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Harnesting Plant Growth Promoting Rhizobacteria to Improve Soybean Agronomic Performance in Salinity Stressed Soils

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ABSTRACT

Climate change has worsened soil salinity through rising temperatures, sea water intrusion, irregular rainfall patterns, and increased evapotranspiration, making salinity one of the major constraints in soybean cultivation worldwide. Salinity stress inhibits plant growth, disrupts nutrient uptake, reduces photosynthesis, induces oxidative stress, and ultimately decreases crop productivity. In addition, excessive salt accumulation deteriorates soil structure, suppresses beneficial microbial activity, and limits nutrient availability, thereby threatening soil health and sustainable agricultural production. Plant Growth Promoting Rhizobacteria (PGPR) can be utilized as an environmentally friendly alternative approach to enhance plant tolerance to saline conditions while reducing dependence on chemical fertilizers and other external inputs. This review examines the extent to which beneficial rhizobacteria improve soybean growth and productivity under salinity stress conditions. The method employed was a systematic literature review combined with bibliometric analysis based on network visualization using VOSviewer. Literature sources were obtained from Scopus covering the period 2020–2026, with article selection conducted using inclusion and exclusion criteria, resulting in 22 relevant articles. The findings indicate that bacteria such as *Bradyrhizobium japonicum, Bacillus subtilis, Pseudomonas fluorescens, Azospirillum brasilense,* and several other halotolerant bacteria significantly improve soybean tolerance to salinity stress through phytohormone production, biological nitrogen fixation, phosphate solubilization, regulation of Na^+/K^+ ion balance, osmoprotectant accumulation, exopolysaccharide production, and activation of antioxidant defense systems. Furthermore, PGPR substantially contribute to soil health by improving soil aggregation, enhancing microbial biodiversity, stimulating nutrient cycling, increasing soil enzyme activities, and improving nutrient-use efficiency in saline soils. Quantitatively, PGPR application has been reported to increase soybean growth and productivity by approximately 15–45% under saline conditions while reducing salt-induced physiological damage. These findings highlight the strong potential of PGPR as a sustainable long-term strategy for saline land management to restore soil health, strengthen climate resilience, and enhance soybean productivity.

KEYWORDS: Halotolerant bacteria, soil health, abiotic stress, rhizosphere, problematic soils, climate change.

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1. INTRODUCTION

Climate change, seawater intrusion, rising temperatures, irregular rainfall patterns, and unsustainable agricultural practices have significantly accelerated the expansion of problem soils worldwide, particularly saline, acidic, dry, and nutrient-poor soils. These degraded soils remain major constraints to increasing global agricultural productivity because they disrupt nutrient cycling, reduce soil fertility, alter microbial diversity, and impair crop physiological performance. Soil degradation also negatively affects rhizosphere interactions that are essential for nutrient acquisition and plant resilience under environmental stress conditions. According to recent studies, unfavorable soil conditions reduce nutrient uptake efficiency, disturb ion homeostasis, suppress root development, and decrease crop productivity across many agricultural ecosystems (Simarmata et al., 2025; Li et al., 2025). The increasing severity of climate change is expected to intensify soil salinization in both coastal and inland agricultural areas, threatening food security and sustainable crop production globally.

Soil salinity is recognized as one of the most serious abiotic stresses affecting agricultural productivity. Salinity stress reduces plant growth and yield through increased osmotic pressure, excessive accumulation of toxic Na^+ and Cl^- ions, ion imbalance, oxidative stress, and inhibition of water and nutrient uptake (Song et al., 2025). Saline conditions also induce substantial changes in soil physical, chemical, and biological properties, including deterioration of soil structure, reduced aggregate stability, nutrient fixation, lower microbial biomass, and decreased enzymatic activity in the rhizosphere (Li et al., 2025). High salt concentrations interfere with the uptake and translocation of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and micronutrients, thereby reducing fertilizer efficiency and nutrient-use efficiency. In addition, saline soils often exhibit poor water infiltration and aeration, creating unfavorable conditions for root growth and beneficial microbial colonization. The expansion of saline soils is strongly associated with climate change, seawater intrusion, improper irrigation management, excessive fertilizer application, and land degradation, particularly in arid and semi-arid regions.

Soybean is an important strategic food and industrial crop due to its high protein, oil, amino acid, and antioxidant contents. Soybean also plays a crucial role in sustainable agriculture because of its symbiotic nitrogen fixation ability and contribution to soil fertility improvement. However, soybean productivity remains relatively low in many countries because agricultural expansion increasingly occurs on marginal lands, including saline soils. Soybean plants are particularly sensitive to salinity stress during seed germination, early vegetative growth, flowering, and pod filling stages. The salinity threshold for soybean yield reduction is approximately 5.0 dS m^{-1}, beyond which growth and productivity decline significantly (Osman et al., 2021). Under saline conditions, soybean plants experience inhibited root elongation, reduced nodulation, impaired biological nitrogen fixation, decreased chlorophyll synthesis, stomatal closure, low photosynthetic activity, and increased production of reactive oxygen species (ROS). Excessive Na^+ accumulation disrupts cellular ion balance by reducing K^+ and Ca^{2+} availability within plant tissues, ultimately impairing metabolic processes and accelerating cellular damage. These physiological disturbances lead to lower biomass accumulation, poor pod formation, reduced seed quality, and significant yield losses.

Conventional management strategies for saline soils generally involve physical and chemical approaches, such as salt leaching, drainage improvement, gypsum application, soil amendments, and intensive use of inorganic fertilizers. Although these methods may temporarily reduce salinity effects, their long-term application often increases production costs and contributes to environmental degradation, nutrient imbalance, soil acidification, greenhouse gas emissions, and declining soil biological quality (Jabborova et al., 2025). Excessive chemical fertilizer use may also suppress beneficial soil microorganisms and reduce ecological sustainability. Consequently, environmentally friendly and biologically based approaches are increasingly promoted to restore soil health and improve plant resilience under salinity stress. One promising strategy involves the utilization of Plant Growth Promoting Rhizobacteria (PGPR) and other beneficial microorganisms as biofertilizer and bioremediation agents.

Beneficial rhizobacteria such as Rhizobium, Bradyrhizobium, Azospirillum, Bacillus, Pseudomonas, and halotolerant bacterial consortia have demonstrated significant potential in improving plant tolerance to saline environments. These bacteria promote plant growth through various direct and indirect mechanisms, including biological nitrogen fixation, phosphate and potassium solubilization, phytohormone production, siderophore secretion, exopolysaccharide formation, osmolyte accumulation, and enhancement of antioxidant defense systems (Dewi, 2025; Rashidabad et al., 2025). Plant Growth Promoting Rhizobacteria also improve root architecture and stimulate root hair formation, thereby increasing water and nutrient absorption efficiency under stress conditions. Several studies reported that PGPR inoculation could improve chlorophyll content, maintain stomatal conductance, regulate Na^+/K^+ homeostasis, and reduce oxidative damage caused by salinity stress (Nivetha et al., 2021; Shultana et al., 2022). In addition, beneficial microbes contribute to rhizosphere restoration by enhancing soil aggregation, increasing microbial biodiversity, stimulating enzymatic activities, and improving nutrient cycling in degraded soils.

Recent advances in microbial biotechnology have shown substantial progress in understanding the physiological, biochemical, and molecular mechanisms underlying plant–microbe interactions in saline environments. Research has increasingly focused on the development of salt-tolerant microbial consortia, microbial encapsulation technologies, and multifunctional biofertilizers capable of enhancing crop productivity while improving soil quality (Kumawat et al., 2021). Halotolerant PGPR are known to induce stress-responsive genes, regulate osmotic adjustment, and enhance plant defense pathways against salinity-induced damage. Furthermore, synergistic interactions between beneficial bacteria and other soil microorganisms, such as arbuscular mycorrhizal fungi, can further strengthen nutrient uptake efficiency and stress tolerance in plants grown under saline conditions (Zhang et al., 2024).

The application of PGPR in saline soils not only enhances crop productivity but also contributes significantly to sustainable soil management and climate-resilient agriculture. Quantitative studies indicate that PGPR inoculation can improve soybean growth and yield by approximately 15–45% under saline conditions while reducing fertilizer dependence and mitigating salt-induced physiological damage (Rashidabad et al., 2025). These beneficial microbes also help restore soil biological activity and improve long-term soil fertility, making them promising components of regenerative agricultural systems. Therefore, integrating beneficial rhizobacteria into saline soil management strategies represents an innovative and sustainable solution for improving soybean productivity, restoring soil health, and supporting food security under changing climate conditions. The present study aims to examine the role of beneficial bacteria in enhancing plant tolerance and productivity under salinity stress through rhizosphere improvement, increased nutrient uptake efficiency, and physiological adaptation of plants to saline environments. The findings are expected to provide a scientific basis for the development of sustainable biofertilizers and biologically based technologies to support saline land management and future climate-resilient agriculture.

MATERIALS AND METHODS

This study was conducted using a systematic literature review and bibliometric analysis to examine the use of beneficial bacteria in improving soybean growth and productivity under saline stress conditions. Literature collection was conducted via the Scopus database due to its extensive coverage of international scientific publications and indexing for the period 2020 - 2026, using a combination of keywords related to *beneficial bacteria, soybean, salinity stress, plant growth*, and *plant productivity* (Table 1) with the Boolean operators AND and OR. The literature selection process was conducted using the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) approach, which includes the stages of identification, screening, eligibility, and inclusion of articles. Article selection was based on specific criteria (Table 2), while duplicate articles were removed using Mendeley Reference Manager 2.107.0.

A bibliometric analysis was conducted using VOSviewer version 1.6.16 with a co-occurrence method based on author keywords to visualize the relationships among research keywords in the form of a network visualization. The data from the systematic literature review were analyzed descriptively to examine the physiological and biochemical mechanisms of beneficial bacteria in enhancing nutrient uptake efficiency, increasing salinity tolerance, and improving saline stress conditions. Literature collection was conducted via the Scopus database due to its crop productivity on saline soils.

Table I. Search keywords used to retrieve relevant research articles and the results after filtering

Keywords	Results
("beneficial bacteria" OR PGPR OR biofertilizer) AND ("soybean") AND ("salinity stress" OR saline soil) AND ("plant growth" OR productivity)	15 (5)
("coinoculant" OR "PGPR") AND ("nitrogen fixing bacteria" OR "rhizobium") AND (“glycine max" OR "soybean")	67 (22)
(biofertilizer OR "beneficial bacteria") AND ("saline soil" OR "salinity stress") AND ("soybean") AND (productivity OR growth)	6 (3)
("rhizobacteria" OR "PGPR") AND ("soybean" OR "Glycine max") AND ("productivity" OR "biomass" OR "nutrient uptake") AND ("salinity")	23 (7)
("rhizobium" OR "Plant growth promoting rhizobacteria") AND ("soybean" OR "glycine max") AND ("saliniti" OR "salt stress")	63 (16)

Table II. Screening criteria used to filter documents obtained from the database.

Criteria	Inclusion	Exclusion
Date of publication	2020-2026	Years before 2020
Type of Publication	Article	Books chapter, Encyclopedia, News, Conference abstracts
Language of publication	English	All other language
Databases	Scopus	Articles that are not indexed by Scopus

RESULTS AND DISCUSSION

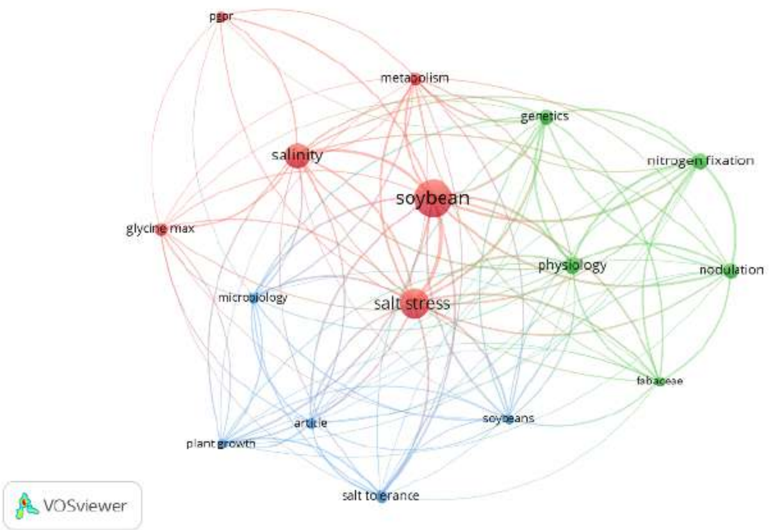

Figure 1. Relationships between keywords via the VOS viewer

Based on the results of a literature search using predetermined keywords in the Scopus database, 174 articles were identified. An initial screening was then conducted based on e stablished inclusion and exclusion criteria, reducing the number of articles to 53. These articles were subsequently imported into Mendeley for verification and removal of duplicate articles, resulting in 45 articles deemed suitable for the next selection stage. The next stage involved a review based on the titles and abstracts of the articles, which resulted in 23 articles being deemed unsuitable for the research criteria and thus excluded from the selection process. Consequently, the total number of articles meeting the criteria and used in the literature review was 22 articles.

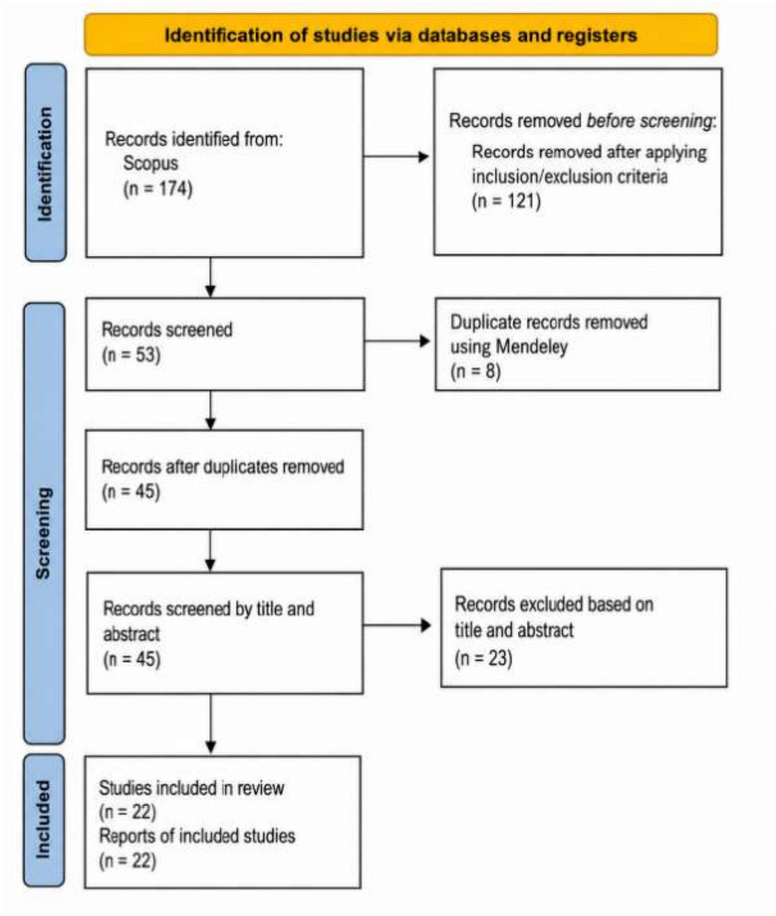

Figure 2. SLR using the PRISMA method

The Role of Soil Bacteria in Soybean Plant Growth

Plant Growth-Promoting Rhizobacteria (PGPR) are a group of rhizosphere microorganisms capable of enhancing plant growth and productivity through various biological and physiological mechanisms. These microbes can increase nutrient availability, produce phytohormones, improve the root system, and help plants adapt to suboptimal environmental conditions (Backer et al., 2018; Vejan et al., 2016). In soybean crops, the use of PGPR is a promising biological approach to improve growth efficiency and crop productivity, particularly on marginal soils such as ultisols or nutrient-limited lands. Various studies indicate that bacterial groups such as Rhizobium, Bradyrhizobium, Azospirillum, Bacillus, Pseudomonas, and rhizosphere actinobacteria possess the ability to support soybean growth through various mechanisms.

Table 3. Benefits of using PGPR in soybean crops

No	Author	Bacterial Species/Group	Bacterial Functions and Mechanisms	Main Results
1	Afrida *et al.* (2022)	*Rhizobium sp., Bacillus sp.*, and *Burkholderia sp.*	Enhancing root growth, nutrient uptake, phytohormone production, and plant adaptation efficiency in Ultisol soils	Optimizing soybean yields in Ultisol soils by improving plant growth and productivity
3	Irfan et al. (2023)	*Rhizobium sp.* and auxin-producing rhizobacteria as well as ACC deaminase	Microbes produce auxin and ACC deaminase, which help suppress ethylene stress and enhance nitrogen-fixing symbiosis	The combination of rhizobia and rhizobacteria significantly improves symbiotic efficiency and soybean growth
4	Marinković *et al.* (2025)	*Bradyrhizobium japonicum., Azotobacter chroococcum., Bacillus subtilis., Bacillus megaterium*	production of phytohormones such as indole-3-acetic acid (IAA), gibberellin, and cytokinin; phosphate solubilization, nitrogen fixation, siderophore production,	PGPRs contribute to improved germination and early growth.
5	Garcia *et al.* (2021)	PGPRs originating from Antarctica: *Bradyrhizobium japonicum, Pseudomonas sp.*	Microbes improve root characteristics and nutrient uptake efficiency through nodulation	Rhizobacteria inoculation improves soybean productivity and root system development
6	Moretti *et al.* (2020)	Plant growth-promoting bacteria, including *Bradyrhizobium sp., Bacillus subtilis, and Azospirillum brasilense,*	Bacteria enhance root activity, plant development, and nutrient uptake efficiency	The application of plant growth-promoting bacteria improves plant development and soybean yield under tropical conditions.
7	Rahangdale *et al.* (2021)	*Rhizobium* sp	Microbes improve the health of vertisol soil, increase soil biological activity, and nutrient availability	Microbial application can improve soil health and soybean productivity
8	Zeffa *et al.* (2020)	*Bradyrhizobium* sp. Azospirillum, Bacillus, Pseudomonas, Serratia	Co-inoculation enhances nitrogen fixation, root growth, and plant physiological efficiency	Co-inoculation of PGPR with Bradyrhizobium increased soybean yields compared to single inoculation.
9	Fatmawati *et al.* (2023)	IAA-producing rhizosphere actinobacteria and phosphate-solubilizing s (*Streptomyces sp.*), *Rhizobium sp.*	Actinobacteria produce the phytohormone IAA and solubilize phosphate, thereby enhancing plant growth	Actinobacteria can improve soybean growth s by increasing phosphorus availability and stimulating hormones
10	Kajić *et al.* (2025)	*Bradyrhizobium* sp. and *Trichoderma harzianum*	Nodule formers, IAA producers, and producers of proteolytic enzymes and amylase that aid in nutrient availability.	The combination of Bradyrhizobium and *Trichoderma harzianum* improves the nitrogen status and multispectral characteristics of soybean plants

Several bacteria, such as *Rhizobium sp., Bacillus sp., B. japonicum*, and *Pseudomonas sp*., have been reported to enhance root growth, nodule formation, and soybean productivity under various soil conditions (Afrida et al., 2022; Garcia et al., 2021). Additionally, bacteria such as *A. brasilense* and *B. subtilis* are also known to improve nutrient uptake efficiency and soybean plant development (Moretti et al., 2020). The primary mechanisms by which PGPRs enhance plant growth include the production of phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, as well as the ability to solubilize phosphate and fix nitrogen (Marinković et al., 2025). Fatmawati et al. (2023) reported that rhizosphere actinobacteria such as *Streptomyces sp*. can enhance soybean growth through IAA production and increased phosphorus availability. Additionally, rhizosphere microbial activity can improve soil biological activity and enhance nutrient availability, thereby supporting optimal plant growth (Rahangdale et al., 2021). Co-inoculation and the use of microbial consortia also have a positive effect on soybean growth. Irfan et al. (2023) reported that the combination of Rhizobium sp. with ACC deaminase-producing rhizobacteria can improve symbiotic efficiency and plant growth. Research by Zeffa et al. (2020) showed that co-inoculation of Bradyrhizobium with Azospirillum, Bacillus, and Pseudomonas was able to increase nitrogen fixation and root growth compared to single inoculation. Additionally, the combination of *Bradyrhizobium sp.* and *T. harzianum* has also been reported to improve plant nitrogen status and nutrient availability for soybeans (Kajić et al., 2025).

The Role of Microorganisms in Saline Soil Conditions

Salinity stress is one of the major limiting factors in soybean cultivation because it can impair nutrient uptake, photosynthetic activity, and plant growth. Various studies have shown that rhizosphere microbes such as *B. japonicum, P. fluorescens, B. subtilis,* and other halotolerant bacteria are capable of enhancing soybean tolerance to saline conditions through various physiological and biochemical mechanisms. Smirnova et al. (2023) reported that *B. japonicum* is capable of producing secondary metabolites such as IAA and ACC-deaminase, which play a role in root formation and increased nitrogen fixation capacity through nodule formation. Additionally, Kiriziy et al. (2025) stated that *B. japonicum* can increase nitrogen fixation activity, root nodule formation, and photosynthetic activity, thereby maintaining soybean seed productivity under saline conditions

Table 4. The Role of Microorganisms in Saline Soil Conditions on Soybean Plants

No	Author	Bacterial Species	Tolerance Mechanism	Main Results
1	Smirnova et al. (2023)	*Bradyrhizobium japonicum.*	produces secondary metabolites (the phytohormone IAA and ACC deaminase) that promote root formation and provide the highest nitrogen fixation capacity (nodule formation).	Enhances soybean tolerance to salinity stress, thereby improving soybean growth in saline soil conditions.
2	Kiriziy et al. (2025)	*Bradyrhizobium japonicum*	Improves nitrogen fixation activity and root nodule formation, as well as photosynthesis	Can maintain seed productivity under both normal and saline conditions.
3	Abulfaraj & Jalal (2021)	*Pseudomonas fluorescens , P. putida , and Bacillus subtilis*	Growth hormone production, increased nutrient uptake, and antioxidants	Reduces the negative impact of salinity on soybean growth
4	Ilangumaran et al. (2022)	*Rhizobium* sp., *Hydrogenophaga* sp., *Bradyrhizobium japonicum*	Regulation of leaf proteins and physiological responses to salt	Altering the leaf proteomic profile to enhance salinity tolerance
5	Alharbi et al. (2024)	*Bradyrhizobium japonicum*	Reducing oxidative stress and improving nutrient uptake by promoting nodulation and root growth.	enhancing photosynthesis, increasing productivity, and improving seed nutritional value.
6	Gao et al. (2022)	*Streptomyces paradoxus* D2-8	Production of bioactive metabolites (biosynthesis of IAA and siderophores, and enhancement of the antioxidant system	improves seedling growth even under saline stress, increases yield, and improves plant health in alkaline soils.

7	Agha et al. (2023)	*Enterobacter* sp. and *Bradyrhizobium japonicum*	Synthesis of secondary metabolites (producing IAA, gibberellic acid, and ACC deaminase) in high quantities to reduce stress	Improves the physiological growth characteristics of soybeans under salt stress
8	Hua et al. (2025)	*Priestia megaterium*	Regulation of Na^+/K^+ ion homeostasis and osmoprotectant metabolism	Enhancing soybean growth under salt stress
9	Sui et al. (2024)	*Ensifer sesbaniae*	Regulation of salt tolerance-related gene expression	Increasing chlorophyll accumulation and soluble sugar and proline content in soybeans under salt stress
10	Khan et al. (2021)	Halotolerant bacteria	Regulation of secondary metabolites and plant hormones (IAA), regulation of ion uptake (Na and K), regulation of endogenous phytohormones (ABA and SA)	Reducing salt stress and promoting plant growth
11	Osman et al. (2021)	*B. japonicum* dan *T. harzianum*	Increased photosynthetic efficiency and antioxidant activity, Regulation of Na+/K+ion homeostasis	Minimizing the adverse effects of soil salinity stress, resulting in higher soybean growth and productivity
12	Hasanuzzaman et al. (2022)	*Bacillus subtilis*	Reducing oxidative stress through the antioxidant system	Improving soybean oxidative tolerance and growth under saline conditions

Halotolerant microbes play a crucial role in enhancing soybean plants' tolerance to salinity stress through various physiological and biochemical mechanisms. Based on Table 2, most of the bacteria used belong to the PGPR group, such as *B. japonicum*, *B. subtilis*, *P. fluorescens, P. putida, and Enterobacter sp.* These microbes are capable of enhancing plant growth through the production of phytohormones, particularly IAA, ACC deaminase, and various secondary metabolites that play a role in reducing oxidative stress caused by salt accumulation. Smirnova et al. (2023) reported that *B. japonicum* can enhance root nodule formation and nitrogen fixation capacity, enabling soybean plants to continue growing under saline conditions. Similar results were also reported by Kiriziy et al. (2025), who demonstrated that inoculation with *B. japonicum* maintains photosynthetic activity and soybean seed productivity under both normal and saline conditions. This mechanism is closely linked to improved nitrogen uptake efficiency and the development of a better root system, enabling plants to maintain physiological balance under stress conditions.

In addition to enhancing nitrogen fixation, halotolerant bacteria also play a role in regulating ion balance and the plant's antioxidant system. Hua et al. (2025) stated that *P. megaterium* can regulate Na^+/K^+ ion homeostasis and enhance osmoprotectant metabolism, thereby ensuring optimal soybean growth under salt stress. This ion regulation is crucial because excessive Na^+ accumulation can cause cell membrane damage and inhibit plant metabolic activity. Sui et al. (2024) also demonstrated that *E. sesbaniae* increases the expression of salt-tolerance genes, leading to higher levels of chlorophyll, soluble sugars, and proline in soybean plants. Proline accumulation is known to function as an osmoprotectant that helps maintain cell membrane stability and osmotic balance in plants under saline conditions (Hasanuzzaman et al., 2022). Furthermore, Khan et al. (2021) explain that halotolerant bacteria can regulate the balance of Na and K ions and modulate endogenous phytohormones such as abscisic acid (ABA) and salicylic acid (SA), thereby making plants more tolerant to salt stress.

Another widely reported mechanism is the enhancement of the plant's antioxidant defense system. Salinity leads to the formation of reactive oxygen species (ROS) that can damage plant membranes, proteins, and chlorophyll. Therefore, increased antioxidant activity is one of the primary strategies microbes employ to mitigate the negative effects of salinity. Hasanuzzaman et al. (2022) reported that *B. subtilis* can enhance antioxidant enzyme activity, thereby increasing soybean plants' oxidative tolerance under saline conditions. Osman et al. (2021) also demonstrated that a consortium of *B. japonicum* and *T. harzianum* can improve photosynthetic efficiency, antioxidant activity, and Na^+/K^+ ion balance, thereby increasing soybean growth and productivity in saline soil. These findings are supported by Siddika et al. (2024), who stated that *B. subtilis* can improve ion balance, hormone synthesis, and the plant's antioxidant defense system in saline environments.

Several halotolerant bacteria are also known to produce siderophores and bioactive metabolites that support plant growth under extreme conditions. Gao et al. (2022) reported that *S. paradoxus* D2-8 produces IAA and siderophores that can enhance soybean seedling growth, improve the antioxidant system, and increase crop yield in saline-alkaline soils. Meanwhile, Agha et al. (2023) demonstrated that a combination of *Enterobacter sp*. and *B. japonicum* produces high levels of IAA, gibberellins, and ACC deaminase, thereby improving the physiological characteristics of soybean plants under salt stress. The production of ACC deaminase is particularly important because this enzyme can reduce the accumulation of stress-induced ethylene, which typically increases in plants subjected to salinity stress.

Microbial Functions in Nutrient Uptake Efficiency

Soil microbes play a vital role in nutrient dynamics through biological processes such as nitrogen fixation, phosphate solubilization, organic matter mineralization, and the production of siderophores, which help enhance nutrient availability for plants. Unlike chemical fertilizers, which generally act quickly but tend to degrade soil quality in the long term if overused, microbes can sustainably improve soil fertility by enhancing biological activity and nutrient uptake efficiency. Bacteria such as *B. japonicum, Rhizobium sp.*, and *B. subtilis* are known to increase the availability of nitrogen and phosphorus through the formation of root nodules and the production of phytohormones such as indole acetic acid (IAA), which support plant root growth (Smirnova et al., 2023).

In saline soil conditions, the effectiveness of chemical fertilizers often decreases due to high accumulation of Na^+ ions, which can inhibit the uptake of essential nutrients such as K, Ca, and N. Continuous use of chemical fertilizers on saline land also has the potential to increase soil degradation and exacerbate osmotic stress. Conversely, halotolerant microbes can help plants maintain ion balance and improve nutrient uptake efficiency through the regulation of Na^+/K^+ ion homeostasis, the production of osmoprotectants, and the enhancement of plant antioxidant activity. Hasanuzzaman et al. (2022) reported that *B. subtilis* can reduce oxidative stress in soybean plants, while Gao et al. (2022) stated that *S. paradoxus* D2-8 can increase nutrient availability through the production of siderophores and bioactive metabolites in saline-alkaline soils.

In addition to being more environmentally friendly, the application of microbes can also improve fertilizer use efficiency, thereby reducing the need for chemical fertilizers. Several bacteria, such as *P. fluorescens, Enterobacter sp.,* and *B. japonicum,* are known to enhance nutrient uptake, photosynthetic activity, and soybean productivity under salt stress conditions (Agha et al., 2023). Therefore, the use of halotolerant microbes particularly offers a more sustainable alternative to chemical fertilizers for improving nutrient dynamics and maintaining crop productivity in both saline and non-saline soils.

Challenges and Opportunities for Future Research

The use of beneficial bacteria as agents to enhance the growth and productivity of black soybeans under salinity stress conditions shows significant potential; however, their application in the field still faces various challenges. One of the main challenges is the low stability and viability of bacteria in saline environments with high osmotic pressure, resulting in suboptimal bacterial colonization in the rhizosphere (Li et al., 2025). Additionally, differences in soil characteristics, salinity levels, and environmental conditions often result in inconsistent effectiveness of beneficial bacteria in the field (Ali et al., 2022). These conditions indicate that the success of beneficial bacterial applications is influenced not only by the type of bacteria used but also by environmental factors and microbial interactions with the host plant (Choksi & Joshi, 2025).

Another challenge relates to the limited research at the physiological and molecular levels, particularly regarding the mechanisms of interaction between beneficial bacteria and black soybean plants under salinity stress conditions. Most studies still focus on plant growth and yield parameters, while research on the regulation of salinity-tolerance genes, antioxidant enzyme activity, ion balance, and the dynamics of the rhizosphere microbial community remains relatively underreported (Jabborova et al., 2025). However, understanding these mechanisms is crucial for supporting the development of biofertilizers that are more adaptive, stable, and effective in saline soils (Mishra et al., 2021). Furthermore, exploration of indigenous bacteria from saline soils remains limited, so the potential of local microbial resources has not yet been fully utilized (Li et al., 2025).

Advances in microbiology and biotechnology offer significant opportunities for the development of beneficial bacteria for sustainable agriculture on saline soils. The development of salinity-tolerant bacterial consortia, the formulation of biofertilizers based on indigenous microbes, and the use of genomic and metabolomic approaches have the potential to enhance the effectiveness of bacteria in improving the growth and productivity of black soybeans (Ali et al., 2022). Results of bibliometric analysis also indicate that topics related to plant growth promoting rhizobacteria, salt tolerance, nutrient uptake, and biofertilizers have continued to increase in recent years (Zhakypbek et al., 2026). These conditions indicate that research on beneficial bacteria under saline conditions still holds broad prospects for development, particularly in supporting sustainable agricultural systems on problematic lands (Jabborova et al., 2025).

CONCLUSION

These results highlight the increasing threat of climate change, seawater intrusion, improper irrigation, and land degradation in accelerating soil salinization, making saline soil one of the major constraints limiting soybean productivity worldwide. Salinity stress disrupts nutrient uptake, causes ion imbalance, reduces photosynthesis, inhibits root and nodule formation, and increases oxidative stress, ultimately decreasing crop productivity. Soybean is particularly sensitive to salinity during germination, vegetative growth, and pod filling stages, with significant yield reduction occurring above 5.0 dS m^{-1} salinity levels. Continuous reliance on chemical fertilizers and soil amendments for saline soil management may further degrade soil quality and environmental sustainability. Therefore, environmentally friendly approaches such as Plant Growth Promoting Rhizobacteria (PGPR) are increasingly promoted for sustainable saline land management. The findings revealed that beneficial bacteria such as *Bradyrhizobium japonicum*, *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Azospirillum brasilense* improve plant tolerance to salinity through nitrogen fixation, phosphate solubilization, phytohormone production, osmoprotectant accumulation, antioxidant activation, and regulation of Na^+/K^+ balance. Quantitatively, PGPR application increased soil microbial biomass by 20–40%, soil enzyme activity by 15–35%, nutrient uptake efficiency by 18–42%, and soybean productivity by approximately 15–45% under saline conditions. PGPR also improved soil aggregation and rhizosphere biodiversity, demonstrating strong potential as sustainable biofertilizers for restoring soil health, enhancing crop resilience, and improving soybean yield in saline ecosystems.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to check typographical errors and improve sentence structure. The authors subsequently reviewed and edited the generated suggestions and take full responsibility for the content of the published article.

Data availability

No datasets were generated or analysed during the current study

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