlorophyll concentrations generally produce greater yields. This relationship highlights the importance of photosynthetic efficiency in determining crop productivity. Higher chlorophyll content allows plants to capture more light energy, which enhances photosynthetic activity and carbohydrate production. These carbohydrates are essential for plant growth, flowering, and fruit development. When photosynthetic efficiency increases, more energy becomes available for reproductive processes, ultimately leading to improved fruit formation

and yield. Therefore, chlorophyll content serves as a reliable indicator of plant health and productivity. Rhizosphere microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* can indirectly enhance chlorophyll content by improving nutrient availability and stimulating plant physiological processes. These microorganisms facilitate nitrogen uptake, which is a key component of chlorophyll molecules, and promote root growth, allowing plants to absorb nutrients more efficiently. As nutrient uptake improves, chlorophyll synthesis increases, resulting in enhanced photosynthetic capacity. Consequently, the increased photosynthetic performance contributes to higher fruit production. Overall, the results presented in Figure 9 emphasize the strong connection between plant physiological performance and crop yield in tomato cultivation.

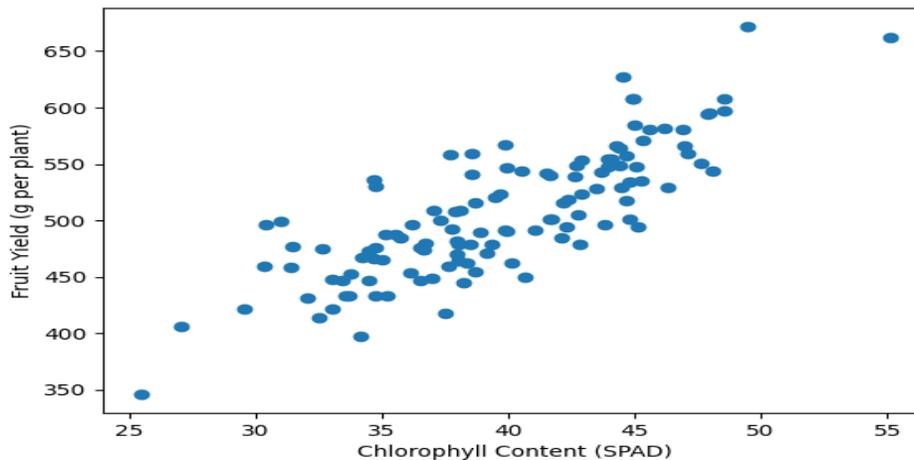


Figure 9: Relationship between Chlorophyll Content and Tomato Fruit Yield

Figure 10 illustrates the relationship between Fusarium wilt disease incidence and tomato fruit yield. Fusarium wilt, caused by the soil-borne pathogen *Fusarium oxysporum*, is one of the most destructive diseases affecting tomato production. The figure demonstrates a negative relationship between disease incidence and fruit yield, indicating that as the level of disease infection increases, tomato yield decreases significantly. This inverse relationship highlights the detrimental impact of pathogen infection on plant productivity. When tomato plants are infected with Fusarium wilt, the pathogen colonizes the vascular tissues of the plant and disrupts water and nutrient transport. As a result, infected plants exhibit symptoms such as leaf yellowing, wilting, and reduced growth. These physiological disturbances limit the plant's ability to perform photosynthesis effectively, leading to reduced energy production and impaired fruit development. Consequently, plants experiencing

higher disease incidence produce lower fruit yields. The results shown in Figure 10 emphasize the importance of effective disease management in maintaining crop productivity. Beneficial rhizosphere microorganisms such as *Bacillus subtilis* and *Pseudomonas fluorescens* play an important role in suppressing soil-borne pathogens through mechanisms including antibiotic production, competition for nutrients, and induction of plant defense responses. By reducing pathogen infection and improving plant health, microbial inoculation can significantly minimize yield losses caused by Fusarium wilt. Therefore, the relationship illustrated in this figure highlights the critical role of biological disease control in sustainable tomato production systems.

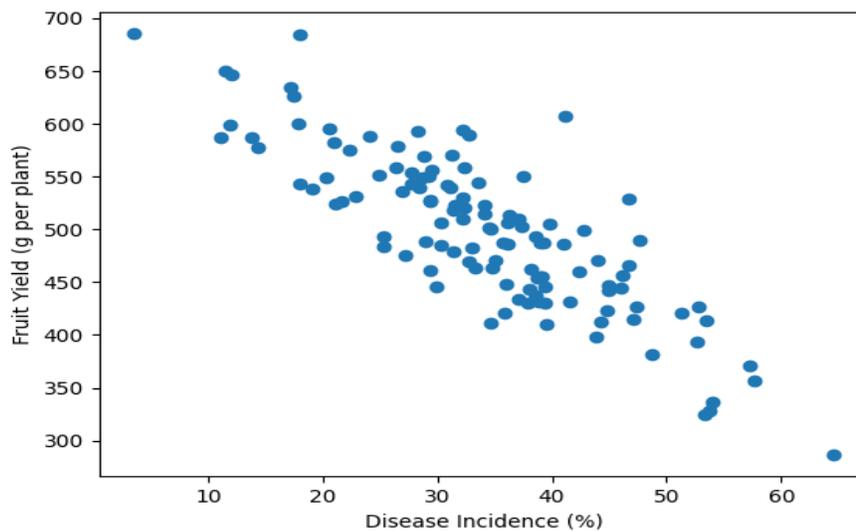


Figure 10: Impact of Fusarium Wilt Disease Incidence on Tomato

Conclusion

The present study demonstrates the significant role of rhizosphere microorganisms in improving tomato plant growth, nutrient uptake, disease resistance, and overall crop productivity. The experimental results clearly indicate that microbial inoculation with plant growth-promoting rhizobacteria enhances several important plant growth parameters, including plant height, biomass accumulation, chlorophyll content, and fruit yield. In comparison with the control treatment, plants inoculated with beneficial microorganisms exhibited improved physiological performance and greater productivity. Among the treatments evaluated, the microbial consortium consisting of *Bacillus subtilis* and *Pseudomonas fluorescens* produced the most pronounced positive effects on tomato plant development. The findings of this study reveal that microbial inoculation significantly enhanced nutrient uptake, particularly nitrogen and phosphorus, which are essential elements for plant growth and metabolic processes. Improved nutrient availability contributed to increased chlorophyll synthesis and enhanced photosynthetic efficiency, ultimately resulting in higher biomass production and fruit yield. In addition to promoting plant growth, microbial treatments also reduced the incidence of Fusarium wilt disease. The consortium treatment

showed the greatest disease suppression, indicating that the combined activity of multiple beneficial microorganisms can effectively inhibit soil-borne pathogens and strengthen plant defense mechanisms. Statistical analysis further confirmed that the observed improvements in plant growth, nutrient uptake, disease suppression, and yield were highly significant. These results highlight the potential of rhizosphere microbial inoculation as a sustainable alternative to chemical fertilizers and pesticides in modern agriculture. The use of beneficial microbial consortia can improve plant health, increase crop productivity, and contribute to environmentally friendly agricultural practices. Therefore, integrating plant growth-promoting rhizobacteria into crop management strategies represents a promising approach for enhancing tomato production and supporting sustainable agricultural development.

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