



RESEARCH ARTICLE

Co-inoculation of saline-tolerant Rhizobacteria and silica application modulates physiological responses of soybean under salinity stress

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Abstract

Salinity is a major abiotic stress limiting legume productivity in coastal agroecosystems. This study investigated the efficacy of co-inoculating indigenous saline-tolerant *Rhizobium* sp. and Phosphate-Solubilising Bacteria (PSB) (*Enterobacter cloacae*), combined with silica (Si) fertiliser, on the growth and physiology of Anjasmoro soybean variety in saline soil (EC 4.12 dS m⁻¹). The experiment employed a Factorial Randomised Block Design (3 x 3) with 3 replications. The first factor was microbial inoculation (Control, 6 g and 12 g seed⁻¹) and the second was silica dosage (0, 150 and 300 kg ha⁻¹). Results indicated that while vegetative morphology showed no significant variance due to high salinity suppression, physiological markers were significantly affected. Co-inoculation at 12 g seed⁻¹ significantly increased chlorophyll content compared to the control ($P < 0.05$). Furthermore, inoculated plants exhibited lower proline levels compared to non-inoculated controls, suggesting successful stress mitigation by the rhizobacteria, thereby reducing physiological requirement of the plant for osmoprotectant accumulation. These findings suggest that while structural growth recovery in highly saline soils may require longer remediation, bio-inoculants effectively improve the physiological competence of soybeans.

Keywords: anjasmoro soybean; phosphate-solubilising bacteria, *Rhizobium*; saline; silica

Introduction

Salinity stress is a critical constraint in modern agriculture, severely impeding plant growth and productivity globally (1). In Indonesia, the utilisation of marginal coastal lands is often hampered by high electrical conductivity and ionic toxicity, which disrupt nutrient uptake and inhibit root proliferation in glycophytes like soybean. Approximately more than a million ha of agricultural land are classified as saline in Indonesia (2). This extensive area of saline land has the potential to reduce the yields of several key crops, including soybeans (*Glycine max*) (3). Effective utilisation of these saline lands could substantially enhance food production in Indonesia (4).

Soybeans is a crucial protein source, serving both as an industrial raw material and a food ingredient (5). However, plants grown in saline conditions experience osmotic and ionic stress, disrupting nutrient balance and hindering essential physiological processes such as transpiration, photosynthesis and root nodule development (6). Silica is known to fortify cell structure and improve water use efficiency, thereby enhancing plant resistance to abiotic stressors like salinity (7). Additionally, the nitrogen-fixing bacterium *Rhizobium* sp. plays a vital role in legume root nitrogen fixation, which is essential for soybean growth (8). When combined with PSB, *Rhizobium* sp. can increase the availability of essential nutrients to plants.

Endophytes, a class of microorganisms residing in the plant endosphere without causing symptoms, are influenced by the nutritional status of host plant (9). *R. laguerreae*, beyond its nitrogen-fixing capabilities, exhibits notable *in vitro* plant growth-promoting (PGP) activities comparable to traditional PGP rhizobacteria. It has been shown to enhance plant growth in both legume and non-legume species. For instance, *R. laguerreae* PEPV40, isolated from *Phaseolus vulgaris*, demonstrates significant siderophore production, indole acetic acid (IAA) synthesis and phosphate solubilisation (10). The combination of *Rhizobium* and PSB has yielded superior results in terms of yield, nitrogen fixation and nodulation. Phosphorus, while not confined to nodules, is locally isolated from the root endosphere. Nodules are considered a significant source of plant growth-promoting rhizobacteria (PGPR) and may serve as valuable agricultural inoculants (11). Our findings suggested that non-rhizobial strains capable of colonising nodules and enhancing their function are also present in the root endosphere (8).

Co-inoculating plants with *Rhizobium* and PSB to enhance symbiotic nitrogen fixation is a promising strategy for increasing nitrogen availability in sustainable agricultural systems. Numerous studies have shown that simultaneous inoculation with specific PGPR improves nodulation and growth in various legume species under different growing conditions (12). According to one study, a

combination has been reported to increase flavonoid levels, total plant nitrogen content, biomass of roots and shoots and nodule number and weight (13). Compared to chemical fertilisers, the *Rhizobium*-PSB combination inoculant offers significant potential to boost legume production at lower costs. This study aims to investigate the effects of combining silica, *Rhizobium* sp. and phosphate-solubilising agents on soybean productivity and physiological responses in saline fields. Various agronomic techniques have been developed to enhance soybean yields on saline land. Utilising soil bacteria such as *Rhizobium* sp. and phosphate-solubilising bacteria, along with silica (Si), shows promise in improving plant physiological conditions and increasing agricultural yields. The findings of this study are expected to contribute to higher soybean productivity in Indonesia and support the development of soybean cultivation technologies better suited to marginal conditions like saline land.

Materials and Methods

Study Sites and Duration

The study was conducted in Bulakbaru Village, Kedung, Jepara, Central Java, Indonesia (6°39'48.8"S 110°39'04.5"E), for 5 months. The study sites were located at an elevation of less than 5 m above sea level, specifically in the coastal area of Bulakbaru Village. This coastal location contributes to the high salinity of the soil, posing significant challenges for plant production. Additionally, extended dry seasons exacerbate soil salinity driven by low rainfall and high evaporation rates, as detailed in the physical and chemical property profile presented in Table 1. The research data were analysed at the Ecology and Plant Production Laboratory, Faculty of Animal Husbandry and Agriculture, Diponegoro University, Semarang. Soil physical analysis was performed at the Testing Laboratory, BPTP, in Ungaran, Central Java, while the chemical analysis of the soil was conducted at the Integrated Research and Testing Laboratory (LPPT) of Gadjah Mada University (Fig. 1).

The materials used in this study included soybean seeds of the Anjasmoro variety, saline soil, cow dung, gypsum, *Rhizobium* sp. strain *rf013* (Fig. 2a), Phosphate-solubilising bacteria (PSB) isolate (*Enterobacter cloacae* strain S25) (Fig. 2b), silica fertiliser, urea fertilizer, KCl, SP-36, markers and plastic. The microbial culture medium for *Rhizobium* sp. were Yeast Mannitol Agar (YEM) + Congo Red (CR) media, which consisted of 10 g Mannitol, 1 g Agar, 2.5 g

Congo Red, 0.5 g K_2HPO_4 , 0.2 g $MgSO_4 \cdot 7H_2O$, 20 g NaCl and 10 g Agar per Liter. Pikovskaya medium, used for subculture propagation, consisted of 10 g glucose, 5 g $Ca_3(PO_4)_2$, 0.5 g $(NH_4)_2SO_4$, 0.2 g KCl, 0.1 g $MgSO_4 \cdot 7H_2O$, 0.1 g $MnSO_4$, 0.1 g $FeSO_4$, 0.5 g yeast extract and 15 g agar per Liter.

The instruments utilised in this study included a TDS meter, Erlenmeyer flasks, a hot plate stirrer, an autoclave, test tubes, Petri dishes, a laminar air flow cabinet, inoculating loops and a Bunsen burner. Additional equipment included an oven, micropipettes, an analytical balance, a blender and a 40-mesh sieve.

Research design

This study used a 3x3 factorial randomised block design with 3 replications. The first factor, was microbial inoculation (R), included levels R0 (0 g seed⁻¹), R1 (6 g seed⁻¹) and R2 (12 g seed⁻¹). The second factor, silica fertiliser (S), included levels S0 (0 kg ha⁻¹), S1 (150 kg ha⁻¹) and S2 (300 kg ha⁻¹). Each combination of treatments was replicated 3 times, resulting in a total of 27 experimental units. Each experimental unit consisted of 30 planting holes. The parameters observed include vegetative morphology and physiological markers.

Preparation of soil and bacteria inoculum

The preparation of saline-tolerant *Rhizobium* and phosphate-solubilising bacteria involved rejuvenation, multiplication and inoculation on a carrier medium (peat). A total of 350 m² of saline soil was prepared for the experiment. The land was prepared by creating raised beds measuring 3 m x 2 m and 30 cm in height. Gypsum (5 t. ha⁻¹) and manure (20 t. ha⁻¹) were applied to the soil. The seeds underwent scarification followed by inoculation with a combination

Table 1. The physical and chemical properties of soil sample

Characteristic	Value	Category
Salinity (dS m ⁻¹)	4.12	Very high
C-organic (%)	1.87	Low
N-Kjeldahl (%)	0.21	Medium
pH H ₂ O	6.81	Neutral
pH KCl	5.69	Acid
CEC (cmol(+) kg ⁻¹)	26.21	High
P ₂ O ₅ HCL 25% (mg 100 g ⁻¹)	70.08	Very high
K ₂ O HCL 25% (mg 100 g ⁻¹)	167.1	Very high
Sand (%)	1.48	-
Silt (%)	33.57	-
Clay (%)	64.95	-

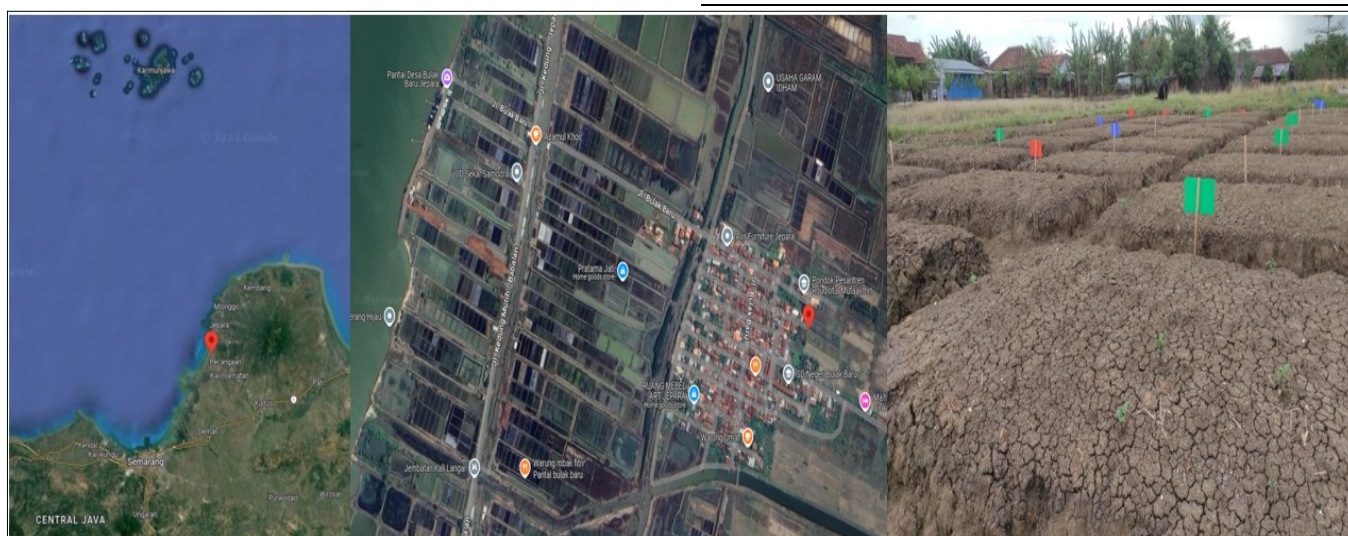


Fig. 1. The study site in Bulakbaru Village, Kedung, Jepara, Central Java, Indonesia (6°39'48.8"S 110°39'04.5"E).

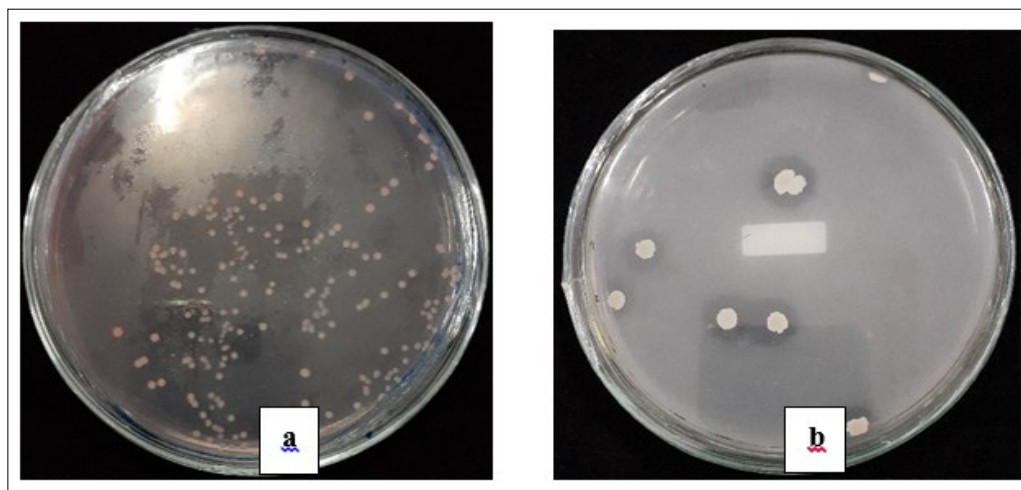


Fig. 2. (a). Culture of *Rhizobium* sp. (b). Phosphate-solubilising bacteria.

of *Rhizobium* and phosphate-solubilising bacteria, according to the treatment specifications at planting time. Silica fertilizer was applied based on the designated treatment dosages. Planting holes were made 3 cm deep, resulting in a total of 810 planting holes. Three soybean seeds were planted in each hole, leaving one plant behind.

Fertilisation and Growth Maintenance

Fertilisation followed the saline land dosage recommendations: 80 kg ha⁻¹ KCl, 125 kg ha⁻¹ SP-36 and 75 kg ha⁻¹ urea. SP-36 and KCl fertilizers were applied at planting, while urea was applied in 2 stages: at planting and 3 weeks later. Thinning was conducted 14 days after planting (DAP) and weeding was performed 21 days after planting. Table 1 depicts Physical and chemical properties of research soil.

Result and Discussion

Vegetative morphology

Salinity stress significantly inhibits soybean plants from achieving their optimal height, reducing overall biomass, yield and causing premature leaf senescence. Table 2. shows that the treatment does not show any significant change on plant height parameter, the tallest soybean plants reached up to 40.64 cm, while the shortest height recorded was 36.03 cm. High salinity levels degrade soil

structure and increase osmotic pressure, thereby impeding ability of the plant to absorb water and nutrients. The number of trifoliate leaves was not significantly affected by the inoculation of *Rhizobium* and phosphate-solubilizing bacteria, the maximum number of leaves observed are 19.67 and the lowest number of leaves that could be observed were 12.67. Salinity-induced osmotic stress adversely affected root length by lowering osmotic potential of the soil relative to plant cells, which led to a loss of turgor pressure and cell death. Consequently, soybean plants grown in saline soil exhibited restricted root extension, with root lengths ranging from a minimum of 11.32 cm to a maximum of 14.37 cm. Soybean plants grown in saline soil exhibited relatively short root extensions and the application of double inoculum *Rhizobium* and phosphate-solubilizing bacteria, did not significantly alter root length, although there was a tendency to increase root length with increasing number of co-inoculum of saline-tolerant *Rhizobium* and phosphate-solubilising bacteria.

Saline land cultivation practices and climatic conditions influenced the plant growth phase, with soil salinity disrupting the equilibrium of water and plant nutrients, thereby inhibiting stem growth and resulting in reduced stem diameters, its stem diameter could not grow more than 0.48 cm. The Anjasmoro variety of soybean typically flowers between 35 and 40 days after planting (DAP), but under salinity stress, plants tend to reach the blooming

Table 2. Soybean plants' average morphological response to saline soil on 64DAP

Co-Inoculum Bacteria (g seed ⁻¹)	Silica fertiliser (kg ha ⁻¹)	Plant height (cm)	Leaves number	Root length (cm)	Stem diameter (cm)	Flowering age (days)
0	-	37.12	15.44	12.37	0.44	34.89
6	-	37.93	15.44	12.55	0.48	32.67
12	-	37.99	16.22	12.89	0.42	34.33
-	0	36.78	14.67	12.35	0.41	33.89
-	150	38.47	17.44	12.00	0.47	34.11
-	300	37.79	15.00	13.46	0.46	33.89
0	0	36.90	14.00	12.53	0.41	34.67
0	150	37.69	19.67	11.32	0.45	34.33
0	300	36.75	12.67	13.26	0.47	35.67
6	0	36.03	12.67	11.87	0.46	32.67
6	150	37.12	14.33	13.04	0.52	34.67
6	300	40.64	19.33	12.75	0.48	30.67
12	0	37.40	17.33	12.64	0.37	34.22
12	150	40.61	18.33	11.65	0.45	33.33
12	300	37.79	13.00	14.37	0.44	35.33
F						
Inoculum Bacteria (IB)		0.20 ns	0.11 ns	2.90 ns	1.00 ns	1.50 ns
Silica fertiliser (Si)		0.61 ns	1.26 ns	2.25 ns	1.00 ns	0.02 ns
IB * Si		1.32 ns	2.47 ns	2.20 ns	0.00 ns	1.01 ns

phase earlier, which was around 30 - 36 DAP. The flowering phase is critical for soybean plants, as water and nutrient availability during this period can significantly impact plant growth. The study data indicated that the co-inoculum of saline-tolerant *Rhizobium* and phosphate-solubilizing bacteria did not affect the flowering age, likely due to the interplay of various factors, including plant genetics, environmental conditions, stress factors and water availability.

Physiological markers

Co-inoculation of saline-tolerant *Rhizobium* sp. and phosphate-solubilising bacteria significantly increased the total chlorophyll content in soybean plants. Specifically, the application of this co-inoculum at a dose of 12 g seed⁻¹ resulted in the highest total chlorophyll content observed with 1.28 mg g⁻¹. When soybean plants were treated with the double bacterial inoculum, the total chlorophyll content was notably higher compared to the treatment without inoculum (Fig. 3). This indicates that the soybean plants were able to utilise nitrogen more efficiently, enhancing their overall chlorophyll production.

Nitrate reductase (NR) is a crucial enzyme in living tissues, playing a vital role in the initial stages of amino acid synthesis [14]. As observed on Table 3, it showed that the treatment effect on NR activity was generate value around 16.37 $\mu\text{mol NO}_2 \text{ g}^{-1} \text{ h}^{-1}$ until 20.94

$\mu\text{mol NO}_2 \text{ g}^{-1} \text{ h}^{-1}$ per hr. Although there is no direct connection between phosphate-solubilizing bacteria, *Rhizobium* sp. and the nitrate reductase enzyme, these components are interconnected through the soil nitrogen cycle. Nitrate reductase operates at the intersection of carbon fixation and nitrate assimilation, both of which are energy-intensive processes, this positioning allows for a regulated response to environmental changes that affect photosynthesis (14). Phosphate-solubilising bacteria enhance plant phosphorus availability and release nitrogen as a byproduct when dissolving organic phosphate. Concurrently, *Rhizobium* sp. bacteria are involved in nitrogen fixation from the atmosphere. The ability of plants to reduce nitrate is regulated by metabolic sensors and signal transduction pathways, which align with the overall metabolic status of the plant.

The proline content parameter were significantly influenced by the treatment with co-inoculation of saline-tolerant *Rhizobium* sp. and phosphate-solubilizing bacteria. Specifically, the co-inoculum treatment (6 g seeds⁻¹ and 12 g seeds⁻¹) resulted in a decrease in proline content in plants compared to the control treatment. This indicates that plants treated with the co-inoculum exhibited lower stress levels compared to plants not treated with the inoculum. The co-inoculum of saline-tolerant of *Rhizobium* bacteria and phosphate

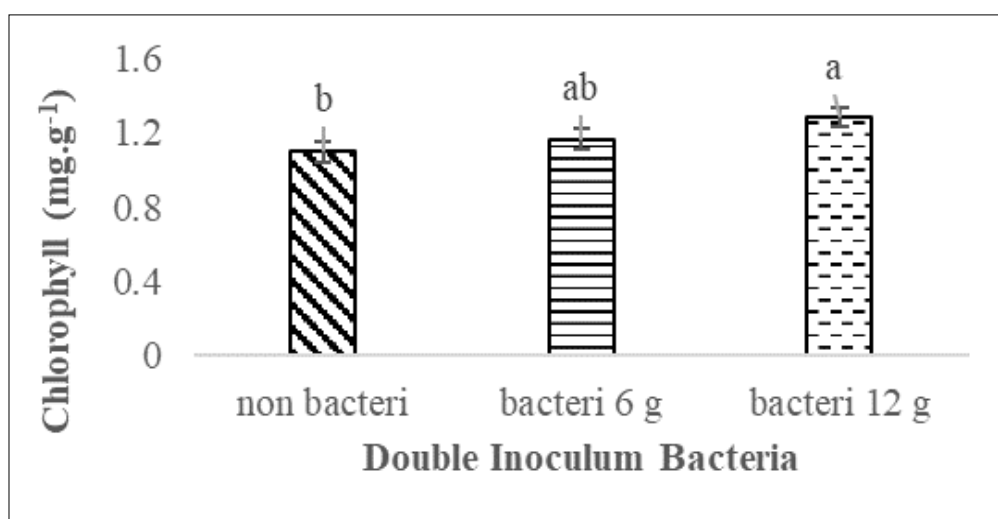


Fig. 3. Co-inoculum of *Rhizobium* sp. and phosphate solubilizing bacteria affects the amount of chlorophyll.

Table 3. Soybean plants' average physiological response to saline soil

Co- Inoculum Bacteria (g seed ⁻¹)	Silica fertiliser (kg ha ⁻¹)	Chlorophyll (mg g ⁻¹)	NRA ($\mu\text{mol NO}_2 \text{ g}^{-1} \text{ per hr}$)	Proline ($\mu\text{mol g. L}^{-1}$)	RWC (%)	Open stomata
0	-	1.10 ^b	18.07	0.09 ^a	0.88	24.56
6	-	1.16 ^{ab}	17.32	0.06 ^b	0.81	21.67
12	-	1.28 ^a	19.06	0.05 ^b	0.78	25.11
-	0	1.17	18.46	0.08	0.78	20.89
-	150	1.19	17.54	0.07	0.89	23.44
-	300	1.19	18.45	0.06	0.81	27.00
0	0	1.13	20.94	0.13	0.92	20.00
0	150	1.15	16.91	0.07	0.85	23.67
0	300	1.01	16.37	0.08	0.88	30.00
6	0	1.18	16.58	0.05	0.65	18.33
6	150	1.13	16.45	0.06	0.88	20.00
6	300	1.18	18.93	0.06	0.91	26.67
12	0	1.17	17.85	0.05	0.79	24.33
12	150	1.19	19.27	0.07	0.92	26.67
12	300	1.19	20.06	0.06	0.64	24.33
F						
Inoculum Bacteria (IB)		4.92 *	0.30 ns	4.50*	0.76 ns	0.23 ns
Silica fertiliser (Si)		0.07 ns	0.11 ns	0.35 ns	0.83 ns	0.82 ns
IB * Si		1.27 ns	0.57 ns	1.83 ns	1.59 ns	0.34 ns

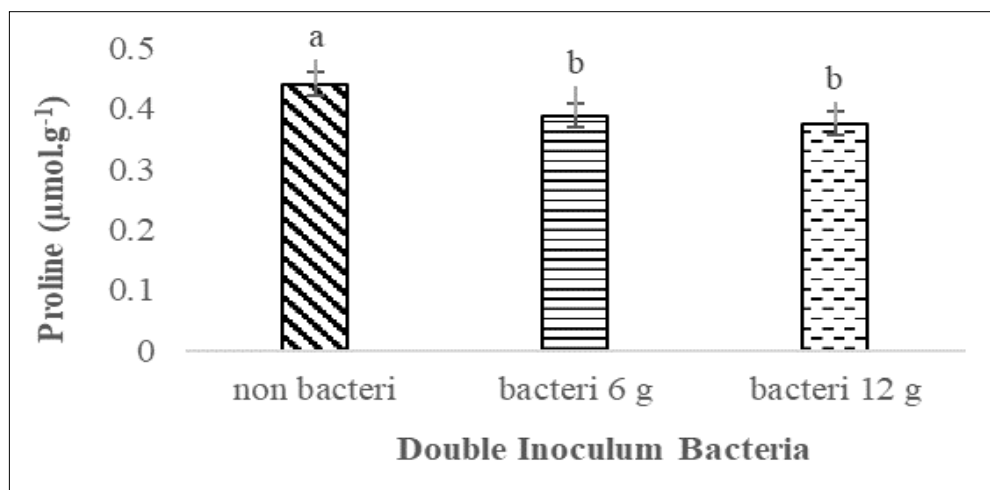


Fig. 4. Co-inoculum of *Rhizobium* sp. and phosphate solubilising bacteria decreased the proline content.

-solubilising bacteria contributed to the decrease in proline concentration in plants (Fig. 4).

In general, several variables, such as temperature, groundwater supply, air humidity, plant genetic characteristics, soil properties (including texture, structure and organic material content) and physiological state of the plant, affect Relative Water Content (RWC). Leaf Relative Water Content (RWC) is a measure of plant dehydration. Photosynthesis can be hampered by water shortages induced by salt stress. The RWC observations indicated that there was no significant effect of the treatment, as the RWC values ranged from 0.64 % to 0.92 %. The study revealed that stomatal openings varied between 18.33 nm and 30.00 nm. The co-inoculum treatment with *Rhizobium* sp. and PSB did not significantly affect the number of open stomata. Although these bacteria supply the necessary nitrogen and phosphorus for plant growth, they do not directly impact the regulation of stomatal apertures. As noted in (15), stressful conditions can lower leaf water potential, subsequently reducing turgor pressure, photosynthetic activity and stomatal conductance, which in turn can decrease crop yield and growth. The inoculation with *Rhizobium* and phosphate-solubilising bacteria, whether applied individually or in combination, did not significantly affect the number and weight of pods. Nevertheless, (Fig. 5, 6) suggest that the application of 150 kg ha⁻¹ silica fertiliser can improve the performance of 6 g and 12 g of bacteria, potentially increasing the number of pods to 12. The highest yields were observed when seeds were treated with 150 kg ha⁻¹ silica fertiliser

and 12 g seed⁻¹ of *Rhizobium* and phosphate-solubilizing bacteria, with a total pod weight reaching 26 g.

The interaction between *Rhizobium* bacteria and plants is determined by their nutritional needs and the prevailing soil conditions. However, the efficacy of phosphate solutions and silica fertilisation under these conditions is limited (16). Specifically, the biochemical activities of phosphate solubilizers and *Rhizobium* bacteria are not directly affected by silica fertilisation. While increased silica improves soil structure and enhances plant resistance to stress, it does not directly influence the availability of nutrients such as phosphate and nitrogen (17). Salt stress in soybean plants is believed to result in suboptimal plant height growth. The accumulation of Na⁺ ions in the roots can impede the absorption of Ca²⁺ elements (18). Additionally, the presence of K⁺ and NO³⁻ ions can lead to symptoms of salt toxicity. Root length metrics in soybean plants remain unaffected by the application of co-inoculum *Rhizobium* and phosphate-solubilising bacteria, or silica fertiliser doses, primarily due to salinity-induced stress. According to (19), saline soil conditions can inhibit root growth by altering external osmotic pressure, which decreases cell turgor pressure. High mitotic activity in root meristem cells, which are essential for root growth and sensitive to salt, makes them particularly susceptible to inhibition of root elongation under saline conditions.

According to one report, the flowering phase of 31 soybean plants is a critical period during which the availability of water and nutrients significantly influences plant growth (20). The research findings indicated that the treatments involving *Rhizobium* sp and

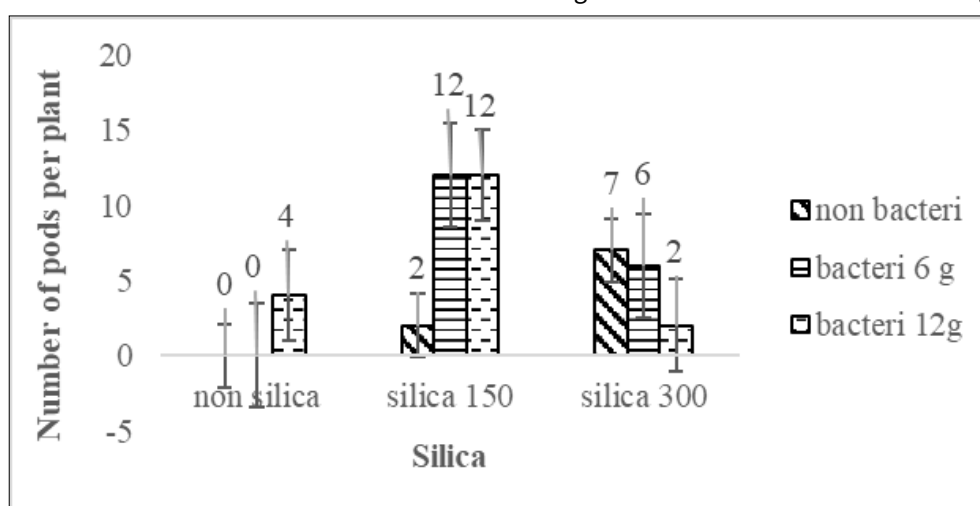


Fig. 5. Number of pods per plant affected by co-inoculum *Rhizobium* sp. + phosphate solubilising bacteria and silica fertiliser.

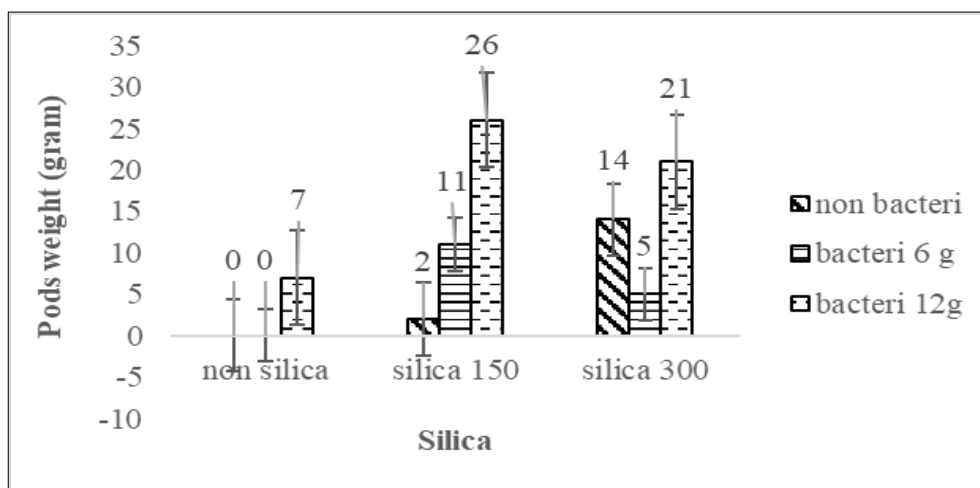


Fig. 6. Pods weight affected by co-inoculum *Rhizobium* sp. + phosphate solubilising bacteria and silica fertiliser.

phosphate-solubilizing bacteria exhibited nearly identical flowering periods when no seed treatment was applied. Specifically, the average flowering ages for treatments with 6 g seed⁻¹ and 12 g seed⁻¹ were 39.88 DAP, 37.66 DAP and 39.33 DAP respectively. It is posited that environments characterized by clay and saline soil conditions contribute to the reduced yield of soybean pods. Additionally, dry season conditions exacerbate soil desiccation, leading to increased evaporation and a consequent decline in the plant's water content, thereby adversely affecting both the number of pods and their weight.

This observation aligns with the findings of (21), which indicate that soybean plants exhibit increased susceptibility to drought conditions, particularly from the flowering stage through to pod filling. During this generative phase, soybeans require more water compared to the vegetative phase. Consequently, reduced soybean yields may result from adverse and unforeseen environmental conditions that affect plant growth. Furthermore, it was noted that plants inoculated with co-inoculum of saline-tolerant *Rhizobium* sp. and PSBup to 6 g seed⁻¹ did not demonstrate a significant increase in overall chlorophyll content. In comparison to the control treatment, which did not receive a co-inoculum of bacteria, the administration of 12 g seed⁻¹ significantly enhanced the overall chlorophyll content of the plants. The treatment involving *Rhizobium* sp. bacteria and phosphate-solubilizing bacteria at a rate of up to 12 g seed⁻¹ resulted in the highest levels of total chlorophyll content. This indicates that increasing the total chlorophyll content of plants can be achieved through the administration of a co-inoculum of *Rhizobium* sp. and phosphate-solubilising bacteria. Similar findings were reported in (22), which suggested that the application of phosphate solutions in conjunction with nitrogen-fixing bacteria could enhance plant growth by increasing the amount of chlorophyll and chloroplasts in leaves. When a double bacterial inoculum was applied to soybean plants, the total chlorophyll content in the treatment with 12 g seed⁻¹ of bacterial inoculum per seed was higher than in the control without inoculum, indicating that the plants were better able to assimilate nitrogen elements.

Nitrate reductase, a primary enzyme present in active tissue, was crucial for initiating the amino acid production process, while there was no direct connection between phosphate-solubilising bacteria, *Rhizobium* sp. and the nitrate reductase enzyme, all 3 are linked through nitrogen cycle of the soil. *Rhizobium* sp. was involved in the fixation of atmospheric nitrogen, whereas PSB can dissolve

organic phosphate and release nitrogen as a byproduct, thereby increasing plant phosphate availability. Regarding the treatment with *Rhizobium* sp. bacteria, no significant changes were observed. The presence of phosphate-solubilising bacteria is also influenced by nitrogen nutritional requirements of the plant being met during the vegetative phase. This indicates that plants not treated with a bacterial inoculum adapt by producing more proline to survive. An increase in proline is a marker of response of the plant to stress (23).

A preceding study indicates that a high proline concentration is a marker of a response to salinity stress of the plant, further supporting this observation (24). Proline, an amino acid, is essential for the growth and development of plants. According to one report, proline helps maintain membrane integrity by regulating the nitrogen requirements of plants and mitigating the effects of cell membrane disruption caused by NaCl toxicity (15). This is corroborated with another study, where, it assert that *Rhizobium* sp. contributes to the nitrogen supply of plants (25). PSB dissolve phosphate in the soil to meet the phosphorus requirements of plants. While there is no direct correlation between phosphate-solubilizing bacteria and stomata density, these bacteria can promote plant development and growth relative to the number of stomata. The increasing number of stomata observed with higher doses of, silica treatment suggests that silica administration can enhance stomata density. A higher stomata density opening in plant tissue can accelerate the rate of CO₂ absorption and transpiration during photosynthesis.

Conclusion

The findings of this study demonstrate that the treatment of Anjasmoro soybean plants with the double inoculum *Rhizobium* sp. and phosphate-solubilising bacteria significantly enhances their physiological responses, as evidenced by increased chlorophyll levels and reduced proline levels in saline soil. In contrast, the application of silica fertiliser did not yield any significant effects on the physiology and growth of Anjasmoro soybean plants cultivated on clay soil with a high salinity level of 4.12 dS cm⁻¹, although there was a tendency for increased production at 150 kg ha⁻¹ silica. These findings underscore the potential benefits of microbial inoculation and silica in mitigating the adverse effects of salinity on soybean plants. This research contributes to sustainable agricultural practices by utilising saline land and informs future strategies for enhancing crop production in saline land.

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Authors' contributions

EF coordinated the research, conducted the research site survey, analysed the soil salinity, analysed the data and drafted the manuscript. EDP summarised the research data; AFA prepared the research materials, conducted the field research and laboratory analysis; AND conducted the field research and laboratory analysis; AA supported manuscript revision. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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