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Isolation, Biochemical Characterization and Plant Growth-Promoting Potential of Rhizobacteria from the Soybean Rhizosphere

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Abstract:

Plant growth-promoting Rhizobacteria (PGPR) are beneficial microorganisms with potential applications in sustainable agriculture. This study aimed to isolate, characterize, and evaluate the plant growth-promoting potential of Rhizobacteria associated with the soybean (*Glycine max* L.). Rhizosphere soil samples were collected from soybean fields of Dera Ghazi Khan, Punjab, Pakistan, and eight bacterial isolates (SRB-1 to SRB-8) were obtained through culture-based isolation. The isolates were characterized based on morphological and biochemical properties and screened for important PGPR traits, including phosphate solubilization, indole-3-acetic acid (IAA) production, siderophores production, and nitrogen fixation. Considerable diversity was observed among isolates in colony characteristics, Gram reaction, and biochemical profiles. All isolates showed positive catalase activity, nitrate reduction, and carbohydrate utilization. Phosphate solubilization ranged from 11.4 to 23.1 mm, while IAA production varied from 16.9 to 38.5 µg mL^{-1}. SRB-8 exhibited the highest phosphate solubilization index (2.75) and IAA production (38.5 µg mL^{-1}), followed by SRB-4 and SRB-6. Integrated evaluation identified SRB-4, SRB-6, and SRB-8 as superior isolates possessing multiple PGPR traits. These findings highlight the potential of indigenous soybean Rhizobacteria as promising bio fertilizer candidates for enhancing soil fertility and sustainable soybean production.

Keywords: Plant growth-promoting Rhizobacteria (PGPR), Soybean (*Glycine max* L.) Rhizosphere solubilization, Bio fertilizer.

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Fungal name: FN 860456. GenBank BioProjects: PRJNA1365736, PRJNA1306032, PRJNA1303219, SRA: RS26138520

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of the most important leguminous crops globally due to its high nutritional value, economic importance and diverse applications in food, feed, and industry (Kumari *et al.,* 2025). It is a rich source of protein, edible oil, carbohydrates, vitamins, minerals and bioactive compounds, contributing significantly to global food security (Oluwole *et al.,* 2023). However, increasing agricultural demands have resulted in extensive use of chemical fertilizers and pesticides to enhance crop productivity, leading to soil degradation, environmental pollution and disruption of beneficial microbial communities (Yasir *at el.,* 2025).

Therefore, sustainable approaches are required to improve crop production while maintaining ecosystem health (Xing *et al.,* 2025). The Rhizosphere represents a dynamic microbial environment where beneficial microorganisms interact with plant roots (Adedayo and Olorunkosebi, 2025). Among these microorganisms, plant growth-promoting Rhizobacteria (PGPR) have gained significant attention due to their ability to enhance plant growth through nutrient mobilization, phytohormone production, stress tolerance, and pathogen suppression (Siyar *et al.,* 2019; Singh *et al.,*2026).

Plant growth-promoting Rhizobacteria (PGPR) is beneficial soil microorganisms that colonize plant roots and improve plant performance through multiple direct and indirect mechanisms (Wang *et al.,* 2026). Direct mechanisms include biological nitrogen fixation, phosphate solubilization, potassium and zinc mobilization siderophores production and synthesis of phytohormone such as indole-3-acetic acid (IAA), gibberellins, and cytokinins (Hnini et al., 2025). These activities enhance root development, nutrient uptake and overall plant growth (Cheng *et al.,* 2025).

Many PGPR also produce ACC deaminizes, which regulates stress-induced ethylene levels and improves plant tolerance to drought, salinity and other environmental stresses (Patel *et al.,* 2026). Additionally, exopolysaccharide production enhances soil structure, water retention, and bacterial colonization of plant roots. Through indirect mechanisms, PGPR suppress plant pathogens by producing antibiotics, siderophores, hydrolytic enzymes, hydrogen cyanide and antifungal metabolites, thereby improving plant health and reducing dependence on chemical inputs (Kumar *et al.,* 2026).

The soybean Rhizosphere contains diverse microbial communities that contribute to nutrient cycling, soil fertility (Karthik *et al.,* 2026) and plant development. Beneficial bacterial genera such as Bacillus, Pseudomonas, Rhizobium (Somaly *et al.,* 2026) Paenibacillus Enterobacter and Azospirillum are commonly associated with soybean roots and play important roles in nitrogen fixation, phosphorus solubilization, disease suppression, and stress adaptation (Bashir *et al.,* 2026). However, Rhizobacteria diversity and functional characteristics are influenced by soil properties, climatic conditions, crop varieties and agricultural management practices (Iqbal, 2026). Therefore, the identification and utilization of indigenous Rhizobacteria adapted to local environmental conditions are essential for developing effective microbial inoculants for sustainable soybean production.

Isolation and characterization of Rhizobacteria are fundamental steps for discovering beneficial microbial strains with agricultural applications (Gehlot *et al.,* 2026). Culture-based isolation combined with morphological and biochemical characterization provides valuable information regarding bacterial diversity, physiological properties and metabolic potential (Sun *et al.,* 2026). Common biochemical assessments, including Gram staining, catalase, oxidase, citrate utilization, urease activity, starch hydrolysis, nitrate reduction and carbohydrate utilization, assist in preliminary identification and functional evaluation of bacterial isolates (Fuadh-Al-Kabir *et al.,* 2026).

The characterization of plant growth-promoting traits, including phosphate solubilization, indole-3-acetic acid production, siderophores production, and nitrogen fixation ability, helps identify promising Rhizobacteria candidates. Such indigenous PGPR strains can serve as eco-friendly bio fertilizers, contributing to improved soybean productivity, enhanced soil health and sustainable agricultural practices (Syakur *et al.,* 2026).

The isolation and characterization of indigenous soybean-associated Rhizobacteria are essential for identifying efficient microbial strains with potential applications as bio fertilizers and biological control agents (Tariq, 2026). The present study focuses on the isolation, biochemical characterization, and evaluation of plant growth-promoting potential of Rhizobacteria from the soybean Rhizosphere.

MATERIALS AND METHODS

Study Area, Experimental Design, and Soil Sample Collection

The study was conducted in agricultural fields of Dera Ghazi Khan District, Punjab, Pakistan, a semi-arid region characterized by soybean cultivation and diverse agricultural practices.

A purposive field-based sampling design was used to collect Rhizosphere soil associated with healthy soybean (*Glycine max* (L. Merr) Plants. Five soybean fields with established soybean crops were selected to provide spatially independent sampling sites. From each field, 10 healthy and representative soybean plants were selected, resulting in a total of 50 plants and 50 Rhizosphere soil samples. Plants were selected based on uniform growth, absence of visible disease symptoms, and comparable developmental stage. Sampling was performed during July–August 2025.

Rhizosphere soil was collected from the root zone of each selected soybean plant. Plants were carefully uprooted using sterile tools, and loosely adhering bulk soil was removed without disturbing the soil tightly attached to the roots. Approximately 50–100 g of Rhizosphere soil associated with each plant was collected aseptically from a depth of approximately 0–15 cm. Each sample was placed in a separately labeled sterile polyethylene bag and transported to the laboratory under cooled conditions.

Samples were processed as soon as possible after collection to minimize changes in the indigenous microbial population. For bacterial isolation, approximately 1 g of each Rhizosphere soil sample was suspended in sterile physiological saline and serially diluted. Appropriate dilutions were spread onto nutrient agar plates and incubated at approximately 28 ± 2°C for 24–48 h. Distinct bacterial colonies differing in colony morphology were selected and repeatedly streaked onto fresh nutrient agar plates to obtain pure cultures (Ebah *et al.,* 2024). Three replicates were prepared for each dilution during the isolation procedure to improve the reliability of colony recovery.

Representative purified isolates were assigned codes SRB-1 to SRB-8 and maintained on appropriate culture media for subsequent characterization. The eight isolates were selected based on differences in colony morphology and their ability to grow consistently in culture. Morphological characterization was followed by Gram staining and biochemical assays, including catalase, oxidase, citrate utilization, urease, indole production, nitrate reduction, starch hydrolysis, and carbohydrate utilization. Each biochemical test was performed using three replicates under standardized laboratory conditions (Yunus *et al.,* 2016).

The plant growth-promoting potential of the selected isolates was subsequently evaluated through phosphate solubilization, phosphate solubilization index (PSI), indole-3-acetic acid (IAA) production, siderophores production, and nitrogen-fixation assays. Quantitative assays were performed in triplicate, and the mean values were used for analysis. The independent soybean plants and fields served as the biological sampling units, whereas repeated measurements or assay replicates represented technical replicates. This experimental design enabled the recovery and comparative characterization of indigenous soybean Rhizobacteria and provided a reproducible basis for identifying isolates with promising plant growth-promoting properties.

Plant Growth-Promoting Trait Assays

Phosphate Solubilization and Phosphate Solubilization Index

The plant growth-promoting potential of the selected isolates was evaluated through phosphate solubilization and phosphate solubilization index (PSI) assays (Teymouri *et al.,* 2016). Quantitative assays were performed in triplicate, and mean values were used for analysis. PSI was calculated as a quantitative measure of phosphate-solubilization efficiency and was not considered an independent PGPR trait.

Indole-3-Acetic Acid Production

Indole-3-acetic acid (IAA) production was evaluated among the soybean Rhizobacteria isolates. Quantitative assays were performed in triplicate, and the results were expressed as µg/m (Khianngam *et al.,* 2023).

Siderophores Production

Siderophores production was evaluated as one of the plant growth-promoting characteristics of the soybean Rhizobacteria isolates. The results were recorded as positive (+) or negative (−). Siderophores production was considered one of the four evaluated PGPR traits (Adeoyo, 2025).

Nitrogen-Fixation Potential

Nitrogen-fixation ability was evaluated as a plant growth-promoting characteristic of the soybean Rhizobacteria isolates (Purwaningsih *et al.,* 2023). The results were recorded as positive (+) or negative (−). Potential nitrogen-fixation ability was observed in SRB-1, SRB-2, SRB-4, SRB-5, SRB-6, and SRB-8.

Experimental Replication

Quantitative assays were performed in triplicate, and mean values were used for analysis. The independent soybean plants and fields served as the biological sampling units, whereas repeated measurements or assay replicates represented technical replicates. No greenhouse or field experiments were conducted

Statistical Analysis

Quantitative measurements of phosphate solubilization and IAA production were analyzed statistically to determine differences among the soybean Rhizobacteria isolates (SRB-1–SRB-8). For each assay, replicate observations were used to calculate the mean and standard error (SE). Differences among isolates were evaluated using one-way analysis of variance (ANOVA), with bacterial isolate treated as the independent factor. When the ANOVA indicated a significant overall difference, Tukey's honestly significant difference (HSD) test was used for post-hoc pairwise comparisons. Statistical significance was assessed at $p < 0.05$. The results are presented as mean ± SE, and different superscript letters in Table 3 indicate statistically significant differences among isolates.

RESULTS

Table 1 summarizes the morphological characteristics of eight Rhizobacteria isolates (SRB-1 to SRB-8) recovered from the soybean Rhizosphere. The isolates exhibited considerable variation in colony color, shape, margin, elevation and surface texture, indicating the presence of diverse bacterial populations. Most isolates formed circular colonies with entire margins and convex or raised elevations, while SRB-3 and SRB-7 showed irregular colonies with rough surfaces.

Gram staining revealed that five isolates were Gram-positive and three were Gram-negative, whereas all isolates exhibited rod-shaped cell morphology.

Table 1. Isolation and Morphological Characterization of Rhizobacteria Isolates from Soybean Rhizosphere.

Isolate Code	Colony Color	Shape	Margin	Elevation	Surface Texture	Gram Reaction	Cell Morphology
SRB-1	Cream	Circular	Entire	Convex	Smooth	+	Rod-shaped
SRB-2	White	Circular	Entire	Raised	Smooth	+	Rod-shaped
SRB-3	Yellow	Irregular	Undulate	Flat	Rough	–	Rod-shaped
SRB-4	Cream	Circular	Entire	Convex	Mucoid	+	Rod-shaped
SRB-5	White	Circular	Entire	Raised	Smooth	–	Rod-shaped
SRB-6	Pale Yellow	Circular	Entire	Convex	Shiny	+	Rod-shaped
SRB-7	White	Irregular	Lobate	Flat	Rough	–	Rod-shaped
SRB-8	Cream	Circular	Entire	Raised	Smooth	+	Rod-shaped

Table 2 presents the biochemical characteristics of eight Rhizobacteria isolates recovered from the soybean Rhizosphere. All isolates were catalase-positive, nitrate reduction-positive, and capable of carbohydrate utilization, indicating active metabolic potential. Oxidase activity was detected in five isolates (SRB-1, SRB-2, SRB-4, SRB-6, and SRB-8), while citrate utilization was positive in all isolates except SRB-5. Urease activity was observed in SRB-2, SRB-4, SRB-5 and SRB-8, whereas iodole production was detected only in SRB-3, SRB-4, SRB-6 and SRB-8. Starch hydrolysis was positive in six isolates but absent in SRB-3 and SRB-7.

Table 2. Biochemical Characterization of Soybean Rhizobacteria Isolates.

Isolate	Catalase	Oxidase	Citrate Utilization	Urease	Indole Production	Nitrate Reduction	Starch Hydrolysis	Carbohydrate Utilization
SRB-1	+	+	+	–	+	+	+	+
SRB-2	+	+	+	+	–	+	+	+
SRB-3	+	–	+	–	+	+	–	+
SRB-4	+	+	+	+	+	+	+	+
SRB-5	+	–	–	+	–	+	+	+
SRB-6	+	+	+	–	+	+	+	+
SRB-7	+	–	+	–	–	+	–	+
SRB-8	+	+	+	+	+	+	+	+

Table 3 presents the plant growth-promoting characteristics of the eight soybean Rhizobacteria isolates (SRB-1–SRB-8). Quantitative analysis showed variation among the isolates in phosphate-solubilization activity and IAA production. Phosphate solubilization ranged from 12.6 ± 0.6 mm in SRB-3 to 22.4 ± 0.7 mm in SRB-4, while IAA production ranged from 18.7 ± 1.1 µg/mL in SRB-3 to 35.8 ± 1.5 µg/mL in SRB-4 among the isolates shown. SRB-4 exhibited the highest phosphate-solubilization activity and IAA production, whereas SRB-3 showed the lowest values. Different superscript letters indicate statistically significant differences among isolates based on the post-hoc comparison at $p < 0.05$. PSI values ranged from 1.85 to 2.65 and were used as a quantitative measure of phosphate-solubilization efficiency rather than as an independent PGPR trait. Siderophores production was detected in all isolates shown, whereas nitrogen-fixation ability varied among the isolates.

Overall, the results demonstrate considerable variation in plant growth-promoting characteristics among the soybean

Rhizobacteria isolates, with SRB-4 showing the strongest quantitative PGPR performance among the isolates presented.

Table 3. Plant Growth-Promoting Traits of Soybean Rhizobacteria Isolates.

Isolate	Phosphate Solubilization (mm)	PSI	IAA Production (μg/mL)	Siderophores	Nitrogen Fixation
SRB-1	18.5 ± 0.5[a]	2.35	28.6 ± 1.2[a]	+	+
SRB-2	15.2 ± 0.8[b]	2.10	22.4 ± 0.9[b]	+	+
SRB-3	12.6 ± 0.6[c]	1.85	18.7 ± 1.1[c]	+	−
SRB-4	22.4 ± 0.7[d]	2.65	35.8 ± 1.5[d]	+	+

Table 4 summarizes the overall plant growth-promoting potential of the eight soybean Rhizobacteria isolates based on their biochemical characteristics and PGPR traits. The biochemical score represents the number of positive reactions obtained from eight biochemical tests, while the PGPR score is based on four functional traits: phosphate solubilization, IAA production, siderophores production, and nitrogen-fixing ability. Phosphate solubilization index (PSI) was considered a quantitative measure of phosphate-solubilizing activity and was therefore not counted as an independent PGPR trait. SRB-4, SRB-6 and SRB-8 showed the strongest overall profiles, with positive results for all four PGPR traits and high biochemical scores. SRB-1 and SRB-2 also demonstrated strong potential, whereas SRB-3 and SRB-5 showed moderate potential. SRB-7 exhibited the lowest overall potential, with fewer positive biochemical and PGPR characteristics. Notably, SRB-2 showed seven positive biochemical reactions out of eight, reflecting its negative reaction in the indole test.

Overall, the scoring system provides a comparative preliminary assessment of the isolates for subsequent evaluation of their plant growth-promoting potential.

Table 4. Overall Plant Growth-Promoting Potential Ranking of Rhizobacteria Isolates.

Isolate	Positive Biochemical Tests (out of 8)	Positive PGPR Traits (out of 4)	Overall Potential
SRB-1	7	4	High
SRB-2	7	4	High
SRB-3	5	2	Moderate
SRB-4	8	4	Very High
SRB-5	5	3	Moderate
SRB-6	7	4	Very High
SRB-7	4	2	Low
SRB-8	8	4	Very High

DISCUSSION

Eight Rhizobacteria isolates (SRB-1 to SRB-8) were successfully isolated from the soybean Rhizosphere and characterized based on their morphological, biochemical and plant growth-promoting (PGPR) properties (Tamrakar *et al.,* 2026). The recovery of morphologically distinct isolates indicates the diversity of cultivable Rhizobacteria associated with soybean roots (Lin *et al.,* 2025).

The Rhizobacteria isolates showed variation in colony color, shape, margin, elevation, and surface texture, indicating phenotypic diversity among the recovered bacterial populations. Most isolates produced circular colonies with entire margins and convex or raised elevations, whereas SRB-3 and SRB-7 produced irregular colonies with rough surfaces. Although some observed characteristics may be consistent with bacterial groups commonly associated with soybean Rhizosphere, such as *Bacillus* and *Pseudomonas*, the isolates were not assigned to these genera based solely on morphological or biochemical characteristics. Definitive taxonomic identification would require molecular characterization, preferably through 16S rRNA gene sequencing and subsequent sequence analysis. Therefore, the isolates are consistently referred to by their experimental codes SRB-1–SRB-8 throughout the manuscript.

The eight purified soybean Rhizobacteria isolates (SRB-1–SRB-8) were subjected to a series of biochemical tests for preliminary physiological characterization and differentiation.

All eight isolates exhibited catalase activity, nitrate reduction, and carbohydrate utilization. Oxidase activity was detected in SRB-1, SRB-2, SRB-4, SRB-6, and SRB-8, whereas SRB-3, SRB-5, and SRB-7 were oxidase-negative. Citrate utilization was observed in all isolates except SRB-5. Urease activity was detected in SRB-2, SRB-3, SRB-4, SRB-5, SRB-7, and SRB-8, according to the biochemical profile. Indole production varied among the isolates, while starch hydrolysis was observed in most isolates but was absent in SRB-3 and SRB-7.

The observed biochemical variation demonstrated physiological diversity among the soybean Rhizobacteria isolates. These biochemical characteristics were used as preliminary phenotypic evidence for differentiating the isolates and selecting candidates for subsequent plant growth-promoting trait evaluation. Because morphological, Gram-staining, and biochemical characteristics alone are insufficient for reliable taxonomic assignment, all isolates were retained under their experimental codes (SRB-1–SRB-8). Molecular identification, preferably based on 16S rRNA gene sequencing followed by sequence comparison and phylogenetic analysis, would be required to establish their taxonomic identities.

Evaluation of plant growth-promoting traits identified substantial differences among the isolates. Phosphate solubilization ranged from 11.4 to 23.1 mm, with SRB-8 exhibiting the largest halo zone, followed by SRB-4 and SRB-6.

The phosphate solubilization index showed a similar trend, with the highest value recorded for SRB-8 (2.75). Indole-3-acetic acid production ranged from 16.9 to 38.5 µg mL^{-1}, and SRB-8 again produced the highest amount, followed by SRB-4 and SRB-6. Siderophores production was detected in six isolates, while nitrogen fixation was positive in six isolates but absent in SRB-3 and SRB-7. The simultaneous expression of multiple PGPR traits indicates that these isolates possess the potential to improve nutrient availability, stimulate root growth and enhance plant development under natural soil conditions.

The integrated evaluation (Table 4) ranked SRB-4, SRB-6 and SRB-8 as the most promising isolates because they combined strong biochemical characteristics with all five positive plant growth-promoting traits. SRB-1 and SRB-2 also demonstrated high potential, whereas SRB-3 and SRB-5 showed moderate performance. SRB-7 exhibited the lowest overall potential due to fewer positive biochemical and PGPR characteristics.

The integrated screening approach indicates that SRB-4, SRB-6, and SRB-8 are the most promising candidates for further investigation because they combined multiple positive plant-growth-promoting characteristics with comparatively strong quantitative performance in the in vitro assays. Their selection was therefore based not on a single phenotype but on the combined expression of phosphate solubilization, IAA production, siderophores production, and potential nitrogen-fixation ability. Among these isolates, SRB-8 showed particularly strong phosphate-solubilization and IAA-production performance, whereas SRB-4 and SRB-6 also demonstrated consistently favorable profiles across the evaluated traits.

Nevertheless, these differences should be interpreted as preliminary in vitro evidence rather than proof of superior plant-growth-promoting efficacy.

The observed functional diversity is consistent with previous studies reporting that soybean-associated Rhizobacteria may express multiple mechanisms involved in nutrient mobilization and plant growth promotion. Phosphate-solubilizing bacteria can increase the availability of otherwise poorly soluble phosphorus compounds, while IAA-producing bacteria may influence root development and nutrient acquisition. Siderophores production may additionally contribute to iron acquisition and microbial competition in the Rhizosphere. However, expression of these traits under laboratory conditions does not necessarily predict their performance in soil or within living plants because bacterial survival, root colonization, soil properties, environmental conditions, and plant–microbe interactions can substantially influence the effectiveness of microbial inoculants.

Accordingly, SRB-4, SRB-6, and SRB-8 should be regarded as candidate PGPR isolates rather than confirmed bio fertilizers. Molecular identification and greenhouse experiments are required to determine their taxonomic identity, root-colonization ability, compatibility with soybean, and actual effects on plant growth and nutrient uptake. The most effective isolate(s) under controlled greenhouse conditions should subsequently be evaluated under field conditions to determine their consistency and agronomic effectiveness. These findings suggest that SRB-4, SRB-6 and SRB-8 are suitable candidates for further molecular identification, greenhouse validation and field evaluation as potential bio fertilizers for sustainable soybean production.

Overall, the study demonstrates that the soybean Rhizosphere harbors metabolically diverse Rhizobacteria with multiple plant growth-promoting properties. The combined ability of selected isolates to solubilize phosphate, produce indole-3-acetic acid and siderophores, and fix atmospheric nitrogen highlights their potential as environmentally friendly microbial inoculants capable of reducing dependence on chemical fertilizers while improving soybean productivity.

CONCLUSION

The present study recovered eight Rhizobacteria isolates (SRB-1–SRB-8) from the soybean Rhizosphere of Dera Ghazi Khan, Punjab, Pakistan, and evaluated their morphological, biochemical, and plant growth-promoting characteristics. The isolates displayed noticeable phenotypic and biochemical variation, reflecting diversity among the cultivable bacterial population associated with soybean roots. Although Gram staining and biochemical profiles provided useful preliminary characterization, these approaches cannot establish bacterial taxonomy; therefore, molecular identification remains necessary.

Functional screening demonstrated variation in phosphate solubilization, PSI, IAA production, siderophores production, and potential nitrogen-fixation ability. Phosphate-solubilization activity ranged from 11.4 to 23.1 mm, while PSI values ranged from 1.85 to 2.75. SRB-8 showed the strongest phosphate-solubilizing performance and the highest PSI. IAA production ranged from 16.9 to 38.5 µg/mL with SRB-8 again showing the highest value. Siderophores production was detected in all eight isolates, whereas potential nitrogen-fixation ability was observed in six isolates. PSI was considered a quantitative indicator of phosphate-solubilization efficiency rather than an additional PGPR trait.

The combined screening results identified SRB-4, SRB-6, and SRB-8 as the most promising candidate isolates because of their multiple positive PGPR characteristics and comparatively strong in vitro performance. In particular, SRB-8 demonstrated notable phosphate-solubilizing and IAA-producing activity. These findings indicate that the selected isolates may possess useful functional characteristics for soybean production; however, their effectiveness as microbial inoculants has not been experimentally demonstrated.

RECOMMENDATIONS

The study was limited to laboratory-based isolation and in vitro characterization, with no greenhouse or field inoculation trials. Consequently, the effects of the selected isolates on soybean growth, nutrient acquisition, root colonization, and yield remain unresolved. Furthermore, their taxonomic identities require molecular confirmation.

Future investigations should therefore include 16S rRNA gene sequencing, quantitative functional assays, and controlled greenhouse experiments. Isolates demonstrating the strongest plant responses should subsequently undergo field evaluation to determine their consistency, agronomic performance, environmental adaptability, and suitability for development as soybean bio fertilizer candidates. Thus, SRB-4, SRB-6, and SRB-8 can presently be regarded as promising indigenous PGPR candidates requiring further validation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

GENERATIVE AI STATEMENT

This study used Generative AI tools in data reorganization. We confirm that all AI-assisted processes were critically reviewed by the author’s to ensure the integrity and reliability of the results. The final decisions and interpretations presented in this article were solely made by the author’s.

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