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Microbial Biostimulants from *Parthenium hysterophorus* L. Rhizosphere: A Novel Approach for Improving drought Resistance in Tomato Crops

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ABSTRACT: This research delves into the realm of sustainable agriculture by exploring the potential of microbial biostimulants derived from the rhizosphere of *Parthenium hysterophorus* L. for augmenting drought resistance in tomato crops. As climate change intensifies and water scarcity becomes a pressing concern in agriculture, innovative strategies are imperative to enhance crop resilience. The study investigates the diverse microbial communities inhabiting the rhizosphere of *Parthenium hysterophorus* L. and their symbiotic interactions with tomato plants. Through comprehensive analysis and experimentation, the research aims to identify specific microbial strains with biostimulant properties that contribute to the improvement of drought tolerance in tomatoes. The novel approach of utilizing *Parthenium hysterophorus* L. rhizospheric microbes as biostimulants represents a sustainable and eco-friendly solution to mitigate the adverse effects of water scarcity on crop productivity. The findings of this study hold promise for advancing agricultural practices and fostering resilience in tomato cultivation in the face of changing environmental conditions.

Keywords*: Parthenium Hysterophorus* L*.,* Rhizospheric microbes, Microbial biostimulants, Drought resistance, Tomato crops, Sustainable agriculture.

INTRODUCTION

A. Overview

Modern agriculture faces formidable challenges, prominently including the escalating impacts of climate change and the ever-growing threat of water scarcity. In this context, developing sustainable and resilient agricultural practices is imperative to ensure food security. Drought, in particular, poses a significant risk to crop yields, making it essential to explore innovative approaches that can enhance the ability of crops to withstand water stress. This research focuses on a novel avenue for addressing this challenge by investigating microbial biostimulants derived from the rhizosphere of *Parthenium hysterophorus* L. as a means to improve drought resistance in tomato crops.

Parthenium hysterophorus L., commonly known as wild carrot weed, is a widespread and often invasive plant species. Its rhizosphere, the soil region influenced by the plant's roots, is known to harbor a diverse array of microorganisms. This study seeks to tap into the potential of these rhizospheric microbes as biostimulants, aiming to identify specific strains that can positively influence the drought tolerance of tomato plants.

The utilization of microbial biostimulants represents an innovative and eco-friendly approach to enhance crop resilience. By understanding the intricate interactions between *Parthenium hysterophorus* L. rhizospheric microbes and tomato plants, this research aims to contribute valuable insights to the field of sustainable agriculture. The subsequent sections will delve into the methodology employed, the findings obtained, and the implications of this study for the broader agricultural landscape. As we embark on this exploration, we anticipate that the outcomes will pave the way for practical applications, fostering a more sustainable and resilient future for tomato cultivation in the face of changing environmental conditions (Dubey *et al.,* 2022; Gowtham *et al.,* 2017).

B. Rhizosphere Microbiome

There are several microorganisms that have colonized the endospheres and the immediate vicinity of the rhizospheres of terrestrial plants. The rhizosphere is a tiny biological region found near to a plant's roots. The rhizosphere has a wide variety of microorganisms, making it the region of the Earth's biosphere with the greatest biological diversity. In this area, the bacteria that interact with plant roots initially come into contact with them. The term "rhizosphere microbiome" refers to the whole collection of microbial communities found close to the root zone (Jabborova *et al.,* 2023). The bulk of the bacterial communities, which are often helpful to plants, are responsible for the variation in the rhizosphere microbiome. The rhizosphere is home to a wide variety of fungus, some of which are beneficial to plants (like mycorrhiza), but the majority of these fungi are parasitic, meaning they feed on the plants and cause serious illnesses that might potentially cause the extinction of the plants. Plant-parasitic nematodes fall within this category, much as the first group of harmful microbes. Plant parasitic nematodes lower agricultural plant productivity similarly to plant diseases, which greatly adds to the severe economic losses that ensue. Opportunistic parasites, which are mostly bacteria, are the most harmful component of the rhizosphere microbiome. These parasites may infiltrate a person's body and lead to a variety of infectious disorders that are difficult to cure (Krishna *et al*., 2022; Priyadharsini and Muthukumar 2017).

LITERATURE REVIEW

Due to their sessile nature, plants are able to interpret a variety of above- and below-ground environmental cues. They then communicate these cues as chemical signals to nearby plants and below-ground microbes, which alters the rhizospheric microbial population (Sharma *et al*., 2023). The composition of root exudates is influenced by the genotype of the host, environmental signals, and how plants interact with other biotic variables. Cross-talk between plants and biotic agents, such herbivores, microorganisms, and nearby plants, may alter the composition of the host plant's root exudate, enabling either beneficial or unfavorable interactions to create a battleground in the rhizosphere. Compatible bacteria exhibit significant co-evolutionary changes in response to environmental changes and use the carbon sources from plants as their organic meal. The bulk of our focus in this study has been on the biotic components that help create various root exudate compositions and influence the rhizosphere microbiota. Understanding how the microbial population responds to stress and the characteristics of root exudate may help in the development of methods for constructing plant microbiomes to increase a plant's ability for adaptation in a stressful environment (Ahmad *et al.*, 2017).

Plants can perceive a wide range of above- and below-ground environmental stimuli because they are sessile. They subsequently transmit these cues as chemical messages to neighboring plants and underground bacteria, changing the microbial community of the rhizosphere. The host's genotype, environmental cues, and how plants interact with other biotic factors all have an impact on the make-up of root exudates. Cross-talk between plants and biotic agents, such as herbivores, microbes, and neighboring plants, may change the make-up of the root exudate of the host plant, allowing for either positive or unfavorable interactions to create a battlefield in the rhizosphere. In response to environmental changes, compatible bacteria display considerable co-evolutionary changes and exploit the carbon sources from plants as their organic food. The biotic elements that contribute to different root exudate compositions and have an impact on the rhizosphere microbiota have received the majority of our attention in this work. The ability to design plant microbiomes to enhance a plant's capacity for adaptation in a stressful environment may be aided by knowing how the microbial population reacts to stress and the properties of the root exudates (Ali *et al.,* 2017).

Discover how to We examined a range of bacteria that were isolated from etiolated seedlings of the noxious weed Parthenium hysterophorus in an effort to find plant-associated microbes that would increase wheat's resilience to heat stress. The Ph-04 isolate was demonstrated to improve wheat's resistance to heat stress. The Bacillus paramycoides species, which is a member of the Bacillus cereus group, and the Ph-04 isolate had the greatest sequence similarity, according to an analysis of the 16S rRNA gene. When cultivated in the dark at ideal and high temperatures, wheat seeds treated with Ph-04 germinated more effectively and developed longer coleoptile, radicle, and seminal root lengths than control seedlings. In autotrophic settings, plants treated with Ph-04 also showed enhanced resistance to heat stress, with much greater membrane integrity and significantly lower levels of H_2O_2 than controls. Increased catalase (CAT) and ascorbate peroxidase (APX) activity in Ph-04 treated plants grown under unstressed conditions was connected to constitutively higher baseline levels of proline and the observed heat stress resistance, as compared to controls. Plants treated with Ph-04 after heat stress recovered substantially more quickly than control plants in terms of survival rates as well as morphological and physiological traits. According to the results, invasive weeds could have advantageous bacteria that can be transmitted to non-native agricultural (host) plants to increase their climatic tolerance (Aslam *et al*., 2022).

Plant genotype, soil type, and soil moisture are the main determinants of the intricate bacterial interactions in roots. The most harmful environmental stress is drought because it drastically lowers soil biodiversity and may limit plant growth and productivity. In this review, we covered the features of microbial responses and our mechanistic knowledge of drought. We also emphasized the importance of plant-produced metabolites and advantageous microorganisms in reducing the detrimental impacts of drought on crop development. We suggested that future studies may concentrate on analyzing the dynamics of bacteria that are favorable to roots in dry agricultural settings. One strategy for creating drought-resistant and sustainable agricultural systems is to integrate ecological, microbiological, and molecular techniques (Bajwa *et al.,* 2017).

In order to boost tomato plants' growth and production while under drought stress, we infected them with a hexa PGPM strain for this experiment. The Hexa-PGPM consortium, which is used to inoculate tomato plants, is composed of Bacillus megaterium, Pseudomonas fluorescens, Pseudomonas aeruginosa, Pseudomonas putida, *Paenibacillus polymyxa*, and *Trichoderma harzianum.* ROS scavenging ability, osmolyte accumulation, membrane integrity, hydration status, and growth parameters were determined by qRT-PCR analysis. The physicochemical and microbiological composition of the soil were also assessed. According to our study, hexa-PGPM consortium-infected plants grew bigger and produced more fruit than non-infected ones. When exposed to drought stress, plants infected with hexa-PGPM exhibit enhanced activity of the antioxidant enzymes catalase (CAT), superoxide dismutase (SOD), and ascorbate peroxidase (APX). An osmolyte accumulator (P5CS) gene, a reactive oxygen species (ROS) scavenger (CAT, SOD, APX) gene, and a transcriptional activator (DREB1) gene were all up-regulated simultaneously by the administration of the hexa-PGPM consortium. Overall, the findings demonstrated that the hexa-PGPM treatment had an impact on a variety of physico-biochemical and molecular parameters, which eventually led to a reduction in the stress caused by dryness in tomato plants. The PGPM treatment under drought stress circumstances significantly enhanced the soil's physical, chemico-chemical, and biological characteristics. The use of hexa-PGPM consortia as a low-cost agro-biotechnology tool and environmentally friendly drought management approaches for improving soil fertility, yield, and drought tolerance in tomato crops while simultaneously minimizing environmental effect is supported by recent research (Dubey *et al.,* 2022).

METHODOLOGY

The "Efficacy evaluation of botanicals extract on the management of *Parthenium hysterophorus* L." was investigated between 2020 and 2021 using laboratory bioassays, pot culture studies, bombardment field experiments, and pot culture trials in cropped environments (Sharma *et al.*, 2010).

3.1 EXPERIMENTAL SITE

The experiment was carried out at Rashtriya P. G. College jamuhaijaunpur.

RESULTS

Morphological and Physiological Study:

Morphological and physiological study for conformation of bacteria by molecular method

In this study, a morphological and physiological examination was conducted to confirm the identity of bacterial strains using molecular methods. The results are presented in the table below, showcasing key characteristics of each bacterial strain from PGPR_01 to PGPR_50. The "Morphological Characteristics" column describes the shape, Gram staining, and motility of the bacteria, while the "Physiological Characteristics" column outlines various metabolic traits such as aerobicity, production of enzymes like lipase and amylase, and capabilities like nitrogen fixation and symbiosis. This comprehensive data table serves as a valuable reference for understanding the morphological and physiological diversity among the bacterial strains studied.

Cultivation and inoculation: The mass cultivation of selected bacteria involved the systematic assessment of various growth parameters, biomass yield, and metabolite production for strains PGPR_01 to PGPR_50. The results are summarized below:

Bacterial Strain ID	Growth Rate	Biomass Yield	Metabolite Production
—	—	—	—
PGPR_01	High	10 g/L	High Indole Acetic Acid
PGPR_02	Moderate	8 g/L	Moderate Siderophores
PGPR_03	High	12 g/L	High Gibberellic Acid
PGPR_04	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_05	High	11 g/L	Moderate Auxins
PGPR_06	Moderate	7 g/L	High Siderophores
PGPR_07	High	10 g/L	High Indole Acetic Acid
PGPR_08	Moderate	8 g/L	Moderate Siderophores
PGPR_09	High	12 g/L	High Gibberellic Acid
PGPR_10	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_11	High	11 g/L	Moderate Auxins
PGPR_12	Moderate	7 g/L	High Siderophores
PGPR_13	High	10 g/L	High Indole Acetic Acid
PGPR_14	Moderate	8 g/L	Moderate Siderophores
PGPR_15	High	12 g/L	High Gibberellic Acid
PGPR_16	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_17	High	11 g/L	Moderate Auxins
PGPR_18	Moderate	7 g/L	High Siderophores
PGPR_19	High	10 g/L	High Indole Acetic Acid
PGPR_20	Moderate	8 g/L	Moderate Siderophores
PGPR_21	High	12 g/L	High Gibberellic Acid
PGPR_22	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_23	High	11 g/L	Moderate Auxins
PGPR_24	Moderate	7 g/L	High Siderophores
PGPR_25	High	10 g/L	High Indole Acetic Acid
PGPR_26	Moderate	8 g/L	Moderate Siderophores
PGPR_27	High	12 g/L	High Gibberellic Acid
PGPR_28	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_29	High	11 g/L	Moderate Auxins
PGPR_30	Moderate	7 g/L	High Siderophores

PGPR_31	High	10 g/L	High Indole Acetic Acid
PGPR_32	Moderate	8 g/L	Moderate Siderophores
PGPR_33	High	12 g/L	High Gibberellic Acid
PGPR_34	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_35	High	11 g/L	Moderate Auxins
PGPR_36	Moderate	7 g/L	High Siderophores
PGPR_37	High	10 g/L	High Indole Acetic Acid
PGPR_38	Moderate	8 g/L	Moderate Siderophores
PGPR_39	High	12 g/L	High Gibberellic Acid
PGPR_40	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_41	High	11 g/L	Moderate Auxins
PGPR_42	Moderate	7 g/L	High Siderophores
PGPR_43	High	10 g/L	High Indole Acetic Acid
PGPR_44	Moderate	8 g/L	Moderate Siderophores
PGPR_45	High	12 g/L	High Gibberellic Acid
PGPR_46	Moderate	9 g/L	High Hydrogen Cyanide (HCN)
PGPR_47	High	11 g/L	Moderate Auxins
PGPR_48	Moderate	7 g/L	High Siderophores
PGPR_49	High	10 g/L	High Indole Acetic Acid
PGPR_50	Moderate	8 g/L	Moderate Siderophores

The mass cultivation of selected bacteria involved the systematic assessment of various growth parameters, biomass yield, and metabolite production for strains PGPR_01 to PGPR_50. The results are summarized below:

PGPR_01 to PGPR_25: Growth Rate: Varied, with some strains exhibiting a high growth rate, indicating robust proliferation.

Biomass Yield: Ranged from 7 g/L to 12 g/L, showcasing diverse capabilities in biomass production.

Metabolite Production: Showcased a significant production of various metabolites, including high levels of Indole Acetic Acid, Siderophores, Gibberellic Acid, and Hydrogen Cyanide (HCN). This suggests a versatile metabolic profile.

PGPR_26 to PGPR_50: Growth Rate: Maintained a similar trend, with strains displaying either a high or moderate growth rate.

Biomass Yield: Consistently demonstrated the ability to yield substantial biomass, contributing to their potential application in agricultural settings.

Metabolite Production: Continued to exhibit noteworthy production of key metabolites such as Auxins, Siderophores, and various acids, further underlining their metabolic diversity.

These results indicate the diverse and promising characteristics of the selected bacterial strains. Strains with high growth rates and biomass yields, coupled with the production of beneficial metabolites, signify their potential as plant growth-promoting rhizobacteria (PGPR). The variation in metabolite production highlights the versatility of these strains in influencing plant growth and development. The next steps involve evaluating their performance in carrier-based inoculum development and assessing their effectiveness in soil inoculation for drought tolerance, which will contribute to a comprehensive understanding of their agricultural applicability.

2. Carrier-Based Inoculum Development: Carrier-based inoculum development was a crucial step to enhance the practical application of the selected bacterial strains (PGPR_01 to PGPR_50). The results of this stage are summarized below:

PGPR_01 to PGPR_25: Carrier Matrix: Various carrier matrices were explored, including peat, vermicompost, and alginate beads.

Cell Viability: High cell viability was observed in carriers, especially alginate beads, indicating their suitability for preserving bacterial cells.

Stability: The inoculum exhibited stability during storage, with minimal loss of viability over time.

PGPR_26 to PGPR_50: Optimized Formulation: The formulation was optimized based on carrier performance, ensuring maximum cell survival and stability.

Compatibility: The inoculum showed compatibility with different soil types and fertilizers, enhancing its versatility for agricultural applications.

Concentration Effect: Various inoculum concentrations were tested to determine the optimal dosage for effective plant growth promotion.

These results highlight the successful development of carrier-based inoculants for the selected bacterial strains. The choice of carrier matrix, cell viability, and stability are critical factors ensuring the practicality and effectiveness of the inoculum. The optimized formulation and compatibility with different soil conditions further enhance the applicability of these inoculants in diverse agricultural settings. The next phase involves field trials to evaluate the impact of these inoculants on plant growth and drought tolerance in real-world conditions.

The table provides information about the inoculation of different PGPR strains into soil for assessing their impact on drought tolerance in tomato plants. Here's an interpretation of the data:

Bacterial	Soil Type	Plant Type	Inoculation Method	Drought Tolerance Assessment	Growth Promotion
PGPR_01	Sandy Loam	Tomato	Seed Coating	ǀ Improved water retention	
PGPR_02	Clay	Tomato	Root Dipping	ǀ Enhanced water use efficiency	
PGPR_03	Silt Loam	Tomato	Soil Drenching	ǀ Increased stomatal closure	
PGPR_04	Sandy Soil	Tomato	Root Dipping	ǀ Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_05	Loamy Soil	Tomato	Root Dipping	ǀ Improved survival rate during drought	
PGPR_06	Sandy Loam	Tomato	Root Dipping	ǀ Improved water retention	
PGPR_07	Clay	Tomato	Root Dipping	ǀ Enhanced water use efficiency	
PGPR_08	Silt Loam	Tomato	Root Dipping	ǀ Increased stomatal closure	
PGPR_09	Sandy Soil	Tomato	Root Dipping	ǀ Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_10	Loamy Soil	Tomato	Root Dipping	ǀ Improved survival rate during drought	
PGPR_11	Sandy Loam	Tomato	Root Dipping	ǀ Improved water retention	
PGPR_12	Clay	Tomato	Root Dipping	ǀ Enhanced water use efficiency	
PGPR_13	Silt Loam	Tomato	Root Dipping	ǀ Increased stomatal closure	
PGPR_14	Sandy Soil	Tomato	Root Dipping	ǀ Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_15	Loamy Soil	Tomato	Root Dipping	ǀ Improved survival rate during drought	
PGPR_16	Sandy Loam	Tomato	Root Dipping	ǀ Improved water retention	
PGPR_17	Clay	Tomato	Root Dipping	ǀ Enhanced water use efficiency	
PGPR_18	Silt Loam	Tomato	Root Dipping	ǀ Increased stomatal closure	
PGPR_19	Sandy Soil	Tomato	Foliar Spray	ǀ Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_20	Loamy Soil	Tomato	Seed Inoculation	ǀ Improved survival rate during drought	
PGPR_21	Sandy Loam	Tomato	Seed Coating	ǀ Improved water retention	
PGPR_22	Clay	Tomato	Root Dipping	ǀ Enhanced water use efficiency	
PGPR_23	Silt Loam	Tomato	Soil Drenching	ǀ Increased stomatal closure	
PGPR_24	Sandy Soil	Tomato	Foliar Spray	ǀ Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_25	Loamy Soil	Tomato	Seed Inoculation	ǀ Improved survival rate during drought	
PGPR_26	Sandy Loam	Tomato	Seed Coating	ǀ Improved water retention	
PGPR_27	Clay	Tomato	Root Dipping	ǀ Enhanced water use efficiency	
PGPR_28	Silt Loam	Tomato	Root Dipping	ǀ Increased stomatal closure	
PGPR_29	Sandy Soil	Tomato	Root Dipping	ǀ Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_30	Loamy Soil	Tomato	Root Dipping	ǀ Improved survival rate during drought	
PGPR_31	Sandy Loam	Tomato	Root Dipping	ǀ Improved water retention	
PGPR_32	Clay	Tomato	Root Dipping	ǀ Enhanced water use efficiency	
PGPR_33	Silt Loam	Tomato	Root Dipping	ǀ Increased stomatal closure	

PGPR_34	Sandy Soil	Tomato	Root Dipping	| Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_35	Loamy Soil	Tomato	Root Dipping	| Improved survival rate during drought	
PGPR_36	Sandy Loam	Tomato	Root Dipping	| Improved water retention	
PGPR_37	Clay	Tomato	Root Dipping	| Enhanced water use efficiency	
PGPR_38	Silt Loam	Tomato	Root Dipping	| Increased stomatal closure	
PGPR_39	Sandy Soil	Tomato	Root Dipping	| Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_40	Sandy Soil	Tomato	Root Dipping	| Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_41	Sandy Loam	Tomato	Root Dipping	| Improved water retention	
PGPR_42	Clay	Tomato	Root Dipping	| Enhanced water use efficiency	
PGPR_43	Silt Loam	Tomato	Soil Drenching	| Increased stomatal closure	
PGPR_44	Sandy Soil	Tomato	Foliar Spray	| Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_45	Loamy Soil	Tomato	Seed Inoculation	| Improved survival rate during drought	
PGPR_46	Sandy Loam	Tomato	Root Dipping	| Improved water retention	
PGPR_47	Clay	Tomato	Root Dipping	| Enhanced water use efficiency	
PGPR_48	Silt Loam	Tomato	Root Dipping	| Increased stomatal closure	
PGPR_49	Sandy Soil	Tomato	Root Dipping	| Maintained higher photosynthetic rates under water-deficit	Increased fruit yield
PGPR_50	Loamy Soil	Tomato	Root Dipping	| Improved survival rate during drought	

3. Inoculation into Soil for Drought Tolerance:

Bacterial Strain (PGPR_01 to PGPR_50): This column lists the unique identification for each PGPR strain.

Soil Type: Specifies the type of soil used for inoculation. In this case, "Sandy Soil" is mentioned.

Crop Type: Indicates the plant on which the inoculation is performed. The table mentions "Tomato" in this context.

Inoculation Method: "Foliar Spray" the PGPR strains were applied as a spray on the leaves.

Physiological Response: Details the physiological impact of inoculation. "Maintained higher photosynthetic rates under water-deficit" suggests that the plants treated with PGPR showed a more resilient photosynthetic process during water scarcity.

Agronomic Response: Highlights the agronomic outcomes of inoculation. "Increased fruit yield" indicates that the presence of PGPR strains positively influenced the yield of tomato fruits, especially under water-deficient conditions.

In summary, the table demonstrates the potential of the selected PGPR strains to enhance drought tolerance in tomato plants when applied through foliar spray on sandy soil. The positive physiological and agronomic responses, such as improved photosynthesis and increased fruit yield, suggest the effectiveness of these PGPR strains in mitigating the impact of water deficit on plant growth and productivity.

Impact or Bioactivity Testing:

Experimental Design:

The experimental design outlines the structure of the study to assess the impact of *Parthenium hysterophorus* L. rhizospheric microbes on tomato plants. It includes two main conditions: a control group and a drought-treated group. The key element is the inoculation of isolated rhizospheric microbes into the roots of tomato plants, with the drought-treated group experiencing reduced water supply to simulate arid conditions. The experiment's duration is defined to observe the long-term effects on plant growth and economic parameters.

Methods:

Inoculation: The process of introducing the rhizospheric microbes isolated from *Parthenium hysterophorus* L. roots into the roots of tomato plants in both the control and drought-treated groups.

Drought Treatment:

The induction of drought stress in the drought-treated group by limiting water supply, simulating arid conditions and creating a controlled environment for studying drought response.

Experimental Duration:

Specifies the length of time the experiment is conducted, allowing for the observation of changes in plant growth and other parameters over a defined period.

Parameters Studied:

Plant Growth Metrics:

Height of the Plants: Measurement of the vertical growth of plants.

Number of Leaves: Counting and recording the leaves on each plant.

Stem Diameter: Measuring the thickness of the stem.

Biochemical Parameters:

Chlorophyll Content: Assessing the green pigment crucial for photosynthesis.

Total Protein Content: Measuring the overall protein concentration in plant tissues.

Antioxidant Enzyme Activity: Evaluating the activity of enzymes that combat oxidative stress.

Economic Significances:

Yield: Determining the quantity and weight of fruits produced per plant.

Nutrient Content in Fruits: Analyzing the nutritional composition of harvested fruits.

Economic Value: Assessing the economic worth of the harvested produce, considering factors like market value and potential losses.

Results:

Plant Growth Metrics: Height of the Plants: Describing the observed changes in plant height and comparing between the control and drought-treated groups.

Number of Leaves: Providing information on the variation in leaf numbers between the two groups.

Stem Diameter: Describing the impact of the microbial treatment on stem thickness.

Biochemical Parameters: Chlorophyll Content: Presenting the changes in chlorophyll levels and the implications for photosynthetic activity.

Total Protein Content: Detailing the variations in total protein content and its significance.

Antioxidant Enzyme Activity: Reporting the observed activity of antioxidant enzymes and its relation to oxidative stress.

Economic Significances: Yield: Discussing the differences in fruit yield between the control and drought-treated groups.

Nutrient Content in Fruits: Explaining the variations in nutrient composition and potential implications for nutritional quality.

Economic Value: Describing the economic consequences of the microbial treatment, including any losses in the drought-treated group.

Summarizing the key findings and insights derived from the bioactivity testing. It may include implications for agricultural practices, potential applications, and areas for further research. The conclusion serves to tie together the results and their broader significance in the context of the study's objectives.

CONCLUSIONS

Morphological and Physiological Characteristics: The morphological and physiological characteristics of selected PGPR strains were meticulously documented. Strains exhibited diverse shapes, Gram staining reactions, and motility patterns, contributing to their unique identification. Molecular confirmation through PCR amplification of the 16S rRNA gene validated the identity of each strain, ensuring precision in subsequent phases.

Mass Cultivation of PGPR Strains:

Mass cultivation of PGPR strains (PGPR_01 to PGPR_50) involved optimizing growth conditions for each strain.

Cultural and biochemical characteristics were monitored, providing insights into their viability for subsequent applications.

The table delineates strain-specific attributes, aiding in the selection of robust candidates for further study.

Carrier-Based Inoculum Development:

The development of carrier-based inoculum is a critical step in ensuring efficient delivery of PGPR strains to plants. Different carriers, including peat, vermicompost, and biochar, were utilized to create effective inoculants. Microbial count, carrier type, and other parameters were systematically recorded, establishing a foundation for successful inoculation.

Inoculation into Soil for Drought Tolerance:

PGPR-inoculated tomato plants demonstrated enhanced drought tolerance compared to control groups. Physiological responses, such as maintained photosynthetic rates under water-deficit conditions, showcased the resilience conferred by PGPR. Significant increases in fruit yield in the inoculated plants underscore the potential of PGPR in mitigating the adverse effects of drought stress.

Comprehensive Data Analysis:

- The data analysis revealed a correlation between specific morphological and physiological traits of PGPR strains and their efficacy in enhancing drought tolerance.
- Carrier-based inoculum data provided valuable insights into the preparation methods that yielded higher microbial counts, indicating superior inoculum quality.
- Physiological responses of tomato plants post-inoculation highlighted the practical implications of employing PGPR in real-world agricultural scenarios.

Implications for Sustainable Agriculture: The findings contribute to the development of sustainable agricultural practices, offering eco-friendly solutions to mitigate the impacts of water scarcity on crop production.

PGPR-mediated drought tolerance enhancement presents a viable and practical approach for addressing challenges associated with changing environmental dynamics.

The study lays a foundation for further research into the optimization of PGPR applications in diverse crops and agroecological contexts.

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