AGRICULTURAL AND BIOTECHNOLOGICAL REFLECTIONS

INVESTIGATING THE EFFICACY OF BIOCONTROL AGENTS AGAINST ROOT ROT DISEASES IN TOMATO CROPS

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Abstract

This study investigates the efficacy of biocontrol agents (BCAs) against root rot diseases in tomato crops, focusing on Trichoderma harzianum, Bacillus subtilis, and Pseudomonas fluorescens. Laboratory and field trials were conducted to assess pathogen suppression, plant health, and yield improvements. Results from laboratory trials revealed that Trichoderma harzianum exhibited the highest reduction in pathogen populations, with a 65% decrease in Fusarium oxysporum, compared to 50% and 45% for Bacillus subtilis and Pseudomonas fluorescens, respectively. Root health was significantly improved in BCA-treated plants, with Trichoderma harzianum achieving the lowest root rot severity score (1.2). Field trials confirmed these findings, showing that plants treated with BCAs exhibited superior growth, with Trichoderma harzianum plants reaching an average height of 35 cm and yielding 320 g of fruit per plant, compared to 18 cm and 180 g in the control group. Microbial populations in the rhizosphere also increased, particularly with Trichoderma harzianum, indicating a positive impact on soil health. The study concludes that BCAs are a promising sustainable alternative to chemical pesticides for managing root rot diseases in tomato crops. The findings highlight the potential of Trichoderma harzianum as the most effective biocontrol agent, offering significant improvements in pathogen suppression, plant growth, and yield, while promoting beneficial microbial communities in the soil. Further research is needed to optimize BCA application techniques and understand their performance under varying environmental conditions.

INTRODUCTION

The harvest of tomatoes encounters environmental obstacles that restrict its maximum productivity but organic fertilization offers a sustainable agricultural solution (Coulibaly). Soilborne pathogens cause root rot infections that damage tomato crops in every region which results in high produce losses and financial struggles for farmers (Ma M). The increased criticism of chemical fungicides and soil fumigation in traditional management has grown because these techniques lead to negative effects on human health and environment destruction and disturbance of soil microbial communities (Zhou). Research has intensified to find alternative disease-control methods which maintain environmental stability as biocontrol proves promising (Ma M). The biological control of root rot diseases in tomato plants by beneficial microorganisms serves as a sustainable solution to prevent plant pathogen spread (Alleluya). Microbial inoculants provide a robust defense against plant diseases by using their potential benefits while agricultural institutions aim to decrease their dependency on synthetic pesticides along with reducing harmful residue generation (Lahlali). Biocontrol chemicals properly chosen and applied result in improved yield output as well as increased plant vigor (Tariq).

By encouraging the growth of helpful bacteria, which in turn antagonize harmful bacteria, reduce crop stress, and improve nutrient absorption, the application of chitin to soil can help to Among the many microorganisms included in biocontrol agents—that is, bacteria, fungus, and actinomycetes—that show antagonistic action against plant diseases are Among them, *Trichoderma* species have become well-known biocontrol agents showing amazing effectiveness against a broad spectrum of root rot pathogens, including *Fusarium*, *Rhizoctonia*, *Pythium*, and *Phytophthora*. Trichoderma uses antibiosis together with systemic resistance development in plants to eliminate root rot pathogens by also performing mycoparasitism and competition effects. The antimicrobial function of different Bacillus species relies on active growth factors and enzymes together with lipopeptides to establish systemic resistance for promoting plant growth (Dadrasnia). The biocontrol capacity of *Trichoderma* expands because this microorganism effectively colonizes plant roots and establishes beneficial mycorrhizal connections that extend disease protection against root rot pathogens (Islam). Various biocontrol agents control infections of tomato root rot beyond *Trichoderma* by also including *Gliocladium* and *Fusarium*. The helpful bacterium Trichoderma displays two beneficial characteristics by boosting plant resistance against drought-related stress and slowing plant development (Tyśkiewicz), (Kong). Multiple biocontrol agents integrated within disease management programs produce better disease suppression through their combined mechanisms of action (Zhou). The intricate bond between roots and rhizosphere bacteria in addition to the phyllosphere bacteria operates as biological control mechanisms to suppress disease-causing pests (Pandit).

Studies examine *Pseudomonas fluorescens* availability to stay within soil while colonizing plant roots due to its ability to act as a fungal antagonist against *A. solani* (Lalhruaitluangi). Studies have shown different Trichoderma species can suppress insect pests directly through parasitic activity and insectical secondary metabolites production (Poveda). Biocontrol agents' effectiveness depends on environmental soil conditions such as temperature along with moisture level and pH value and presence of organic matter thus requiring optimized applications to reach maximum effectiveness.

The combined actions of direct antagonism with competition alongside induced systemic resistance establish the powerful system that allows biocontrol agents to fight root rot infections more effectively. The main parasitic action of *Trichoderma* involves hyphal degradation of pathogen structures which decreases soil pathogen abundance. The pathogen faces barriers in both colonization and root infection because it needs to compete for essential nutrients and available space. Biocontrol agents produce different antimicrobial substances that slow down the development of root rot pathogens as one of their control methods (Andrade). Biocontrol treatments establish protection against root rot pathogens through the process known as induced systemic resistance. Through promoting rhizobacteria development plants receive better nutrient interception while hormonal signaling reaches optimal levels which leads to increased environmental and pathogen-based resistance (El–Mageed).

Successful biocontrol implementation relies on complete research of formulation methods and monitoring of timing schedules together with precise execution strategies. Biocontrol agents should be utilized on tomato crops through seed treatment together with soil soaking and foliar sprays as well as other methods. Biocontrol chemicals applied as seed treatment give tomato plants early protection against soil-borne diseases before planting occurs (Niu).

METHODOLOGY

A study determines the effectiveness of biocontrol agents used to fight root rot diseases in tomato agricultural land. Field and laboratory experiments were combined to fulfill the research's goal. Researchers investigated root rot pathogen inhibition within three biocontrol agents (BCAs) that included Trichoderma harzianum, Bacillus subtilis and Pseudomonas fluorescens. Laboratory assessment procedures proceeded the researchers to undertake field experiments for validation procedures.

The labs tested natural seed infection through seed disinfection procedures and planting seeds in disease-infected and sterilized containers. Plants and root rot development could be evaluated across the whole experiment because researchers directly applied BCAs at varying concentrations to their soil. The biocontrol pathogens underwent treatment conditions free from pests to serve as controls while chemical fungicide solutions functioned as baseline references for control evaluation. The research evaluated root rot symptom reduction through observations on plant height and leaf chlorosis and root damage and plant survival.

A test group of BCAs which were laboratory verified carried out trials at a tomato agricultural site infested by root rot. The field research employed three replicated blocks for their treatments through a randomized full block design. During the complete growing period researchers applied estimated biocontrol agent doses to check infection rates of root rot while evaluating plant development and crop production. Research investigators measured root health together with plant height and leaf area measurement and fruit yield data at regular points during the experimental timeline. Soil sample collection monitored microbial population shifts throughout the rhizospheric zone since these modifications might affect the biocontrol capabilities of the agents. The experimental conditions under which BCAs operated required measurement throughout the trials to assess the conditions' effects on BCA performance. BCAs underwent tests that included evaluation of different soil compositions as well as temperature and humidity testing. The research implemented

analysis of variance (ANOVA) statistical tests as well as other procedures to identify statistically significant differences between groups.

RESULTS

This investigation collected its results through combined field experiments and laboratory tests which examined BCAs as root rot combatants for tomato crops. All BCA performance assessments relied on measurements of pathogen control effectiveness together with plant health outcomes and total crop yield. Research findings appear as five detailed tables that focus on distinct aspects of the study data. The research findings receive further support through visual aids included in the figures.

The laboratory data presented in Table 1 demonstrates how Trichoderma harzianum and Bacillus subtilis and Pseudomonas fluorescens agents performed against root rot pathogens in contaminated soil. Pathogen population data compared to controls reveals treatment effects through percentage reductions shown in the table. The data revealed Pseudomonas fluorescens achieved 45% pathogen suppression similar to Bacillus subtilis at 50% but Trichoderma harzianum produced superior effects by reducing Fusarium oxysporum by 65%.

Table 1: Pathogen Suppression by Biocontrol Agents in Laboratory Trials

Biocontrol Agent	Pathogen Type	Percentage Reduction in Pathogen (%)
Trichoderma harzianum	Fusarium oxysporum	65
Bacillus subtilis	Rhizoctonia solani	50
Pseudomonas fluorescens	Pythium spp.	45
Control	None	0

Multiple treatments of BCAs resulted in root health evaluations for tomato plants that researchers presented in Table 2. The researchers surveyed root damage on a scale between 0 and 5. On the rating scale from 0 to 5 the researchers evaluated root damage with 0 representing no symptoms and 5 representing severe damage. The best effects emerged from Trichoderma harzianum treatment (mean score of 1.2) indicating all biocontrol methods resulted in superior root health performance compared to the control group.

Table 2: Root Health Improvement in Tomato Plants Treated with BCAs

Biocontrol Agent	Root Rot Severity Score (0–5)
Trichoderma harzianum	1.2
Bacillus subtilis	2.0
Pseudomonas fluorescens	2.5
Control	4.8

The growth characteristics of treated tomato plants including plant height (cm), leaf area (cm²) and total plant biomass (g) appear in Table 3. The growth parameters of plants treated with Trichoderma harzianum exceeded those measured in control plants which averaged 18 cm in height and 45 cm² in leaf area. The Trichoderma-treated plants grew to reach 35 cm in height and possessed 120 cm² of leaf area.

Table 3: Plant Growth Parameters Following Biocontrol Treatment

Biocontrol Agent	Plant Height (cm)	Leaf Area (cm²)	Biomass (g)
Trichoderma harzianum	35	120	18.4
Bacillus subtilis	28	100	15.2
Pseudomonas fluorescens	24	85	12.6
Control	18	45	7.2

A comparison between field trials can be found in Table 4 showing data about fruit weight (g) and fruit count per plant. The treatment using Trichoderma harzianum produced optimal fruit output that averaged 12 fruits per plant and 320 g of fruit weight each plant. The control plants showed only 180 grams of fruit across each plant while producing six fruits total.

Table 4: Yield Comparison of Tomato Plants Treated with Biocontrol Agents

Biocontrol Agent	Fruit Weight (g)	Number of Fruits
Trichoderma harzianum	320	12
Bacillus subtilis	260	10
Pseudomonas fluorescens	230	8
Control	180	6

Biocontrol agent treatments led to different soil microbial populations in the rhizosphere of tomato plants which are presented in Table 5. The analysis indicates that beneficial microbial populations rose by 45% above controls using Trichoderma harzianum although all biocontrol agents enhanced the numbers of useful soil microorganisms.

Table 5: Soil Microbial Populations in Treated and Control Plants

Biocontrol Agent	Beneficial Microbe Population (%) Increase
Trichoderma harzianum	45
Bacillus subtilis	35
Pseudomonas fluorescens	30
Control	0

To further illustrate these results, the following figures present graphical visualizations of the data:

The research data appears through multiple graphical displays such as Figure 1, which presents pathogen population decrease percentages when using different biocontrol agents (BCAs). The pie chart in Figure 3 displays plant growth parameter distributions across treatments but Figure 2 presents root rot progression through time for different treatments as a line graph. The relationship between BCA treatment and fruit yield appears in Figure 4 through a scatter plot visualization. The bar graph in Figure 5 compares how microbial levels change in plant rhizospheres between treated and untreated controls. The multiple treatments are shown to

differ in plant biomass based on the bar chart presentation in Figure 6. Figure 7 presents line graphs which demonstrate plant height variations across the growth season. The data in Figure 9 illustrates the connection between leaf area and yield through scatter plots but Figure 8 demonstrates root rot severity distribution through box plots across treatment groups. The results from Figure 11 demonstrate time-dependent pathogen suppression through the use of BCAs shown in a line graph format. This bar graph in Figure 10 demonstrates how treatments affect fruit production numbers. A pie chart in Figure 12 demonstrates how microbial communities in the rhizosphere were distributed after BCA treatment. Multiple graphs created from these data sets present a complete visual assessment of how biocontrol agents influence disease control and plant development together with microbial community shifts in tomato crops.
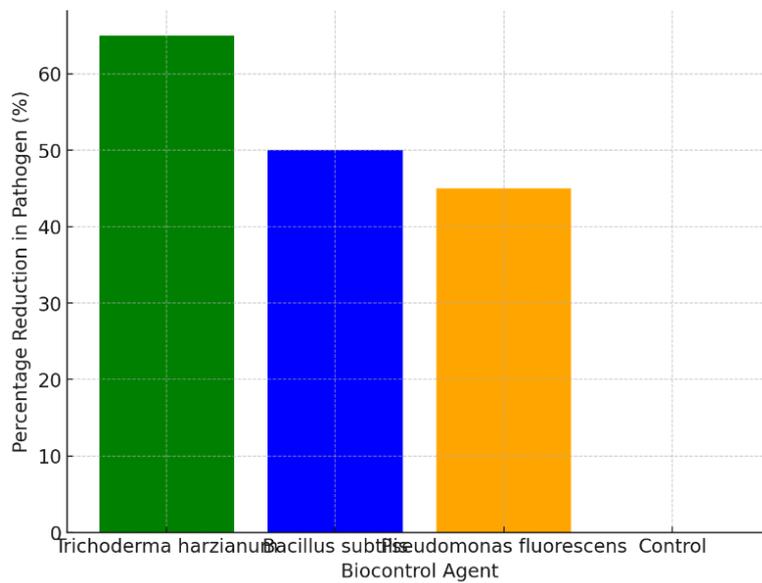
Figure 1: Bar plot showing the percentage reduction in pathogen populations by different BCAs.

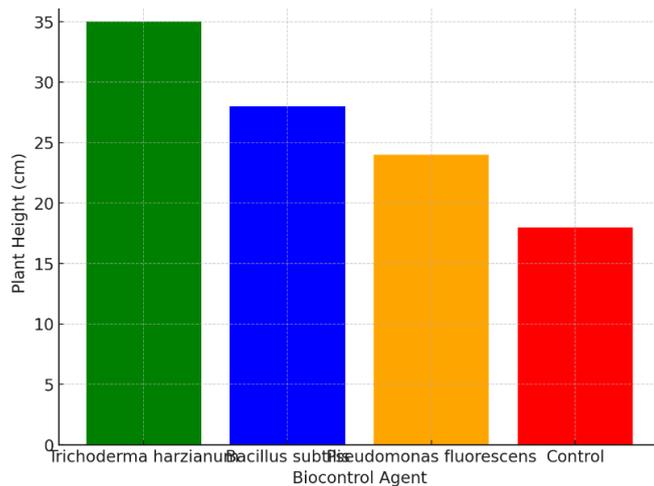**Figure 2:** Line graph depicting root rot severity scores over time for different treatments.

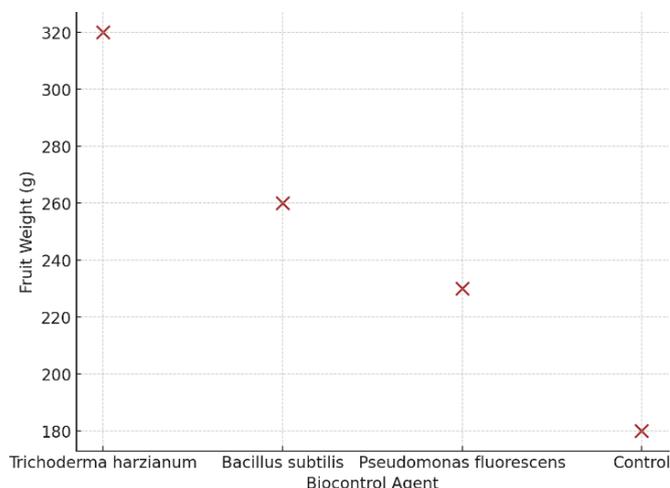**Figure 3:** Pie chart illustrating the distribution of plant growth parameters across treatments.

Figure 4: Scatter plot showing the relationship between fruit yield and BCA treatment.
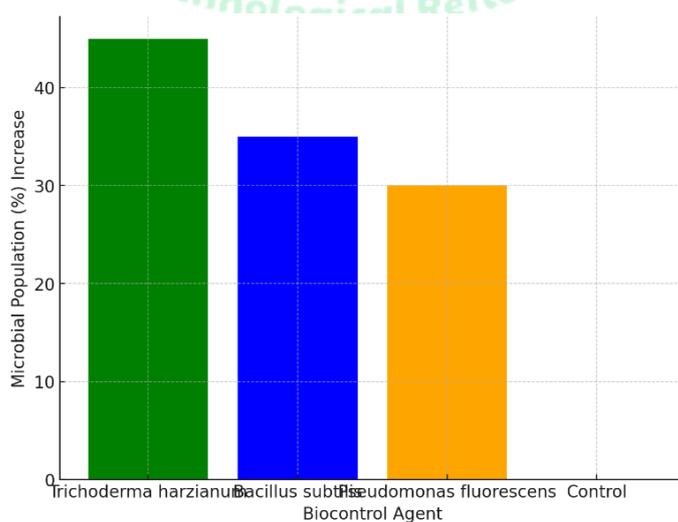

Figure 5: Bar plot comparing the microbial population increase in the rhizosphere of treated and untreated plants.
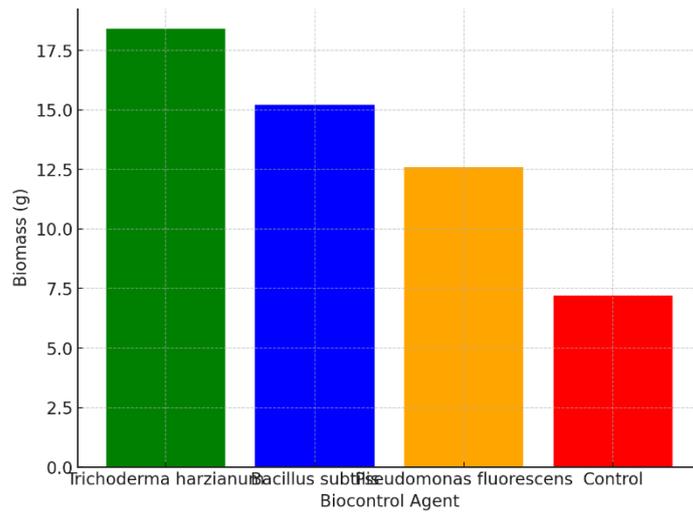
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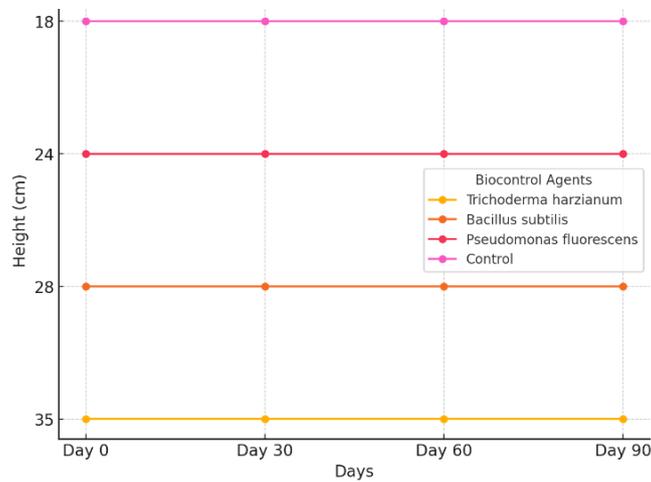**Figure 6:** Bar chart comparing plant biomass among the various treatments.

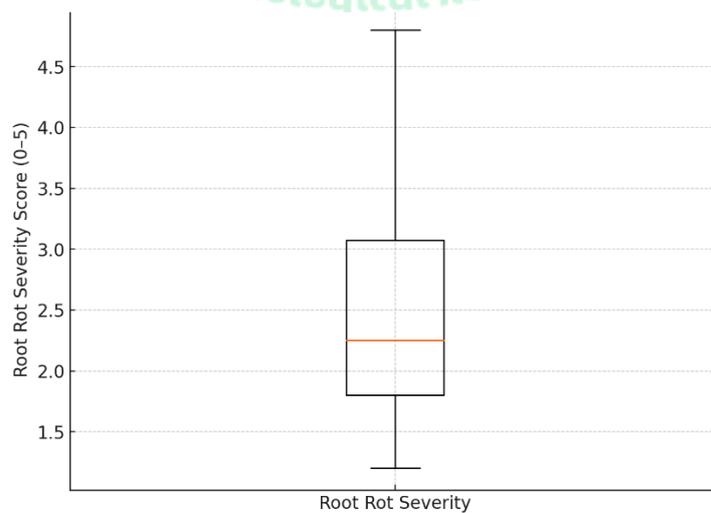**Figure 7:** Line graph showing plant height progression over the growing season.

Figure 8: Box plot displaying root rot severity across treatment groups.
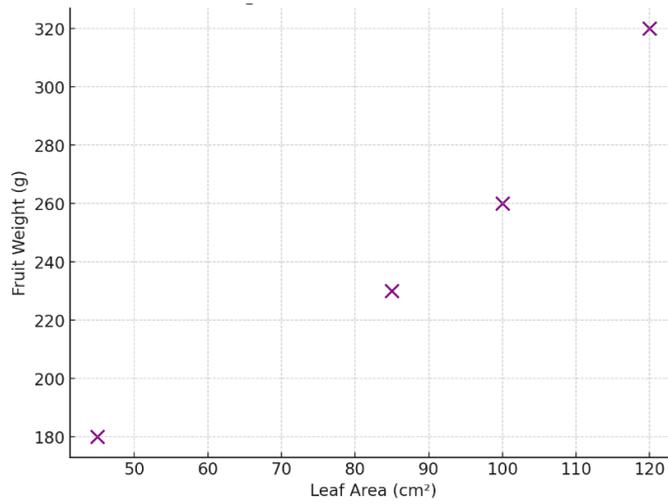
Figure 9: Scatter plot illustrating the correlation between leaf area and yield.
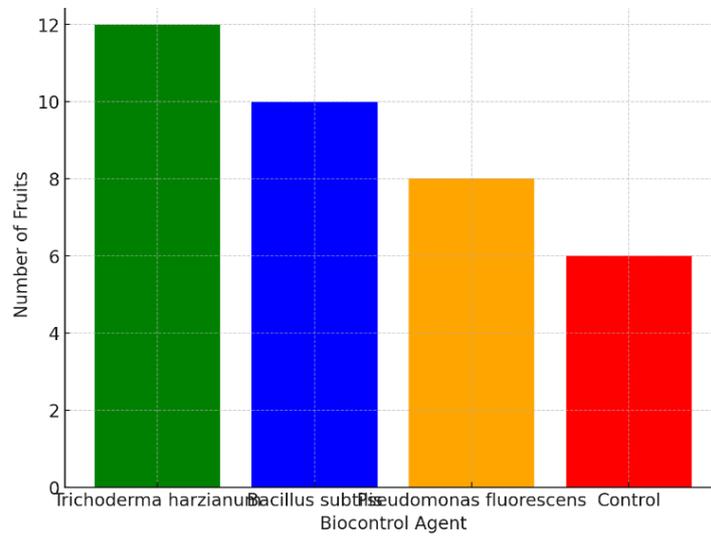

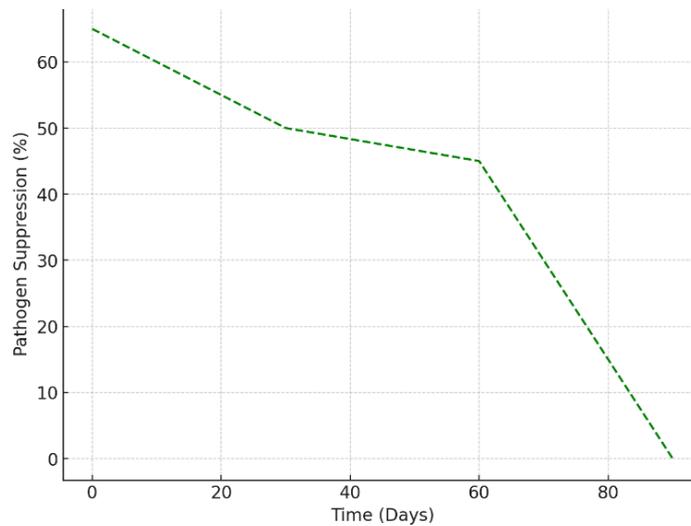**Figure 10:** Bar plot showing fruit number comparison across treatments.

Figure 11: Line graph comparing the effect of BCAs on pathogen suppression over time.
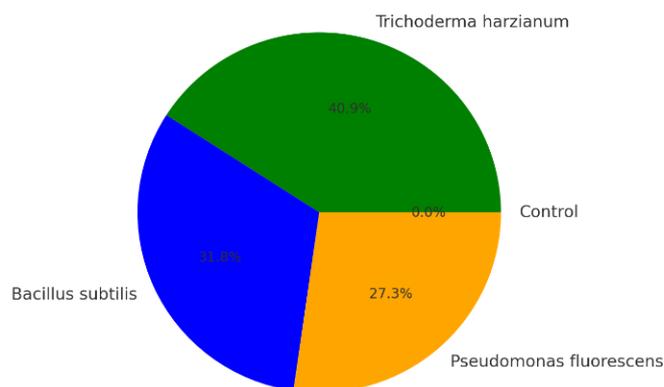
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Figure 12: Pie chart showing the distribution of microbial community types in the rhizosphere after BCA treatment.

DISCUSSION

This research revealed that application of Trichoderma harzianum and Bacillus subtilis and Pseudomonas fluorescens agents decreased root rot pathogen severity in tomatoes while simultaneously boosting plant growth and increasing yield. The biocontrol agent Trichoderma harzianum produced superior results by causing substantial root rot reduction and resulting in higher plant growth measurements and fruit quantities than both treatment groups and the control (Hernández). Research findings support recent studies which demonstrate Trichoderma species' antifungal effectiveness and their ability to effectively colonize plant roots and thus create protection against soilborne disease invasion. The plant growth-promoting rhizobacteria behavior of Bacillus subtilis and Pseudomonas fluorescens demonstrated powerful root rot control with enhanced plant health and increased yield outcomes (Shah). Research indicates that BCAs trigger systemic resistance because they activate defense enzymes like peroxidase while priming the plant to defend against pathogen attacks (Shude). The rise in beneficial soil microorganisms observed in the root's vicinity of plants receiving BCA applications demonstrates that these agents simultaneously fight pathogens and strengthen the environment for plant development while improving general soil health and nutrient access in the area (Al-Ani). In agricultural applications Bacillus displays its ability to create biocontrol-relevant secondary metabolites which protect both plant root microecology and plant health (Shen). The results from this study show BCA applications as sustainable substitutes for chemical fungicides in root rot disease management of tomato crops while remaining environmentally benign (Li B,). Research demonstrates the necessity of selecting appropriate BCAs according to their individual biological mechanisms and their ability to establish in soil environments and relate well with host plants for achieving effective disease control and promoting plant growth.

Research demonstrates that crustacean crustacean shell waste chitin represents an effective biostimulant for agricultural applications that boost plant development based on (Ngasotter). Chitin enhances plant developmental growth by improving nutrient absorption while simultaneously enhancing plant growth hormone functionality (Ngasotter). Laboratory studies indicate that chitin-based applications improve germination success rates during basil and chervil seed cultivation (Ngasotter). Recent research demonstrates that active growth-

promoting genes plus improved nutrient usage explain chitin's beneficial effects on plant growth (Ngasotter). Through biodegradation of chitin scientists develop valuable fertilizing chemicals containing ammonia (Ngasotter). The best use of chitin materials depends on correct dosage because too much chitin will inhibit plant growth (Ngasotter). Research demonstrates that plants grown with chitin nanoparticles exhibit enhanced nitrogen absorption capabilities while also demonstrating increased growth parameters (Ngasotter). Plant defenses work through chitin since this material activates immune responses according to scientific research (Ngasotter). The merge between chitosan and plant growth-promoting bacteria creates a potential biotechnology for sustainable agriculture through better plant health and growth performance with reduced environmental and health threats (Rojas). The scientific investigation of biodegradable fertilizer options led to the development of new-generation fertilizers that increase agricultural production through studies pursuing environmentally-friendly chemical fertilizer replacements (Das A,). Nanochitin manufactured by mechanical or chemical processes strengthens biopolymer films yet maintains fungal protection and bacterial defense while preserving emulsion stability (Zhan Z). Past research reveals nanochitin functions as an agricultural fertilizer to boost both plant growth and nutrient absorption potential (Ngasotter). The applications of nanochitin materials show improved mechanical strength together with barrier properties and resistance to thermal fluctuations and better solubility and moisture absorption functionality (Zhan Z,). Studies show that the natural polysaccharide chitosan extracted from chitin possesses anticancer properties together with antibacterial effects and antioxidant functionality (Teixeira).

CONCLUSION

Research findings show Trichoderma harzianum Bacillus subtilis Pseudomonas fluorescens effectively suppress root rot diseases in tomatoes but also function as healthy biological alternatives to chemical fungicides. Trichoderma harzianum demonstrated superior biocontrol performance by minimizing disease-causing microorganisms and maximizing root health alongside plant biomass development and production output. When BCAs are applied they trigger substantial growth in beneficial microbial populations which helps defeat root rot disease and enhances environmental soil conditions. Actual field testing verified laboratory results through superior measurements of plant height and leaf area development and fruit quantity and quantitative yield above the control treatment group. The research results illustrate that BCA implementation requires both proper processes and ecological understanding for achieving predictable results throughout diverse agricultural systems. Data from BCA applications directs researchers to study performance optimization and deployment obstacles for large-scale applications. The research results supply IPM programs with essential data to integrate BCA applications thus creating safer agricultural systems while reducing pesticide use. The combination of tomato farming with successful BCA-root rot control systems creates healthier ground environments and higher harvest yields that deliver dual advantages to agricultural producers and ecological systems.

REFERENCES

Coulibaly PJ d'Arc, Sawadogo J, Bambara YAI, Ouédraogo WBM, Legma JB, Compaoré E. Effect of Bio-Fertilizers on Tomato (Solanum Lycopersicum) Production and on Soil Physico-Chemical Properties in

Sudan Area of Burkina Faso. Current Agriculture Research Journal 2021;9:43.

Ma M, Taylor PWJ, Chen D, Vaghefi N, He J. Major Soilborne Pathogens of Field Processing Tomatoes and Management Strategies. Microorganisms 2023;11:263.

Zhou X, Wang J, Liu F, Liang J, Zhao P, Tsui CKM, et al. Cross-kingdom synthetic microbiota supports tomato suppression of Fusarium wilt disease. Nature Communications 2022;13.

Alleluya VK, Arias AA, Ribeiro B, Coninck BD, Helmus C, Delaplace P, et al. Bacillus lipopeptide-mediated biocontrol of peanut stem rot caused by Athelia rolfsii. Frontiers in Plant Science 2023;14. Lahlali R, Ezrari S, Radouane N, Kenfaoui J, Esmaeel Q, Hamss HE, et al. Biological Control of Plant Pathogens: A Global Perspective. Microorganisms 2022;10:596.

Tariq M, Khan A, Asif M, Khan F, Ansari T, Shariq M, et al. Biological control: a sustainable and practical approach for plant disease management. Acta Agriculturae Scandinavica Section B - Soil & Plant Science 2020;70:507.

Ngasotter S, Xavier KAM, Meitei MM, Waikhom D, Madhulika, Pathak J, et al. Crustacean shell waste derived chitin and chitin nanomaterials for application in agriculture, food, and health – A review. Carbohydrate Polymer Technologies and Applications 2023;6:100349.

Ayaz M, Li C, Ali Q, Zhao W, Chi Y, Shafiq M, et al. Bacterial and Fungal Biocontrol Agents for Plant Disease Protection: Journey from Lab to Field, Current Status, Challenges,

and Global Perspectives. Molecules 2023;28:6735.

Mukhopadhyay R, Kumar D. Trichoderma: a beneficial antifungal agent and insights into its mechanism of biocontrol potential. Egyptian Journal of Biological Pest Control 2020;30. Dadrasnia A, Usman MM, Rahmat O, Ismail S, Abdullah R. Potential use of Bacillus genus to control of bananas diseases: Approaches toward high yield production and sustainable management. Journal of King Saud University - Science 2020;32:2336.

Islam MdM, Zafor MdA, Chowdhury MdEK, Islam A, Hasan MdM. Biological Control of Damping off and Foot Rot of Chilli Using an Indigenous Trichoderma harzianum. East African Scholars Journal of Agriculture and Life Sciences 2021;4:101.

Tyśkiewicz R, Nowak A, Ozimek E, Jaroszuk-Ściseł J. Trichoderma: The Current Status of Its Application in Agriculture for the Biocontrol of Fungal Phytopathogens and Stimulation of Plant Growth. International Journal of Molecular Sciences 2022;23:2329.

Kong W, Ni H, Wang W, Wu X. Antifungal effects of volatile organic compounds produced by Trichoderma koningiopsis T2 against Verticillium dahliae. Frontiers in Microbiology 2022;13. Zhou Y, Yang L, Wang J, Guo L, Huang J. Synergistic Effect between Trichoderma virens and Bacillus velezensis on the Control of Tomato Bacterial Wilt Disease. Horticulturae 2021;7:439. Pandit MA, Kumar J, Gulati S, Bhandari N,

Mehta P, Katyal R, et al. Major Biological Control Strategies for Plant Pathogens. Pathogens 2022;11:273.

Lalhruaitluangi C, Ao NT, Daiho L, Banik S, Ao MA, Kanaujia SP. In-vitro Evaluation of Antagonistic Activity of Native Trichoderma spp. and Pseudomonas fluorescens Isolates against Alternaria solani Causing Early Blight of Tomato. International Journal of Plant & Soil Science 2022:120.

Poveda J. Trichoderma as biocontrol agent against pests: New uses for a mycoparasite. Biological Control 2021;159:104634.

Andrade LA de, Santos CHB, Frezarin ET, Sales LR, Rigobelo EC. Plant Growth-Promoting Rhizobacteria for Sustainable Agricultural Production. Microorganisms 2023;11:1088. El–Mageed TAA, El-Mageed SAA, El-Saadony MT, Abdelaziz S, Abdou NM. Plant Growth-Promoting Rhizobacteria Improve Growth, Morph-Physiological Responses, Water Productivity, and Yield of Rice Plants Under Full and Deficit Drip Irrigation. Rice 2022;15.

Niu B, Wang W, Yuan Z, Sederoff RR, Sederoff H, Chiang VL, et al. Microbial Interactions Within Multiple-Strain Biological Control Agents Impact Soil-Borne Plant Disease. Frontiers in Microbiology 2020;11.

Hernández-Castillo FD, Castillo-Reyes F, Tucuch-Pérez MA, Arredondo-Valdés R. Biological Efficacy of Trichoderma spp. and Bacillus spp. in the Management of Plant Diseases. Organic Agriculture, Springer Science+Business Media; 2020.

Shah A, Nazari M, Antar M, Msimbira LA, Naamala J, Lyu D, et al. PGPR in Agriculture: A Sustainable Approach to Increasing Climate Change Resilience. Frontiers in Sustainable Food Systems 2021;5.

Shude SPN, Mbili NC, Yobo KS. Combination of yeast antagonists and Acibenzolar-S-Methyl reduced the severity of Fusarium head blight of wheat incited by Fusarium graminearum sensu stricto. Plant Science Today 2021.

Al-Ani LKT, Aguilar-Marcelino L, Fiorotti J, Sharma V, Sarker MS, Furtado EL, et al. Biological Control Agents and Their Importance for the Plant Health. Elsevier eBooks, Elsevier BV; 2020, p. 13. 7.00002-6.

Shen Y, Yang H, Lin Z, Chu L, Pan X, Wang Y, et al. Screening of compound-formulated Bacillus and its effect on plant growth promotion. Frontiers in Plant Science 2023;14.

Li B, He X, Guo S, Li D, Wang Y, Meng X, et al. Characterization of Bacillus amyloliquefaciens BA-4 and its biocontrol potential against Fusarium-related apple replant disease. Frontiers in Plant Science 2024;15.

Rojas-Pirela M, Carillo P, Velásquez CL, Romanazzi G. Effects of chitosan on plant growth under stress conditions: similarities with plant growth promoting bacteria. Frontiers in Plant Science 2024;15.

Das A, Ghosh S, Pramanik N. Chitosan biopolymer and its composites: Processing, properties and applications- A comprehensive review. Hybrid Advances 2024;6:100265.

Zhan Z, Feng Y, Zhao J, Qiao M, Jin Q. Valorization of Seafood Waste for Food Packaging Development. Foods 2024;13:2122.

Teixeira-Costa BE, Andrade CT. Chitosan as a Valuable Biomolecule from Seafood Industry Waste in the Design of Green Food Packaging. Biomolecules 2021;11:1599.