Plant Archives Vol. 26, No. 2, 2026 pp. 2023-2034 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.2.278

SYNERGISTIC EFFECT OF RICE BRAN AND MULTIFUNCTIONAL PLANT GROWTH-PROMOTING RHIZOBACTERIA ON GROWTH ENHANCEMENT OF GREENGRAM (*Vigna radiata* L.)

Lizy Mol Sajeevan, Rajasanthiya Rajapandiyan, Rajashree Ranganathan, Harthik Subhash and Oviya Govindaraj*

Department of Agricultural Microbiology, Adhiyamaan College of Agriculture and Research, Athimugam, Krishnagiri, Tamil Nadu, India.

*Corresponding author E-mail : goviya96@gmail.com

(Date of Receiving-04-07-2026; Date of Revision-12-09-2026; Date of Acceptance-25-09-2026)

ABSTRACT

Greengram (*Vigna radiata* L.) is a significant pulse crop, but its production is limited by deteriorating soil fertility and an over-reliance on artificial fertilisers. The current study explored the synergistic effect of rice bran and multifunctional plant growth-promoting rhizobacteria (PGPR) as a sustainable nutrient management technique for greengram growth. Rice bran biomass composition was determined and PGPR isolated from the greengram rhizosphere were tested for plant growth-promoting features such as indole-3-acetic acid (IAA) synthesis, phosphate and zinc solubilisation, biofilm formation and antagonistic activity. Selected isolates were then evaluated utilising seed germination and greenhouse pot culture experiments with various PGPR combinations incorporating rice bran. Rice bran was found to be high in structural carbohydrates, with 54% cellulose, 19% hemicellulose and 12% lignin, indicating its potential as an organic substrate for microbial development. Ten PGPR isolates, including *Rhizobium*, *Azotobacter*, phosphate-solubilizing bacteria (PSB), and zinc-solubilizing bacteria (ZSB), showed significant heterogeneity in plant growth-promoting properties. PSB2 produced the most IAA, although RZ7 indicated higher biofilm-forming potential. Combined PGPR inoculation considerably increased seed germination, with the *Azotobacter* + PSB treatment yielding the greatest germination rate (83%). In the pot culture experiment, PGPR consortia with rice bran increased shoot length, root length, plant dry weight chlorophyll content and total plant development when compared to individual inoculations, rice bran alone and the untreated control. *Rhizobium*, *Azotobacter*, and PSB combined with rice bran produced the best overall performance. The study shows that combining rice bran with multifunctional PGPR improves nutrient availability, rhizosphere colonisation, and plant growth, resulting in an effective and environmentally sustainable biofertilizer strategy for increasing greengram productivity while decreasing reliance on chemical fertilisers.

Key words : Green gram, PGPR, Rice bran, Bioinoculant, Sustainable Agriculture.

Introduction

Green gram (*Vigna radiata* L.) is one of the most significant pulse crops grown in Asia because to its high nutritional content, short growing season, and capacity to improve soil fertility through biological nitrogen fixation (Pratap *et al*., 2021). It provides an affordable supply of protein, carbs, minerals and vitamins, making it a significant part of food and nutritional security. Despite its importance, greengram production is below potential due to low soil fertility, nutrient inadequacies, declining soil organic matter and an increased reliance on chemical fertilisers (FAO, 2022). Long-term use of inorganic fertilisers has caused degradation of soil health, nutritional imbalance, diminished microbial diversity, and environmental pollution. As a result, long-term nutrient management solutions that increase crop output while maintaining soil quality are critically needed.

Plant growth-promoting rhizobacteria (PGPR) are a varied group of beneficial soil bacteria that colonise the rhizosphere and stimulate plant growth via various

processes (Lugtenberg and Kamilova, 2009). These bacteria promote plant development directly through biological nitrogen fixation, phosphate and zinc solubilisation, phytohormone production, siderophore synthesis, and ACC deaminase activity, while indirectly protecting plants from pathogens via antibiotics, lytic enzymes, biofilm formation and induced systemic resistance (Backer *et al*., 2018; Grover *et al*., 2021). Multifunctional PGPR with numerous growth-promoting properties have sparked widespread interest as eco-friendly alternatives to chemical fertilisers. Agricultural waste is a rich renewable resource that can be transformed into organic additives for sustainable agriculture. Rice bran, a key byproduct of rice milling, contains carbohydrates, fatty acids, proteins, lipids, minerals, and bioactive substances (Chojnacka *et al*., 2020). Rice bran incorporation into soil increases organic carbon, nutrition availability, moisture retention, and microbial activity while minimising agricultural waste disposal problems. Recent research has demonstrated that agricultural waste-based bio-organic fertilisers improve soil fertility, nutrient cycling, and microbial diversity (Naher *et al*., 2021). Riddech *et al*. (2025) reported that bio-organic fertilisers made from agricultural waste combined with PGPR greatly increased plant growth, nutrient availability and microbial diversity while lowering reliance on chemical fertilisers.

The synergistic combination between PGPR with organic substrates creates an optimal environment for microbial growth and activity. Organic materials provide carbon and nutrients for microbial growth, whereas PGPR promotes breakdown, mineralisation, and nutrient solubilisation, boosting nutrient availability to plants (Bibi *et al*., 2022). Such synergistic solutions improve seed germination, root architecture, chlorophyll synthesis, nutrient uptake, and biomass output more than each component alone (Grover *et al*., 2021). Rice bran is especially useful due to its nutrient-dense composition and capacity to promote microbial growth.

Although, multiple studies have independently revealed the benefits of PGPR and rice bran, evidence on their combined use in greengram production is scarce. Understanding the interaction between multifunctional PGPR and rice bran could help to produce long-term biofertilizer formulations that improve crop growth while using less chemical fertiliser. As a result, the current study assessed the combined effect of rice bran and multifunctional PGPR on greengram growth by measuring PGPR characteristics, seed germination, plant growth, and biomass output. The study's goal is to develop an environmentally sustainable pulse production method based on the efficient use of agricultural waste and beneficial rhizobacterium.

Materials and Methods

Collection and Compositional analysis of Rice bran

Fresh rice bran was procured from a local rice milling unit in Krishnagiri District, Tamil Nadu, India. The collected samples were transported to the laboratory in sterile polyethylene bags, air-dried at room temperature (27 ± 2°C) to reduce moisture content, and homogenized using a laboratory grinder. The powdered samples were passed through a 40-mesh sieve to obtain uniform particle size and stored in airtight containers at 4°C until further analysis. The structural composition of rice bran, including cellulose, hemicellulose, lignin, ash and extractives, was determined according to the standard NREL protocols described by Sluiter *et al*. (2008).

Collection of Rhizosphere soil and isolation of Plant Growth-Promoting Rhizobacteria (PGPR)

Rhizosphere soil samples were collected aseptically from healthy greengram (*Vigna radiata* L.) plants cultivated in the experimental fields of Adhiyamaan College of Agriculture and Research (ACAR), Krishnagiri District, Tamil Nadu, India. Soil adhering firmly to the root surface was gently collected after uprooting the plants and transferred into sterile polyethylene bags. The samples were transported to the laboratory under refrigerated conditions and processed within 24 h to preserve the native microbial population. Plant growth-promoting rhizobacteria (PGPR) were isolated using CRYEMA, Waksmann No 77 medium, Pikovskaya's medium and Bunt and Rovira medium by serial dilution and plating method.

Following incubation, morphologically distinct bacterial colonies differing in size, shape, elevation, pigmentation, margin and surface characteristics were selected and purified by repeated streaking on fresh medium to obtain pure cultures. The purified isolates were maintained on Nutrient Agar slants at 4°C for routine laboratory use and preserved in Nutrient Broth containing 20% glycerol at –20°C for long-term storage. The isolates were subsequently subjected to morphological and biochemical characterization, (Cappuccino and Sherman, 2014; Glick, 2012).

Screening of Plant Growth-Promoting traits

The purified bacterial isolates were screened for important plant growth-promoting (PGP) attributes, including indole-3-acetic acid (IAA) production, phosphate solubilization, zinc solubilization, biofilm formation and antagonistic activity against major phytopathogenic fungi.

These assays were performed to identify multifunctional PGPR capable of enhancing plant growth through improved nutrient mobilization, phytohormone production, rhizosphere colonization, and biological control of plant pathogens. All experiments were conducted in triplicate under aseptic conditions and the results were expressed as the mean of three independent observations.

Indole-3-Acetic Acid (IAA) Production

The production of indole-3-acetic acid (IAA) by the bacterial isolates was qualitatively determined following the method described by Patten and Glick (2002) with slight modifications. Fresh bacterial cultures were inoculated into Luria–Bertani (LB) broth supplemented with 100 µg mL^{-1} L-tryptophan and incubated at 28 ± 2°C for 72 h under shaking conditions (150 rpm). After incubation, the cultures were centrifuged at 10,000 rpm for 10 min, and 1 mL of the cell-free supernatant was mixed with 2 mL of Salkowski reagent (1 mL of 0.5 M $FeCl_3$ in 50 mL of 35% perchloric acid). The reaction mixture was incubated in the dark for 30 min at room temperature. The development of a pink to reddish colour indicated IAA production, and the absorbance was measured at 530 nm using a UV–Visible spectrophotometer. The IAA concentration was estimated using a standard curve prepared with analytical-grade IAA and expressed as µg mL^{-1}.

Phosphate solubilization

The phosphate-solubilizing ability of the bacterial isolates was evaluated on Pikovskaya's agar medium containing tricalcium phosphate as the insoluble phosphorus source according to Pikovskaya (1948). Fresh overnight bacterial cultures were spot inoculated onto sterile agar plates and incubated at 28±2°C for 5–7 days. The formation of a clear halo zone surrounding the bacterial colony indicated phosphate solubilization. The diameter of both the colony and the halo zone was measured and the phosphate solubilization index (PSI) was calculated using the following equation:

PSI = Halo zone diameter/ Colony diameter

Higher PSI values indicated greater phosphate-solubilizing efficiency.

Zinc solubilization

Zinc-solubilizing activity was determined using mineral salt agar medium supplemented separately with 1% zinc oxide (ZnO) as an insoluble zinc source following the procedure of Ramesh *et al*. (2014). Bacterial isolates were spot inoculated onto the medium and incubated at 28±2°C for 5 days. The appearance of a transparent halo around the bacterial colony was considered positive for zinc solubilization. The halo diameter was measured, and zinc solubilization efficiency was calculated based on the diameter of the clear zone surrounding the colony.

Biofilm Formation assay

The biofilm-forming ability of the bacterial isolates was qualitatively assessed using the test tube method described by Christensen *et al*. (1985). A loopful of each bacterial isolate was inoculated into 10 mL of Tryptic Soy Broth (TSB) and incubated under static conditions at 28±2°C for 48 h. Following incubation, the culture broth was discarded, and the tubes were gently washed three times with sterile phosphate-buffered saline (PBS; pH 7.2) to remove non-adherent cells. The tubes were air-dried and stained with 0.1% crystal violet for 15 min. Excess stain was removed by rinsing with distilled water, and the tubes were allowed to dry. The formation of a violet film along the inner wall and bottom of the tube indicated positive biofilm formation. Based on staining intensity, the isolates were categorized as weak, moderate, or strong biofilm producers.

Antagonistic activity

The antagonistic activity of selected PGPR isolates against *Fusarium oxysporum* and *Macrophomina phaseolina* was evaluated using the dual culture technique described by Dennis and Webster (1971). A 5-mm mycelial disc obtained from the actively growing margin of each fungal culture was placed at one side of a Potato Dextrose Agar (PDA) plate, while the bacterial isolate was streaked approximately 2 cm away from the fungal plug. Control plates containing only the fungal pathogen were maintained simultaneously. The plates were incubated at 28±2°C for 5–7 days and inhibition of fungal growth was assessed by measuring the radial growth of the pathogen.

Seed Germination assay

The plant growth-promoting effect of the selected PGPR isolates was evaluated using the Petri plate method. Surface-sterilized greengram seeds were bacterized with individual and combined PGPR inoculants and placed on sterile moist Whatman No. 1 filter paper in Petri dishes. The plates were incubated at 28±2°C for 7 days and germination percentage were recorded.

Pot Culture experiment

A pot culture experiment was conducted under greenhouse conditions using a Completely Randomized Design (CRD) with nine treatments and three replications to evaluate the effect of plant growth-promoting rhizobacteria (PGPR) and rice bran on the growth of greengram (*Vigna radiata* L.). Plastic pots (10 kg

capacity) were filled with 7 kg of air-dried soil and rice bran was incorporated at the rate of 5 g pot^{-1} before sowing. Surface-sterilized greengram seeds were bacterized with the respective PGPR inoculants and sown in the designated pots. The experiment was maintained for 65 days under uniform irrigation and recommended agronomic practices. Growth parameters, including root length, shoot length and plant dry weight were recorded at 15, 30 and 45 days after sowing (DAS). The treatment combinations used in the pot culture experiment are presented in Table 1.

Table 1 : Treatment combinations used to evaluate the combined effect of rice bran and plant growth-promoting rhizobacteria (PGPR) on greengram (*Vigna radiata* L).

Treatment	Description
T_1	*Rhizobium* + Rice bran
T_2	*Azotobacter* + Rice bran
T_3	Phosphate-solubilizing bacteria (PSB) + Rice bran
T_4	*Rhizobium* + *Azotobacter* + Rice bran
T_5	*Azotobacter* + PSB + Rice bran
T_6	PSB + *Rhizobium* + Rice bran
T_7	*Rhizobium* + *Azotobacter* + PSB + Rice bran
T_8	Rice bran alone (5 g pot^{-1})
T_9	Untreated control

Statistical analysis

All the experiments were conducted in triplicate and expressed as mean ± standard error. The experimental data were subjected to analysis of variance (ANOVA), and significant differences among means were tested using Duncan's Multiple Range Test (DMRT) at $P < 0.05$ in SPSS. Graphical representations of the experimental data were prepared using GraphPad Prism (Version 9.0, GraphPad Software Inc., San Diego, CA, USA).

Results and Discussion

Biomass composition of Rice bran

The relative composition of rice bran is illustrated in Fig. 1. Among the major constituents, cellulose accounted for the highest proportion (54 ± 0.82%), followed by hemicellulose (19±0.95 %), lignin (12± 0.47%), moisture content (10± 0.62%), ash (4± 0.32%), and biomass extractives (1± 0.002%). The predominance of cellulose indicates that rice bran is a carbohydrate-rich lignocellulosic biomass (LCB) capable of serving as a sustainable carbon source for beneficial microorganisms. Cellulose and hemicellulose together constitute more than

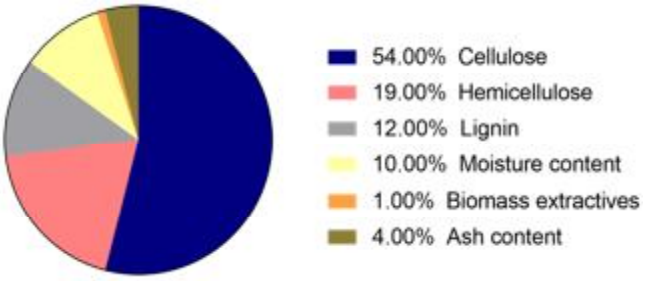


Fig. 1 : Biomass composition of rice bran. Data in the graph represents the mean of three replicates ± standard error (SE).

70% of the biomass, providing readily degradable polysaccharides that support microbial colonization, nutrient mineralization, and soil fertility improvement (Sun and Cheng, 2002; Binod *et al.*, 2010). The low moisture content also suggests good storage stability and reduced risk of microbial spoilage, making rice bran suitable for use as an organic carrier in biofertilizer formulations (Sharif *et al.*, 2014).

The moderate lignin content (12%) indicates that rice bran possesses sufficient structural integrity while remaining amenable to microbial degradation, allowing gradual release of nutrients into the soil (Kumar *et al.*, 2009). Likewise, the relatively low proportions of ash (4%) and biomass extractives (1%) indicate that the biomass contains adequate mineral nutrients and a limited amount of soluble compounds, thereby maintaining a high proportion of structural carbohydrates. The compositional profile observed in the present study is consistent with previous reports on rice bran and confirms its suitability as an organic amendment for sustainable agriculture (Juliano, 1985; Sharif *et al.*, 2014). The abundance of cellulose and hemicellulose, together with moderate lignin content, is expected to promote the survival and activity of plant growth-promoting rhizobacteria (PGPR), thereby enhancing nutrient availability, soil biological activity, and greengram growth.

Isolation, Morphological and Biochemical Characterization of Plant Growth-Promoting Rhizobacteria (PGPR)

A total of 10 morphologically distinct bacterial isolates were successfully isolated from the rhizosphere soil of healthy greengram plants using selective media, namely CRYEMA, Waksman No. 77, Pikovskaya's, and Bunt and Rovira media. Based on colony morphology, growth characteristics and biochemical properties, the isolates were tentatively identified as three *Rhizobium* isolates, three *Azotobacter* isolates, two phosphate-solubilizing bacterial (PSB) isolates, and two zinc-solubilizing bacterial (ZSB) isolates. The use of selective media facilitated the recovery of functionally diverse rhizobacteria possessing

Table 2 : Morphological characteristics of selected Plant Growth-Promoting Rhizobacterial (PGPR) isolates.

Parameters	Rz4	Rz5	Rz7	Az1	Az4	Az6	PSB2	PSB3	ZSB 2	ZSB3
Colour	White	White	White	Creamy white	Creamy white	Creamy white	Creamy Orange	Creamy orange	Whitish creamy	Whitish creamy
Growth	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Shape	Circular	Circular	Circular	Irregular	Irregular	Irregular	Circular	Circular	Filamen-tous	Filamen-tous
Margin	Undulate	Undulate	Undulate	Lobate	Lobate	Lobate	Entire	Entire	Filamen-tous	Filamen-tous
Surface	Smoot Shiny	Smooth shiny	Smooth shiny	Smooth	Smooth	Smooth	Dry	Dry	Rough	Rough
Elevation	Convex	Convex	Convex	Raised	Raised	Raised	Covex	Convex	Convex	Convex
Staining	Gram -ive	Gram -ive	Gram -ive	Gram -ive	Gram -ive	Gram -ive	Gram +ive	Gram +ive	Gram -ive	Gram +ive

Rz- Rhizobium, Az- Azotobacter, ZSB- Zinc solublizing bacteria, PSB- Phosphate solubilizing bacteria.

potential plant growth-promoting properties. Similar isolation strategies have been widely employed for the recovery of beneficial rhizosphere microorganisms from leguminous crops (Cappuccino and Sherman, 2014; Glick, 2012). The diversity of isolates obtained in the present study suggests that the greengram rhizosphere harbours a rich microbial community capable of contributing to nutrient cycling and plant growth promotion.

Morphology

The morphological characteristics of the ten selected PGPR isolates are presented in Table 2. Distinct variations in colony morphology were observed among the isolates, indicating the presence of diverse bacterial groups in the greengram rhizosphere. The *Rhizobium* isolates (RZ4, RZ5 and RZ7) produced white, circular colonies with undulate margins, smooth shiny surfaces, convex elevation and were Gram-negative. The *Azotobacter* isolates (AZ1, AZ4 and AZ6) formed creamy-white, irregular colonies with lobate margins, smooth surfaces, raised elevation, and were also Gram-negative. The phosphate-solubilizing bacterial (PSB) isolates (PSB2 and PSB3) exhibited creamy-orange, circular colonies with entire margins, dry surfaces, convex elevation, and were identified as Gram-positive bacteria. The zinc-solubilizing bacterial (ZSB) isolates displayed whitish-creamy colonies with filamentous shape and margins, rough surfaces, convex elevation. Among the ZSB isolates, ZSB2 was Gram-negative, whereas ZSB3 was Gram-positive. All isolates showed moderate growth on their respective selective media, indicating their ability to adapt and proliferate under laboratory conditions.

The observed colony morphology and Gram reaction are consistent with the typical characteristics of beneficial rhizobacteria reported in earlier studies. *Rhizobium* species are generally described as Gram-negative, smooth, circular colonies with convex elevation, whereas *Azotobacter* species produce irregular, mucoid or smooth creamy colonies due to the production of extracellular polysaccharides (Somasegaran and Hoben, 1994; Cappuccino and Sherman, 2014). Likewise, phosphate-solubilizing bacteria commonly produce dry or opaque colonies, while zinc-solubilizing bacteria exhibit considerable morphological diversity depending on the bacterial genus (Rodríguez and Fraga, 1999; Ramesh *et al*., 2014). The morphological diversity observed among the isolates reflects their taxonomic and functional variability, suggesting that the greengram rhizosphere harbours a heterogeneous microbial community with different physiological characteristics. These observations served as a preliminary basis for selecting representative isolates for subsequent biochemical characterization and evaluation of plant growth-promoting traits such as indole-3-acetic acid production, nutrient solubilization, biofilm formation and antagonistic activity.

Biochemical characterization

The biochemical characteristics of the ten selected PGPR isolates are presented in Table 3. The isolates exhibited considerable variation in carbohydrate utilization and enzyme production, indicating their metabolic diversity and adaptability to the rhizosphere environment. Among the *Rhizobium* isolates, RH4 and RH5 utilized glucose, lactose, maltose and sucrose, whereas RH7 did not ferment any of the tested carbohydrates. All *Azotobacter* isolates (AZ1, AZ4 and AZ6) showed positive reactions for glucose, lactose, maltose, and sucrose utilization, demonstrating broad substrate utilization capacity. The phosphate-solubilizing and zinc-solubilizing isolates exhibited selective carbohydrate utilization, with ZSB2,

Table 3 : Biochemical characteristics of selected Plant Growth-Promoting Rhizobacterial (PGPR) isolates.

Bacterial Culture	Glucose	Lactose	Maltose	Sucrose	Amylase	Cellulase
Rz4	+	+	+	+	+	+
Rz5	+	+	+	+	+	+
Rz7	-	-	-	-	+	+
Az1	+	+	+	+	+	+
Az4	+	+	+	+	+	+
Az6	+	+	+	+	+	+
ZSB2	+	-	+	+	+	+
ZSB3	+	-	+	+	+	+
PSB2	+	-	+	+	+	+
PSB3	+	-	+	-	+	+

Rz- Rhizobium, Az- Azotobacter, ZSB- Zinc solublizing bacteria, PSB- Phosphate solubilizing bacteria.

ZSB3 and PSB2 fermenting glucose, maltose, and sucrose, while PSB3 utilized only glucose and maltose. All isolates were positive for amylase production and negative for cellulase activity, indicating their ability to hydrolyze starch but not cellulose under the experimental conditions. The ability to utilize a wide range of carbohydrates and produce amylase enhances bacterial survival and colonization in the rhizosphere by efficiently utilizing carbon compounds released through root exudates (Hassan *et al*., 2019). Such metabolic versatility is considered an important characteristic of effective plant growth-promoting rhizobacteria, facilitating nutrient cycling, microbial establishment, and improved plant growth (Jacoby *et al*., 2019; Wang *et al*., 2019).

Screening of Plant Growth-promoting rhizobacteria

IAA activity

The indole-3-acetic acid (IAA) production by the isolated plant growth-promoting rhizobacteria (PGPR) is presented in Fig. 2. Considerable variation in IAA production was observed among the ten bacterial isolates, with values ranging from 7.48 to 24.84 µg mL^{-1}, demonstrating strain-specific differences in auxin biosynthesis. Among the isolates, PSB2 recorded the highest IAA production (24.84 µg mL^{-1}), followed by AZ6 (23.61 µg mL) and RZ4 (7.48 µg mL^{-1}) produced comparatively lower amounts of IAA. The wide variation among the isolates indicates that the ability to synthesize IAA is dependent on the bacterial species and their metabolic capacity.

IAA is one of the most important phytohormones synthesized by PGPR, which stimulates cell elongation, root initiation, lateral root development, and root hair proliferation, thereby improving nutrient and water uptake by plants (Patten and Glick, 2002). The higher IAA production exhibited by PSB2, AZ6 and RZ5 suggests that these isolates possess superior plant growth-promoting potential and could significantly enhance root architecture and seedling establishment in greengram. Similar variability in IAA production among *Rhizobium*, *Azotobacter*, and phosphate-solubilizing bacteria has been reported by Spaepen *et al*. (2007) and Glick (2012), who demonstrated that auxin production differs among bacterial strains depending on genetic makeup and growth conditions. Likewise, Mohite (2013) reported IAA production ranging from 6 to 28 µg mL^{-1} in rhizobacterial isolates, which closely corresponds with the results obtained in the present study. The identification of high IAA-producing isolates is important for developing efficient bioinoculants, as bacterial IAA production enhances root growth, nutrient acquisition and overall crop productivity. Therefore, the superior isolates identified in the present investigation were selected for subsequent evaluation of additional plant growth-promoting traits and pot culture studies.

Phosphate Solubilization activity

The phosphate-solubilizing ability of the selected PGPR isolates is presented in Fig. 3. Considerable variation in phosphate solubilization efficiency was observed among the ten bacterial isolates, indicating differences in their capacity to mobilize insoluble phosphate. The phosphate solubilization index of the bacterial isolates varied considerably among the tested strains. Among all the isolates, PSB2 recorded the highest phosphate solubilization index (2.85), indicating its superior phosphate-solubilizing potential. This was followed by RZ5 (2.78) and RZ4 (2.60). Moderate phosphate solubilization was observed in AZ4 (2.40), ZSB2 (2.35), ZSB3 (2.28), RZ7 (2.20) and PSB3 (2.10). The lowest phosphate solubilization indices were recorded in AZ1 (1.70) and AZ6 (1.55). These findings indicate that PSB2 was the most efficient phosphate-solubilizing isolate among the tested bacterial strains and has greater potential for

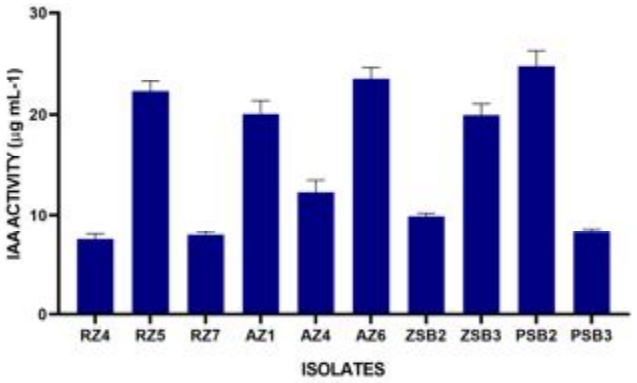


Fig. 2 : IAA production by rhizobacterial isolates from the greengram rhizosphere. Data in the graph represents the mean of three replicates ± standard error (SE).

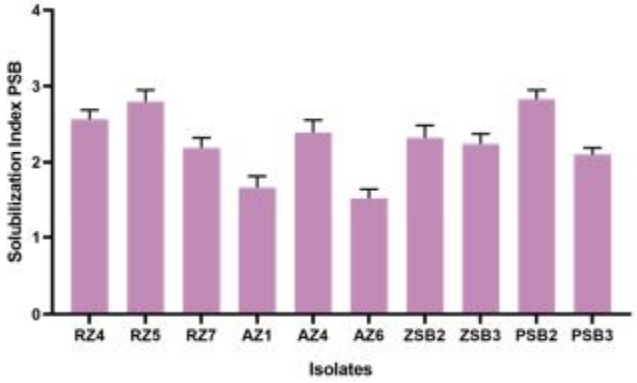


Fig. 3 : Phosphate-solubilization efficiency of selected rhizobacterial isolates. Data in the graph represents the mean of three replicates ± standard error (SE).

improving phosphorus availability in soil (Fig. 3).

Phosphate-solubilizing bacteria play an essential role in improving phosphorus availability in soil by lowering the pH of the rhizosphere through the production of organic acids such as gluconic, citric, oxalic, and lactic acids, thereby releasing soluble phosphate from insoluble mineral complexes (Rodríguez and Fraga, 1999). The superior phosphate-solubilizing activity exhibited by PSB3, RZ7, and RZ4 suggests their potential to enhance phosphorus uptake and plant growth in greengram under phosphorus-deficient conditions. Similar findings were reported by Chen *et al*. (2006), who observed significant variability in phosphate-solubilizing efficiency among rhizobacterial isolates. Likewise, Sharma *et al*. (2013) reported that highly efficient phosphate-solubilizing bacteria significantly improve phosphorus availability, root development and crop productivity. Therefore, the isolates exhibiting higher phosphate-solubilizing efficiency in the present study were considered promising candidates for developing PGPR-based biofertilizer formulations in combination with rice bran for sustainable greengram cultivation.

Zinc Solubilization activity

The zinc-solubilizing efficiency of the selected PGPR isolates is presented in Fig. 4. The zinc solubilization index of the bacterial isolates varied among the tested strains. Among all the isolates, AZ4 exhibited the highest zinc solubilization index (1.50), followed by PSB2 (1.47), RZ5 (1.40) and ZSB3 (1.36), indicating their superior zinc-solubilizing ability. Moderate zinc solubilization was observed in RZ4 (1.25), RZ7 (1.18), AZ1 (1.16) and PSB3 (1.14). The lowest zinc solubilization indices were recorded for AZ6 (1.10) and ZSB2 (1.06). These findings indicate that AZ4 was the most efficient zinc-solubilizing isolate among the tested bacterial strains and has promising potential for enhancing zinc availability in soil for improved plant growth (Fig. 4).

Zinc is an essential micronutrient involved in several physiological and biochemical processes, including enzyme activation, protein synthesis, chlorophyll formation and auxin metabolism. Zinc-solubilizing bacteria improve zinc availability primarily through the secretion of organic acids, siderophores and chelating compounds, which convert insoluble zinc minerals into soluble forms readily absorbed by plant roots (Ramesh *et al*., 2014). The superior zinc-solubilizing activity exhibited by AZ1, AZ6, RH5 and RH7 indicates their potential to enhance zinc nutrition and plant growth in greengram. Similar variations in zinc-solubilizing efficiency among rhizobacterial isolates have been reported by Fasim *et al*. (2002) and Ramesh *et al*. (2014), who demonstrated that efficient zinc-solubilizing bacteria significantly improve micronutrient availability and crop productivity under zinc-deficient soils.

Biofilm formation

The biofilm-forming ability of the selected PGPR isolates is presented in Fig. 5. Considerable variation in biofilm formation was observed among the ten isolates, with optical density (OD) values ranging from 0.345 to 1.351. Among the isolates, RZ7 exhibited the highest biofilm formation (OD = 1.351), indicating strong adherence and colonization ability, followed by PSB2 (0.840) and least was observed in ZSB2 (0.345). The differences in biofilm production among the isolates indicate strain-specific variability in their ability to establish stable microbial communities on root surfaces. Biofilm formation is a key trait of plant growth-promoting rhizobacteria, as it enhances bacterial adhesion, persistence and protection against environmental stresses while facilitating efficient root colonization and sustained delivery of plant growth-promoting metabolites (Backer *et al*., 2018). Similar observations have been reported by Ngalimat *et al*. (2021) and Olanrewaju *et al*. (2019), who demonstrated that strong biofilm-forming PGPR exhibit superior rhizosphere competence, improved nutrient

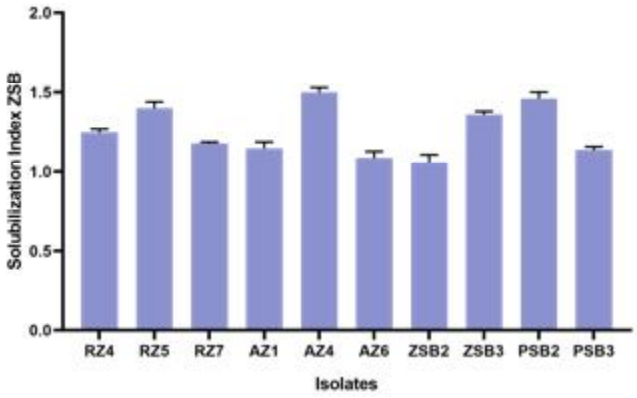


Fig. 4 : Zinc-solubilization efficiency of selected rhizobacterial isolates. Data in the graph represents the mean of three replicates ± standard error (SE).

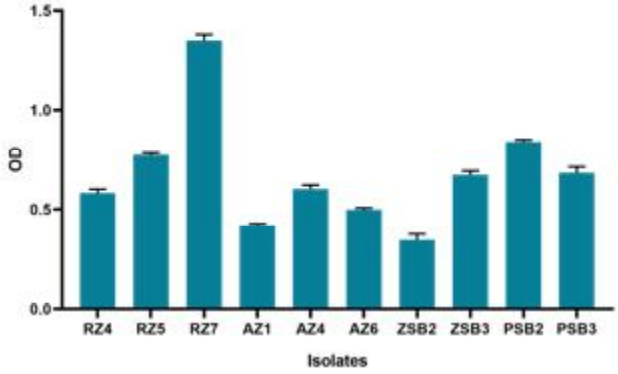


Fig. 5 : Biofilm-forming ability of the isolated plant growth-promoting rhizobacterial (PGPR) strains. Data in the graph represents the mean of three replicates ± standard error (SE).

acquisition, and enhanced plant growth under both normal and stress conditions. The high biofilm-forming ability of RZ7 and PSB2 suggests that these isolates possess greater potential for successful rhizosphere colonization and could serve as effective bioinoculants for sustainable greengram production.

Antagonistic activity

The antagonistic activity of selected plant growth-promoting rhizobacterial (PGPR) isolates against the fungal pathogens *Fusarium oxysporum* and *Macrophomina phaseolina* was evaluated using the dual culture technique (Fig. 5). The tested bacterial isolates exhibited varying degrees of inhibition against the fungal pathogens, as evidenced by the formation of clear inhibition zones and suppression of fungal mycelial growth. Among the isolates, PSB strain 3 showed effective antagonistic activity against both *F. oxysporum* and *M. phaseolina*, indicating its broad-spectrum antifungal potential. *Azotobacter* strain 4 and *Azotobacter* strain 1 also inhibited the growth of *F. oxysporum*, although the extent of inhibition varied between the strains. Similarly, ZSB strain 3 and PSB strain 2 effectively restricted the radial

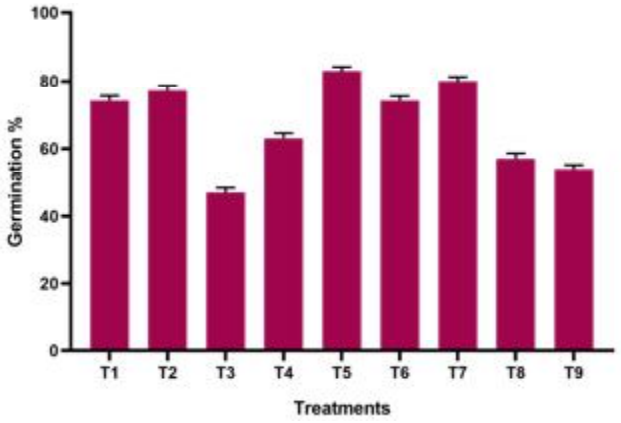


Fig. 6 : Seed germination percentage of greengram under different PGPR treatments in the plate assay. Data in the graph represents the mean of three replicates ± standard error (SE).

growth of *F. oxysporum*, producing distinct inhibition zones between the bacterial streak and fungal colony. Overall, the results demonstrated that all selected PGPR isolates possessed antagonistic activity against the tested fungal pathogens, with PSB strain 3 exhibiting the broadest spectrum of inhibition. The present investigation demonstrated that selected PGPR isolates possess considerable antagonistic activity against the important soil-borne phytopathogens *Fusarium oxysporum* and *Macrophomina phaseolina*. The inhibition of fungal growth observed in the dual culture assay indicates that these bacterial isolates can suppress phytopathogens through multiple mechanisms, including the production of antifungal metabolites, hydrolytic enzymes, volatile organic compounds, siderophores, hydrogen cyanide (HCN), and competition for nutrients and ecological niches. Such mechanisms are well documented in phosphate-solubilizing bacteria, zinc-solubilizing bacteria, and *Azotobacter* species, which contribute not only to nutrient mobilization but also to biological control of plant diseases.

Effect of PGPR treatments on Seed germination of greengram

The effect of different PGPR inoculations on the seed germination of greengram is presented in Fig. 6. Seed germination was significantly influenced by both individual and combined PGPR treatments. Among all the treatments, T_5 (Azotobacter + PSB) recorded the highest germination percentage (83%), followed by T_7 (Rhizobium + Azotobacter + PSB) with 80% and T_2 (Azotobacter) with 77%. Treatments T_1 (Rhizobium) and T_6 (PSB + Rhizobium) each recorded 74% germination, while T_4 (*Rhizobium* + *Azotobacter*) exhibited 63% germination. The untreated control showed a germination percentage of 57%, whereas the lowest germination (47%) was observed in T_3 (PSB). The results indicate

that the combined inoculation of PGPR strains was more effective in enhancing seed germination than individual bacterial inoculation.

The enhanced germination observed in T_5 and T_7 may be attributed to the synergistic interaction between *Azotobacter*, phosphate-solubilizing bacteria and *Rhizobium*, which improves seed vigour through the production of phytohormones such as indole-3-acetic acid (IAA), enhanced nutrient solubilization and increased availability of essential nutrients during the early stages of seedling development (Patten and Glick, 2002; Glick, 2012). *Azotobacter* is known to produce growth-promoting substances, including IAA, gibberellins and cytokinins, which stimulate embryo growth and accelerate seed germination (Vessey, 2003). Furthermore, phosphate-solubilizing bacteria improve phosphorus availability, an essential nutrient required for energy metabolism during germination (Rodríguez and Fraga, 1999). Similar improvements in seed germination following PGPR inoculation have been reported by Bashan and de-Bashan (2010) and Ahemad and Kibret (2014), who demonstrated that consortium-based PGPR inoculation enhances seed germination and early seedling establishment more effectively than single-strain inoculation. Therefore, the superior performance of *Azotobacter* + PSB (T_5) and the three-strain consortium (T_7) highlights the potential of PGPR combinations as efficient bioinoculants for improving greengram establishment and subsequent crop growth.

Pot culture study

Shoot length

The effect of different PGPR and rice bran treatments on the shoot length of greengram at 15, 30, and 45 days after sowing (DAS) is presented in Fig. 7. Significant differences in shoot growth were observed among the treatments throughout the experimental period. At 15 DAS, the maximum shoot length was recorded in T_6 (PSB + Rhizobium + Rice bran) (10.93 cm), followed by T_7 (Rhizobium + Azotobacter + PSB + Rice bran) (10.27 cm), whereas the minimum shoot length was observed in T_8 (Rice bran alone) (6.17 cm). At 30 DAS, T_7 exhibited the highest shoot length (22.00 cm), followed by T_6 (20.47 cm) and T_5 (Azotobacter + PSB + Rice bran; 19.47 cm), while T_1 and T_8 recorded comparatively lower values of 16.00 cm and 16.83 cm, respectively. At the final observation (45 DAS), the highest shoot length was recorded in T_5 (26.73 cm), followed by T_7 (25.13 cm), T_9 (Control; 24.40 cm), T_6 (23.97 cm) and T_4 (23.73 cm). The enhanced shoot growth observed in the consortium treatments may be attributed to the synergistic

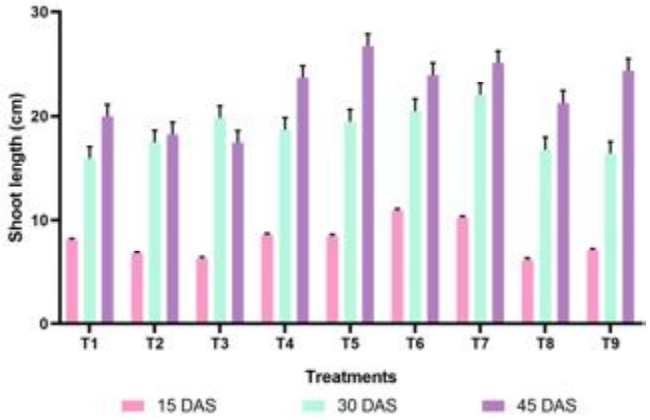


Fig. 7 : Effect of rice bran and PGPR treatments on shoot length of greengram at 15, 30 and 45 DAS. Data in the graph represents the mean of three replicates ± standard error (SE).

action of Rhizobium, Azotobacter and phosphate-solubilizing bacteria, which collectively improve nitrogen fixation, phosphorus solubilization, phytohormone production, and nutrient uptake. The incorporation of rice bran further supports microbial proliferation by serving as an organic carbon source, thereby enhancing PGPR activity in the rhizosphere. Similar findings have been reported by Olanrewaju *et al*. (2019), who demonstrated that multifunctional PGPR significantly improve plant growth through enhanced nutrient acquisition and phytohormone production. Likewise, Kour *et al*. (2020) reported that microbial consortia outperform single inoculants due to complementary plant growth-promoting mechanisms, while Mahanty *et al*. (2021) highlighted that combining PGPR with organic amendments improves rhizosphere microbial activity, resulting in greater vegetative growth and biomass accumulation. These findings indicate that the combined application of PGPR with rice bran is an effective strategy for enhancing shoot growth and early crop establishment in greengram.

Root length

The effect of different PGPR and rice bran treatments on the root length of greengram at 15, 30 and 45 days after sowing (DAS) is presented in Fig. 8. Significant differences in root growth were observed among the treatments during the experimental period. Among all treatments, T_7 (Rhizobium + Azotobacter + PSB + Rice bran) consistently recorded the highest root length at 15 DAS (3.80 cm), 30 DAS (8.67 cm) and 45 DAS (12.87 cm), followed by T_4 (*Rhizobium* + *Azotobacter* + Rice bran) with 11.50 cm at 45 DAS. The lowest root length at the final stage was observed in T_8 (Rice bran alone) (7.43 cm), while the untreated control (T_9) recorded 9.30 cm. The enhanced root development observed in the consortium treatments may be attributed

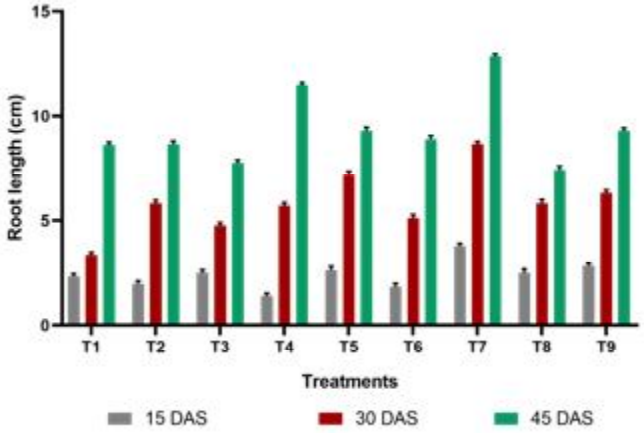


Fig. 8 : Effect of rice bran and PGPR treatments on root length of greengram at 15, 30, and 45 DAS. Data in the graph represents the mean of three replicates ± standard error (SE).

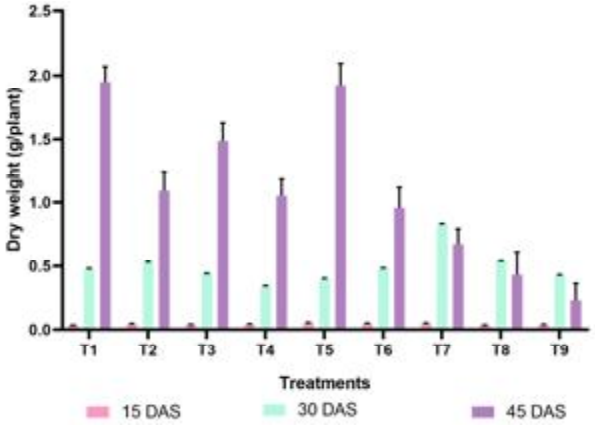


Fig. 9 : Effect of rice bran and PGPR treatments on plant dry weight of greengram at 15, 30 and 45 DAS. Data in the graph represents the mean of three replicates ± standard error (SE).

to the synergistic interaction of *Rhizobium*, *Azotobacter* and phosphate-solubilizing bacteria, which improve nitrogen fixation, phosphorus availability, phytohormone production, and nutrient uptake, resulting in increased root proliferation. The addition of rice bran likely served as an organic carbon source that enhanced microbial survival and rhizosphere colonization. Similar findings were reported by Singh *et al*. (2022), who demonstrated that microbial consortia significantly improve root architecture and nutrient acquisition compared to single inoculants. Likewise, Chaudhary *et al*. (2021) observed that PGPR combined with organic amendments enhanced root growth through improved microbial activity and soil nutrient availability, while Bhattacharyya *et al*. (2023) reported that multifunctional PGPR stimulate root elongation and overall plant establishment by increasing auxin production and improving rhizosphere competence.

Plant dry weight

The effect of different PGPR and rice bran treatments on the dry weight of greengram plants showed a progressive increase from 15 DAS to 45 DAS across all treatments. At 15 DAS, all treatments recorded comparatively lower dry weight with only slight variations. A marked increase was observed at 30 DAS, with T_7 (*Rhizobium* + *Azotobacter* + PSB + Rice Bran) recording the highest plant dry weight, followed by T_8 and T_2. At 45 DAS, the highest dry weight was again observed in T_7, followed by T_1 and T_5, indicating the beneficial effect of combined microbial inoculation with rice bran on biomass accumulation. The control treatment (T9) recorded the lowest dry weight throughout the experimental period (Fig. 9).

Total chlorophyll estimation

The effect of different PGPR and rice bran treatments on the photosynthetic pigments of greengram is presented in Fig. 10. Significant variations were observed in chlorophyll a, chlorophyll b, and carotenoid contents among the treatments. The highest chlorophyll a content was recorded in T_1 (Rhizobium + Rice bran) (14.75 mg g^{-1}), closely followed by T_7 (Rhizobium + Azotobacter + PSB + Rice bran) (14.56 mg g^{-1}), whereas the lowest value was observed in T_8 (Rice bran alone) (5.97 mg g^{-1}). For chlorophyll b, the maximum content was recorded in T_8 (9.998 mg g^{-1}), followed by the control (T_9; 9.316 mg g^{-1}) and T_6 (PSB + Rhizobium + Rice bran; 8.446 mg g^{-1}), while the minimum value was observed in T_7 (5.852 mg g^{-1}). Among the treatments, T_7 recorded the highest carotenoid content (4.563 mg g^{-1}), followed by T_4 (4.253 mg g^{-1}), T_5 (4.183 mg g^{-1}) and T_8 (4.110 mg g^{-1}), whereas the lowest carotenoid content was recorded in T_2 (3.384 mg g^{-1}). The enhanced chlorophyll and carotenoid contents in the PGPR-treated

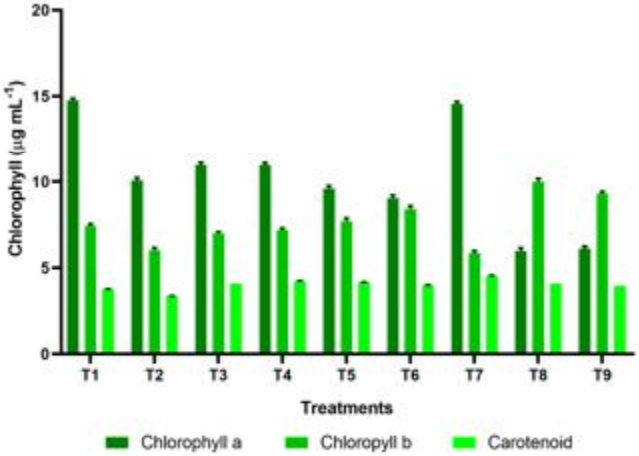


Fig. 10 : Effect of rice bran and PGPR treatments on root length of greengram at 15, 30 and 45 DAS. Data in the graph represents the mean of three replicates ± standard error (SE).

plants can be attributed to improved nutrient availability, particularly nitrogen and phosphorus, enhanced phytohormone production and increased photosynthetic efficiency resulting from better root development and rhizosphere colonization. PGPR-mediated improvement in mineral uptake promotes chlorophyll biosynthesis and protects the photosynthetic apparatus through increased carotenoid accumulation, thereby enhancing plant growth and stress tolerance. Similar observations were reported by Basu *et al*. (2021), who demonstrated that PGPR inoculation significantly increases chlorophyll pigments through improved nutrient assimilation. Likewise, Kumar *et al*. (2022) reported that PGPR consortia enhance photosynthetic pigment content by stimulating plant metabolism and nutrient acquisition, while Sharma *et al*. (2023) observed that the combined application of biofertilizers and organic amendments improves chlorophyll synthesis, antioxidant activity, and overall crop productivity. These findings indicate that the integrated use of PGPR and rice bran positively influences the photosynthetic capacity and physiological performance of greengram.

Conclusion

The current study found that combining rice bran with multifunctional plant growth-promoting rhizobacteria significantly enhanced greengram growth and physiological performance. Rice bran functioned as an effective organic amendment by providing an adequate carbon source for microbial survival and rhizosphere activity. The isolated PGPR demonstrated a variety of positive characteristics, including IAA generation, phosphate and zinc solubilisation, biofilm formation and antagonistic action, indicating their potential as effective bioinoculants. Consortium-based inoculation, particularly the combination of *Rhizobium, Azotobacter* and phosphate-solubilizing bacteria with rice bran, consistently improved seed germination, root and shoot development, chlorophyll content and overall plant vigour when compared to individual inoculants and the untreated control. These findings support the synergistic interaction of organic residues and beneficial rhizobacteria as a sustainable alternative to chemical fertilisers.

Acknowledgement

The authors gratefully acknowledge the Management of Adhiyamaan College of Agriculture and Research (ACAR), Krishnagiri, Tamil Nadu, India, for providing the necessary laboratory facilities, greenhouse infrastructure and institutional support to carry out this research. The authors are grateful to the Department of Agricultural Microbiology for its technical assistance and continuous support throughout the study. The constructive cooperation of the faculty members, technical staff and students involved in the experimental work is gratefully acknowledged.

References

Backer, R., Rokem J.S., Ilangumaran G., Lamont J., Praslickova D., Ricci E., Subramanian S. and Smith D.L. (2018). Plant growth-promoting rhizobacteria: Context, mechanisms of action and roadmap to commercialization of biostimulants for sustainable agriculture. *Front. Plant Sci*., **9**, 1473.

Basu, A., Prasad P., Das S.N., Kalam S., Sayyed R.Z., Reddy M.S. and El Enshasy H. (2021). Plant growth-promoting rhizobacteria (PGPR) as green bioinoculants: Recent developments, constraints and prospects. *Sustainability*, **13**, 1140.

Bhattacharyya, P.N., Goswami M. and Bhattacharyya L.H. (2023). Plant growth-promoting rhizobacteria and sustainable agriculture: Recent advances and future prospects. *Rhizosphere*, **26**, 100706.

Binod, P., Sindhu R., Singhania R.R., Vikram S., Devi L., Nagalakshmi S., Kurien N., Sukumaran R.K. and Pandey A. (2010). Bioethanol production from rice straw: An overview. *Bioresource Technology*, **101**, 4767–4774.

Bridgwater, A.V. (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*, **38**, 68–94.

Cappuccino, J.G. and Sherman N. (2014). *Microbiology: A Laboratory Manual*. 10th ed., Pearson Education, New York.

Chaudhary, P., Sharma A., Singh B. and Nagpal A.K. (2021). Bioinoculants as a sustainable approach for improving crop productivity and soil health. *J. Appl. Microbiol*., **131**, 1680–1698.

Chen, Y.P., Rekha P.D., Arun A.B., Shen F.T., Lai W.A. and Young C.C. (2006). Phosphate-solubilizing bacteria from subtropical soil and their tricalcium phosphate-solubilizing abilities. *Appl. Soil Ecol*., **34**, 33–41.

Christensen, G.D., Simpson W.A., Younger J.J., Baddour L.M., Barrett F.F., Melton D.M. and Beachey E.H. (1985). Adherence of coagulase-negative staphylococci to plastic tissue culture plates: A quantitative model for the adherence of staphylococci to medical devices. *J. Clin. Microbiol.*, **22**, 996–1006.

Deka, J., Thakuria D., Khyllep A. and Ahmed G. (2019). Isolation and functional characterization of beneficial bacteria associated with roots of *Thysanolaena maxima* and rhizospheric soil enzymatic activities. *Curr. Agricult. Res. J.*, **7**, 237–250.

Demirbas, A. (2004). Effects of temperature and particle size on biochar yield from pyrolysis of agricultural residues. *J. Anal. Appl. Pyrolysis*, **72**, 243–248.

Dennis, C. and Webster J. (1971). Antagonistic properties of species-groups of *Trichoderma*. *Trans. British Mycolog. Soc*., **57**, 363–369.

Duncan, D.B. (1955). Multiple range and multiple F tests. *Biometrics*, **11**, 1–42.

Fasim, F., Ahmed N., Parsons R. and Gadd G.M. (2002). Solubilization of zinc salts by a bacterium isolated from the air environment of a tannery. *FEMS Microbiol. Lett.*, **213**, 1–6.

Glick, B.R. (2012). Plant growth-promoting bacteria: Mechanisms and applications. *Scientifica*, **2012**, 963401.

Gomez, K.A. and Gomez A.A. (1984). *Statistical Procedures for Agricultural Research*. 2nd ed., John Wiley and Sons, New York.

Gouda, S., Kerry R.G., Das G., Paramithiotis S., Shin H.S. and Patra J.K. (2018). Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. *Microbiolog. Res.*, **206**, 131-140.

Gupta, R., Gigras P., Mohapatra H., Goswami V.K. and Chauhan B. (2003). Microbial α-amylases: A biotechnological perspective. *Process Biochem.*, **38**, 1599–1616.

Hassan, M.K., McInroy J.A. and Kloepper J.W. (2019). The interactions of rhizodeposits with plant growth-promoting rhizobacteria in the rhizosphere: A review. *Agriculture*, **9**, 142.

Himmel, M.E., Ding S.Y., Johnson D.K., Adney W.S., Nimlos M.R., Brady J.W. and Foust T.D. (2007). Biomass recalcitrance: Engineering plants and enzymes for biofuels production. *Science*, **315**, 804–807.

IBM Corp (2019). *IBM SPSS Statistics for Windows*. Version 26.0. IBM Corporation, Armonk, New York.

Jacoby, R.P., Kopriva S. and Koprivova A. (2019). Metabolic niches in the rhizosphere microbiome: New tools and approaches to analyse metabolic mechanisms of plant–microbe nutrient exchange. *J. Exp. Bot.*, **70**, 1087–1094.

Juliano, B.O. (1985). *Rice: Chemistry and Technology*. 2nd ed., American Association of Cereal Chemists, St. Paul, Minnesota.

Kour, D., Rana K.L., Yadav A.N., Sheikh I., Kumar V., Dhaliwal H.S. and Saxena A.K. (2020). Microbial biofertilizers: Bioresources and eco-friendly technologies for agricultural and environmental sustainability. *Biocatal. Agricult. Biotechnol.*, **23**, 101487.

Kumar, A., Singh S., Gaurav A.K., Srivastava S. and Verma J.P. (2022). Plant growth-promoting bacteria: Biological tools for sustainable agriculture and improved plant productivity. *Front. Plant Sci.*, **13**, 1026998.

Kumar, P., Barrett D.M., Delwiche M.J. and Stroeve P. (2009). Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. *Indust. Engg Chem. Res.*, **48**, 3713–3729.

Kumar, R., Farda B., Mignini A., Djebaili R., Koolman L., Paul A. and Mitra D. (2025). Microbial solutions in agriculture: enhancing soil health and resilience through bio-inoculants and bioremediation. *Bacteria*, **4(3)**, 28.

Mahanty, T., Bhattacharjee S., Goswami M., Bhattacharyya P., Das B., Ghosh A. and Tribedi P. (2021). Biofertilizers: A potential approach for sustainable agriculture development. *Environ. Sci. Poll. Res.*, **28**, 347–369.

Mohite, B. (2013). Isolation and characterization of indole acetic acid-producing bacteria from rhizospheric soil and its effect on plant growth. *J. Soil Sci. Plant Nutr.*, **13**, 638–649.

Ngalimat, M.S., Raja Abd Rahman R.N.Z., Yusof M.T., Syahir A. and Sabri S. (2021). A review on the biotechnological applications of the operational group *Bacillus amyloliquefaciens* in agriculture. *Microorganisms*, **9**, 614.

Olanrewaju, O.S., Glick B.R. and Babalola O.O. (2019). Mechanisms of action of plant growth-promoting bacteria. *World J. Microbiol. Biotechnol.*, **35**, 197.

Patten, C.L. and Glick B.R. (2002). Role of *Pseudomonas putida* indoleacetic acid in development of the host plant root system. *Appl. Environ. Microbiol.*, **68**, 3795–3801.

Pikovskaya, R.I. (1948). Mobilization of phosphorus in soil in connection with the vital activity of some microbial species. *Mikrobiologiya*, **17**, 362–370.

Ramesh, A., Sharma S.K., Sharma M.P., Yadav N. and Joshi O.P. (2014). Inoculation of zinc-solubilizing *Bacillus aryabhattai* strains for improved growth, zinc bioavailability and yield of soybean. *Appl. Soil Ecol.*, **96**, 70–77.

Rodríguez, H. and Fraga R. (1999). Phosphate-solubilizing bacteria and their role in plant growth promotion. *Biotechnol. Adv.*, **17**, 319–339.

Sharif, M.K., Butt M.S., Anjum F.M. and Khan S.H. (2014). Rice bran: A novel functional ingredient. *Crit. Rev. Food Sci. Nutr.*, **54**, 807–816.

Sharma, A., Singh P., Kumar S. and Sharma R. (2023). Plant growth-promoting rhizobacteria and organic amendments improve photosynthetic pigments, nutrient uptake, and crop productivity under sustainable agricultural systems. *Front. Microbiol.*, **14**, 1194876.

Singh, R., Yadav A.N., Rajput V.D., Minkina T. and Mandzhieva S. (2022). Plant growth-promoting rhizobacteria for sustainable agriculture: Current perspectives and future challenges. *Microbiolog. Res.*, **263**, 127154.

Sluiter, A., Hames B., Ruiz R., Scarlata C., Sluiter J., Templeton D. and Crocker D. (2008). *Determination of Structural Carbohydrates and Lignin in Biomass*. National Renewable Energy Laboratory (NREL), Golden, Colorado.

Somasegaran, P. and Hoben H.J. (1994). *Handbook for Rhizobia: Methods in Legume–Rhizobium Technology*. Springer-Verlag, New York.

Spaepen, S., Vanderleyden J. and Remans R. (2007). Indole-3-acetic acid in microbial and microorganism–plant signaling. *FEMS Microbiol. Rev.*, **31**, 425–448.

Sun, Y. and Cheng J. (2002). Hydrolysis of lignocellulosic materials for ethanol production: A review. *Bioresource Technology*, **83**, 1–11.

Tang, H., Xiao X., Xu Y., Li C., Cheng K., Pan X. and Li W. (2019). Utilization of carbon sources in the rice rhizosphere and non-rhizosphere soils with different long-term fertilization management. *J. Basic Microbiol.*, **59**, 621–631.

Vessey, J.K. (2003). Plant growth-promoting rhizobacteria as biofertilizers. *Plant and Soil*, **255**, 571–586.

Vijayabaskar, P., Babinastarlin S., Shankar T., Sivakumar T. and Anandapandian K.T.K. (2011). Quantification and characterization of exopolysaccharides from *Bacillus subtilis*. *Int. J. Biolog. Technol.*, **2**, 71–76.

Vijayabaskar, P., Babinastarlin S., Shankar T., Sivakumar T. and Anandapandian K.T.K. (2011). Quantification and characterization of exopolysaccharides from Bacillus subtilis (MTCC 121). *Adv Biol Res.*, **5(2)**, 71-76.

Wang, W., Wang H., Feng Y. *et al.* (2019). Microbiomes inhabiting rice roots and rhizosphere. *FEMS Microbiol. Ecol.*, **95**.