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Enhancing macronutrient uptake and growth of soybean in coastal areas through integrated biofertilizer applications

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Abstract Results showed that the incorporation of soybean cultivars with microbial and bioenzyme-based biofertilizers markedly improved soil quality, plant growth, and macronutrient absorption in comparison to inorganic fertilizers. Anjasmoro had the most biomass and nutrient buildup, while Dega I and Dering I had moderate responses. Biofertilizer treatments raised the pH of the soil, as well as the levels of nitrogen, phosphorus, and potassium in the tissue. They also made better use of nutrients overall. These results showed that combining better cultivars with biofertilizers could be a long-term way to improve soybean growth and reduce the need for chemical inputs.

Keywords: Soybean, Coastal soils, Biofertilizer, Nutrient uptake

Introduction

The coastal areas have high agricultural potential, but several land limitations exist that inhibit productivity. Coastal soils usually show low organic content, are sandy, have low ability to retain water and nutrients, and cause salt stress to crops (Sarkar *et al*., 2025; Tarolli *et al*., 2024). Such soil conditions directly affect the nutrient availability and make nutrients like nitrogen, phosphorus, and potassium less available in the soil. The deficiency in nutrient availability makes nutrient uptake by plants difficult, hence contributing to poor productivity of agricultural products, including soybean production in the coastal area (Guo *et al*., 2025; Miller *et al*., 2025). There is therefore a need for innovation and sustainable soil fertility improvement practices in the coastal lands to ensure efficient nutrient uptake and hence soybean productivity.

Traditionally, using inorganic fertilizers has been a quick way to deal with nutrient shortages in coastal soils. While these chemical fertilizers can quickly boost crop growth, their excessive use often leads to negative effects. These include lower soil fertility, soil structure deterioration, environmental pollution,

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and a drop in the diversity of microorganisms that are vital for soil health (Howe *et al*., 2024; Li *et al*., 2023). Therefore, we need alternative methods that improve crop yield and support the sustainability of coastal ecosystems. One promising option is using biofertilizers. Biofertilizers contain living microorganisms that enhance nutrient availability, improve the physical, chemical, and biological qualities of soil, and promote plant growth (Bertham *et al*., 2025; Samantaray *et al*., 2024; Zhang *et al*., 2025). Using biofertilizers can help you use less chemical fertilizers, make fertilization more effective, and keep the soil healthy (Mahmud *et al*., 2021; Zhao *et al*., 2024). Biofertilizers have two uses for coastal lands: they provide nutrients and help plants deal with salinity stress and low levels of organic matter (Alotaibi *et al*., 2024; Ding *et al*., 2024; Shan *et al*., 2023).

A number of soil microbes have been found to be very useful as bio-fertilizers, including arbuscular mycorrhizal fungi (AMF), Bradyrhizobium, phosphate-solubilizing bacteria, and potassium-solubilizing bacteria. The former helps plants absorb nutrients via their external hyphae through the extension of the root zone. As a result, the absorption of water and phosphorus (P) is improved, especially in poor soils. Not only do AMF assist in nutrient absorption, but they also boost plant tolerance to environmental stresses, such as salinity and drought, through maintaining osmotic balance and stress-induced signaling (Ghorui *et al*., 2025; Singh *et al*., 2025). At the same time, Bradyrhizobium forms nodules within leguminous plants like soybean. This leads to the biologically-based nitrogen (N) fixation process that provides a sustainable nitrogen supply and reduces the use of artificial fertilizers, thus preventing soil acidification and contamination (DelPercio *et al*., 2025; Figiel *et al*., 2025).

The phosphate solubilizing bacteria are significant in converting insoluble or immobilized phosphorus to plant-available phosphorus, which is crucial for photosynthesis, ATP synthesis, and reproduction such as flower and seed formation (Damo *et al*., 2024; Silva *et al*., 2023). Similarly, the potassium solubilizing bacteria make potassium ions available through its action of mobilization of potassium ions from insoluble soil minerals. This makes potassium available for osmoregulation, stomatal movement, enzyme activation, and metabolic processes (Damathia *et al*., 2025).

The efficacy of biofertilizers could be enhanced by incorporating substances such as bioenzymes and humic acid. The role of bioenzymes is that they accelerate the degradation of organic material as well as nutrient release. Thus, nitrogen (N), phosphorus (P), and potassium (K) become easier to uptake from the soil by plants. Moreover, bioenzymes stimulate the processes occurring in soil microorganisms. Hence, they provide favorable conditions for nutrient uptake in the rhizosphere (Jia *et al*., 2025). Humic acids improve the physical properties of soil and increase its ability to retain cations. They also promote nutrient chelation in the rhizosphere, which enhances nutrient availability for plants (Fan *et al*., 2023; Rathor *et al*., 2025). The combination of humic acids and soil microorganisms increases the availability of macronutrients and makes the plant root system stronger for more effective uptake.

Therefore, a biofertilizer consortium of AMF, Bradyrhizobium, bacteria that solubilizes phosphorus and potassium, bioenzymes, and humic acids are expected to work synergistically in enhancing the availability and uptake of NPK in soybean. Quite apart from its usefulness in supporting vegetative and reproductive growth, enhanced nutrient uptake has also been found to have potentials of improving efficiency of in-organic fertilizer application, enhancing soil fertility in coastal soils, and sustainable agriculture on marginal lands. Hence, this study examined the impacts of integrated applications of biofertilizers on nutrient uptake and growth performance of three different soybean cultivars in coastal agroecosystems.

Materials and methods

The study was carried out between May and August 2025 in the coastal region of the Pasar Pedati village, Central Bengkulu regency. The preparation of biofertilizer inoculants was conducted at the Soil Biology Laboratory, Faculty of Agriculture, Universitas Bengkulu, while analyses of soil, plant tissues, microbial populations, and carbon stock assessments were conducted at the Soil Science Laboratory, Faculty of Agriculture, Universitas Bengkulu. A split plot design was used, with the main plot consisting of three soybean cultivars: Anjasmoro, Dering I, and DEGA and the sub-plots consisting of fertilizer inputs: (P1) recommended inorganic fertilizer; (P2) arbuscular mycorrhizal fungi (AMF) + Bradyrhizobium + potassium-solubilizing bacteria + bioenzyme; (P3) Bradyrhizobium + phosphate-solubilizing bacteria + potassium-solubilizing bacteria + bioenzyme; (P4) Bradyrhobium + potassium-solubilizing bacteria + humic acid; and (P5) Bradyrhibium + phosphate-solubilizing bacteria + potassium-solubilizing bacteria + humic acid. These factors were combined to give 15 treatment combinations, each replicated three times giving a total of 45 experimental units. The data collected were analyzed using an analysis of variance (ANOVA) at a 5% significance level. For the treatments that demonstrated a significant difference, Duncan's Multiple Range Test (DMRT) was used at the 5% level.

The experiment began with clearing the field of shrubs and weeds at the study site. Prior to land preparation, soil samples were collected randomly from five points within the experimental area and composited for initial analysis of soil physical, chemical, and biological properties. The soil was then tilled manually using hoes, and plots measuring 1.5 m × 3 m were established, with 50 cm spacing between plots and 100 cm between replications.

Soil amendments were applied, consisting of coffee pulp compost at 10 t ha^{-1} and dolomite at 200 kg ha^{-1}, to improve soil chemical properties and enhance *Bradyrhizobium* colonization. Base inorganic fertilizer was applied at 25% of the recommended dose. Urea (46% N) was applied in two stages: half at planting and the remaining half one month later, whereas triple superphosphate (44%-48% P_2O_5) and potassium chloride (60%-63% K_2O) were applied entirely at planting. The recommended inorganic fertilizer rates were 75 kg ha^{-1} of urea, 100 kg ha^{-1} of SP-36, and 100 kg ha^{-1} of KCl (Ferayanti *et al*., 2020). Additionally, bioenzymes were applied at a rate of 1 L per 20 L of water by evenly spraying the soil surface two days before planting.

Planting holes were made using a wooden dibbler to a depth of approximately 5 cm, with two soybean seeds sown per hole. The planting distance was 30 cm × 30 cm (Bertham *et al*., 2020). Prior to sowing, soybean seeds were inoculated with biofertilizers containing phosphate-solubilizing bacteria and *Bradyrhizobium* using a triple-coating strategy with 40% gum powder as an adhesive (Bertham *et al*., 2025). Potassium-solubilizing inoculants and arbuscular mycorrhizal fungi (AMF) were applied directly into the planting holes at rates of 50 mg per hole for potassium-solubilizing bacteria and 2.5 g per hole for AMF (Bertham *et al*., 2019).

Crop management involved watering, filling in gaps, removing weeds, and controlling pests and diseases. Watering was done every afternoon if there was no rain. Gaps were filled by planting seeds that hadn't sprouted. Weeding was done using machinery. For pests and diseases, an organic method using soursop leaf extract was applied. Harvesting happened in two rounds, matching the plant's growth stages. The first harvest took place 40 days after planting, when about 10% of the plants started to flower. At this time, five plants from the middle of each plot were collected, along with mixed soil samples from each plot. The second harvest happened once the soybean pods dried out and turned brown, showing they were fully mature.

The parameters which are measured are: soil chemical characteristics, plant nutrient content and uptake and plant growth parameter. The chemical characteristics of soil such as Soil Organic Carbon was determined by using walkley black method. Soil pH was determined in HO and KCl solution. The nutrients present in plant tissues were determined after being digested by using HSO, such as N, P, and K. The nutrients were then calculated as concentration in plant tissues. Also, plant growth parameter as plant height, shoot dry weight and root dry weight was determined. Plant nutrient uptake was calculated as concentration in plant tissues multiplied with corresponding dry biomass.

Results

The study was conducted on coastal soils with relatively low fertility. Total nitrogen and organic carbon were measured at 0.23% and 1.96%, respectively, placing both in the low category. The soils also showed a limited ability to retain nutrients, as reflected by a cation exchange capacity of 15.47 me 100 g^{-1}. The availability of macronutrients was also low with exchangeable potassium (K-dd) and available phosphorus levels of 0.24 me 100 g^{-1} and 5.19 ppm, respectively. There was slight acidity in soils with pH levels of 5.89 in H_2O and 5.63 in KCl. Further, the presence of mild salinity (2.07 dS m^{-1}) could lead to physiological stress in plants grown on such soils. The texture of the soil was sandy loam with sand, clay, and silt contents of 73.96%, 20.21%, and 5.84%, respectively. Together with the low nutrient status, these characteristics highlighted the difficulties of maintaining sustainable crop production in coastal areas.

The results revealed that the interaction between soybean varieties and fertilizer inputs had a significant effect on soil pH (KCl) and phosphorus content in plant tissue. Soybean varieties significantly affected only phosphorus uptake and the dry weight of plants. In contrast, fertilizer inputs exhibited a significant effect on all observed variables (Table 1).

Table 1. Summary of analysis of variance

Observation Variables	Calculated F Value		
	Soybean Varieties	Fertilizer Inputs	Interaction
pH H_2O	1.03 ^{ns}	15.31*	1.37 ^{ns}
pH KCl	2.70 ^{ns}	3.20*	2.50*
Organic Carbon	0.43 ^{ns}	67.13*	1.23 ^{ns}
Nitrogen Content in Tissue	0.49 ^{ns}	38.90*	1.08 ^{ns}
Phosphorus content in tissue	4.49 ^{ns}	34.35*	3.31*
Potassium Content in Tissue	3.92 ^{ns}	20.45*	1.08 ^{ns}
Nitrogen uptake	2.18 ^{ns}	35.80*	0.99 ^{ns}
Phosphorus uptake	11.01*	37.57*	1.41 ^{ns}
Potassium uptake	5.74 ^{ns}	18.71*	0.55 ^{ns}
Plant height	3.66 ^{ns}	50.07*	1.11 ^{ns}
Dry weight of plants	9.45*	17.83*	0.47 ^{ns}

Notes = * significant different at $p < 0.05$, ns = not significant different at $p \geq 0.05$

The combination of soybean cultivars and fertilizer inputs resulted in significant variations in soil pH (KCl) and phosphorus content in plant tissues (Table 2). The combination of Anjasmoro with AMF + *Bradyrhizobium* + potassium-solubilizing bacteria + bioenzyme (V1P2) produced the highest pH value of 6.21 and a tissue phosphorus content of 0.36%. In general, treatments with microbial consortia resulted in higher pH values and tissue phosphorus content compared to the recommended inorganic fertilizer (P1), which showed the lowest values, ranging from 5.60 to 5.72 for pH and 0.24–0.25% for tissue phosphorus. Among the three soybean cultivars evaluated, Anjasmoro (V1) showed the best response to biofertilizer application, while Dega I (V2) and Dering I (V3) responded moderately and accumulated comparatively lower amounts of phosphorus.

Plant dry weight was highest in Anjasmoro cultivar (28.10 g), while Dega and Dering had lower values of 27.55 g and 25.41 g, respectively (Table 3). The pattern of phosphorus uptake was similar to that of the plant dry weight with the significant higher in Anjasmoro at equal to 0.09 ns significantly different from both Dega and Udini which is at equal to nether found not significantly different from each other although has a lowest value(0.08 g) than anjasmor o (Table 3). These results suggested differences between cultivars for their ability to use the available P for biomass production.

Table 2. Effect of the combination of soybean varieties and fertilizer inputs on pH KCl and phosphorus content in tissue

Treatment	pH KCl	Phosphorus content in tissue (%)
V1P1	5.72 bcd	0.24 h
V1P2	6.21 a	0.36 a
V1P3	5.81 bcd	0.33 abcd
V1P4	5.94 ab	0.34 abc
V1P5	5.64 cd	0.36 ab
V2P1	5.60 cd	0.25 gh
V2P2	5.86 bcd	0.32 cde
V2P3	5.67 bcd	0.28 fgh
V2P4	5.61 cd	0.32 bcde
V2P5	5.90 bc	0.30 def
V3P1	5.60 d	0.24 h
V3P2	5.74 bcd	0.37 a
V3P3	5.86 bcd	0.28 efg
V3P4	5.84 bcd	0.30 def
V3P5	5.90 bc	0.30 def

Notes: Values with the same letter at the same column show that they are not significantly different at 5% in the DMRT test. V1 = Anjasmoro, V2 = Dega I, V3 = Dering I, P1 = recommended inorganic fertilizer; P2 = AMF + *Bradyrhizobium* + potassium solubilizing + bioenzyme, P3 = *Bradyrhizobium* + phosphate solubilizing + potassium solubilizing bacteria + bioenzyme; P4 = *Bradyrhizobium* + potassium solubilizing + humic acid, and P5 = *Bradyrhizobium* + phosphate solubilizing + potassium solubilizing + humic acid

Table 3. Effect of soybean varieties on dry weight of plants and phosphorus uptake

Soybean varieties	Dry weight of plants (g)	Phosphorus uptake (g)
Anjasmoro	28.10 a	0.09 a
Dega	27.55 a	0.08 b
Dering	25.41 b	0.07 b

Notes: Values with the same letter at the same column show that they are not significantly different at 5% in the DMRT test.

Fertilizer treatments had differential effects on soil pH (H_2O), soil organic carbon content, plant height, and soybean dry weight (Table 4). Treatment P2 (AMF + *Bradyrhizobium* + potassium-solubilizing bacteria + bioenzyme) produced the highest soil pH and the greatest plant dry weight, whereas P5 (*Bradyrhizobium* + phosphate-solubilizing bacteria + potassium-solubilizing bacteria + humic acid) resulted in the tallest plants. Treatments P3 and P4 also improved soil quality and plant growth compared to the inorganic fertilizer treatment. In contrast, P1 (recommended inorganic fertilizer) consistently produced the lowest values across all observed parameters. These results indicated that biofertilizers are more effective than the recommended inorganic fertilizer in enhancing soil chemical properties while simultaneously promoting soybean growth.

Table 4. The effect of fertilizer inputs on pH H_2O, organic carbon, plant height and dry weight of plants

Fertilizer Inputs	pH H_2O	Organic Carbon (%)	Plant height (cm)	Dry weight of plants (g)
P1	5.81 c	2.14 b	29.11 b	19.90 c
P2	6.48 a	3.08 a	55.51 a	30.78 a
P3	6.37 ab	2.99 a	52.81 a	26.54 b
P4	6.36 ab	3.06 a	55.01 a	27.82 ab
P5	6.25 b	2.95 a	56.78 a	30.07 a

Notes: Values with the same letter at the same column show that they are not significantly different at 5% in the DMRT test. P1 = recommended inorganic fertilizer; P2 = AMF + *Bradyrhizobium* + potassium solubilizing + bioenzyme, P3 = *Bradyrhizobium* + phosphate solubilizing + potassium solubilizing bacteria + bioenzyme; P4 = *Bradyrhizobium* + potassium solubilizing + humic acid, and P5 = *Bradyrhizobium* + phosphate solubilizing + potassium solubilizing + humic acid

Biofertilizer treatments based on microbial consortia and bioenzymes significantly increased tissue nitrogen and potassium content, as well as N, P, and K uptake in soybean plants. Treatment P2 (AMF + *Bradyrhizobium* + potassium-solubilizing bacteria + bioenzyme) produced the highest values across all parameters, followed by the combination of *Bradyrhizobium* + phosphate-solubilizing bacteria + potassium-solubilizing bacteria + humic acid (P5). Treatments P3 and P4 also improved tissue nutrient status and nutrient uptake compared to the recommended inorganic fertilizer, although their nutrient uptake values were lower than those of P2 and P5. In contrast, the recommended inorganic fertilizer (P1) consistently produced the lowest values for all parameters (Table 5). These results indicated that biofertilizers can enhance nutrient availability and uptake efficiency more effectively than inorganic fertilizers, thereby supporting more optimal soybean growth.

Table 5. The effect of fertilizer inputs on nitrogen content in tissue, potassium content in tissue, nitrogen uptake, phosphorus uptake and potassium uptake

Fertilizer Inputs	Nitrogen Content in Tissue (%)	Potassium Content in Tissue (%)	Nitrogen uptake (g)	Phosphorus uptake (g)	Potassium uptake (g)
P1	1.89 b	0.81 b	0.38 d	0.05 d	0.16 c
P2	2.57 a	1.09 a	0.79 a	0.11 a	0.34 a
P3	2.51 a	1.05 a	0.67 c	0.08 c	0.28 b
P4	2.49 a	1.02 a	0.69 bc	0.09 b	0.29 b
P5	2.54 a	1.06 a	0.76 ab	0.10 b	0.32 ab

Notes: Values with the same letter at the same column show that they are not significantly different at 5% in the DMRT test. P1 = recommended inorganic fertilizer; P2 = AMF + *Bradyrhizobium* + potassium solubilizing + bioenzyme, P3 = *Bradyrhizobium* + phosphate solubilizing + potassium solubilizing bacteria + bioenzyme; P4 = *Bradyrhizobium* + potassium solubilizing + humic acid, and P5 = *Bradyrhizobium* + phosphate solubilizing + potassium solubilizing + humic acid

Discussion

These findings suggested that the effect of interactions between soybean cultivars and different biofertilizer treatments (microbial consortia and bioenzymes) significantly influences the soil chemical characteristics and the content of nutrients in plants. The increased soil pH and tissue phosphorus contents in the presence of microbial consortia and bioenzyme treatments prove the ability of biofertilizers in promoting soil characteristics and nutrient uptake. This is similar to other studies that have found that biofertilizers could enhance phosphorus solubility as well as nutrient mineralization from soil through various activities of soil microorganisms (Le *et al*., 2025). In addition, some research has been carried out regarding the influence of microbial consortia and bioenzymes on soil quality, where soil microorganism populations as well as nutrients and water contents are improved (Bertham *et al*., 2025).

There were variations among the different varieties of soybeans used in terms of their responsiveness to the application of biofertilizers, especially when considering biomass and phosphorus accumulation. Anjasmoro variety demonstrated the greatest degree of responsiveness to biofertilizers such as Rhizobium, contributing to increased nodule formation, height growth, nitrogen absorption, and dry seed yields. On the other hand, Dega I and Dering I had average responses, indicating variation among soybeans in terms of using phosphorus in growth and development processes. This observation is supported by other research studies that have found evidence of cultivar variation when it comes to nutrient absorption and the physiological response to the application of biofertilizers that include phosphate-solubilizing bacteria and mycorrhizae that increase phosphorus concentration in the soil (Mu *et al*., 2024; Peng *et al*., 2025).

Inoculation of arbuscular mycorrhizal fungi (AMF), Bradyrhizobium, potassium-solubilizing bacteria, and bioenzymes had a major impact on vegetation, including plant height, dry weight, and nutrient content in plant tissues. The interaction between the described microbes increases nutrients in the soil, enhances its structure, and improves enzyme activities in the soil. All these processes promote vegetative development and facilitate the maintenance of a chemical balance within the soil by increasing pH level and nutrient absorption (Ansabayeva *et al*., 2025). Certain inoculation treatments were more successful in increasing the plant height, proving the effectiveness of certain microbes' action. As AMF facilitates the process of phosphorous absorption, while Bradyrhizobium and potassium-solubilizing bacteria ensure the presence of necessary nutrients in the soil, they all promote increased production of growth hormones, such as auxins and cytokinins (Ahemad and Kibret, 2014). Thus, the described combination contributes to an increased biomass and better root system (Ahemad and Kibret, 2014). On the other hand, the use of the recommended inorganic fertilizer resulted in poor outcomes across the majority of metrics. It proves the lack of effectiveness in terms of soil quality improvement and plant development, as such fertilizer cannot affect any parameters related to microbial, physical, and chemical soil.

The biofertilizer preparations containing microbial consortia and bioenzymes increased nitrogen and potassium levels in plant tissues. In addition, they had an impact on the effectiveness of nitrogen, phosphorus, and potassium uptake by soybean plants. The preparation with the most significant improvements in all parameters included arbuscular mycorrhizal fungi (AMF), Bradyrhizobium, potassium-solubilizing bacteria, and bioenzymes. Another treatment with high impact involved Bradyrhizobium, phosphate-solubilizing bacteria, potassium-solubilizing bacteria, and humic acid. It is worth noting that other types of biofertilizers also helped improve plant tissue nutrient levels and nutrient uptake efficiency, but they did not show as good results as the above-listed variants. Thus, it is possible to state that microbial consortia contribute to nutrients' availability. Overall, it is evident that the use of biofertilizers can help make nutrients more available to the plants due to such mechanisms as phosphate and potassium solubilization, activation of soil microorganisms, improved metabolism, and symbiotic effects (Ajeng *et al*., 2020; Kumar *et al*., 2022; Nosheen *et al*., 2021).

In general, the above-mentioned findings indicate that the use of bio-fertilizers composed of microbial populations and bioenzymes can help improve soil characteristics, enhance plant growth, and make nutrient uptake processes more effective. As for the real-life implications of this study, they include making fertilizer production processes more environmentally friendly, cutting the use of inorganic fertilizers, and increasing soybean yields. At the same time, the above findings provide valuable insights into conducting future research aimed at examining how cultivars, microbial populations, and bioenzymes affect plant growth and development processes.

The utilization of biofertilizers and bioenzymes in soybean cultivars improves the soil's chemical characteristics, crop growth, and macro-nutrient absorption compared to the use of inorganic fertilizers. In terms of biomass production and nutrient absorption, Anjasmoro showed the highest values, while Dega I and Dering I showed average performance. The biofertilizer treatments enhanced soil pH, dry biomass, tissue nitrogen, phosphorus, and potassium concentrations, as well as the efficiency of nutrient uptake. Based on the findings, combining advanced cultivars with biofertilizers might serve as an effective strategy for increasing soybean growth, reducing the use of artificial fertilizers, and managing nutrients in each cultivar.

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Conflict of interest

The authors declare no conflict of interest.

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