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Integrating soybean variety and biofertilizer management to improve nutrient uptake and yield in coastal regions facing climate change

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Abstract The results showed significant interactions were found between soybean variety and fertilizer treatment for N, P, and K uptake, effective nodule dry weight, shoot dry weight, and root dry weight. The highest N uptake (0.67 mg), P uptake (0.14 mg), K uptake (0.70 mg), and shoot dry weight (36.55 g) were achieved when the tested soybean variety was supplied with the biofertilizer package AMF + *Bradyrhizobium* + K-solubilizer (P2). In contrast, Anjasmoro receiving *Bradyrhizobium* + phosphate-solubilizer + K-solubilizer exhibited moderate P (0.13 mg) and K uptake (0.68 mg) but produced the greatest root dry weight (3.81 g). Overall, the results indicate differential varietal adaptability to coastal soils, with biological inputs (biofertilizers/bioenzymes) outperforming chemical fertilizer in improving nutrient uptake, nodulation effectiveness, and plant biomass, highlighting their potential as sustainable inputs for soybean production in coastal environments.

Keywords: AMF, *Bradyrhizobium*, Phosphate solubilizer, Potassium solubilizer

Introduction

Soybean (*Glycine max*) is one of the most important legume crops worldwide, valued for its extensive applications and high economic significance. Rich in essential amino acids and energy, soybean plays a vital role in human nutrition and livestock productivity, while its high content of vegetable oil makes it indispensable for the food and feed industries. Beyond its economic value, soybean contributes to sustainable agriculture through its ability to associate with nitrogen-fixing bacteria, converting atmospheric N_2 into plant-available forms, and through symbiosis with arbuscular mycorrhizal fungi, which enhance water and nutrient uptake (Islam *et al.*, 2022; Li *et al.*, 2025; Peng *et al.*, 2025). These rhizospheric interactions not only support plant growth but also improve soil

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physical, chemical, and biological properties, contributing to healthier soils (Iqbal *et al*., 2025; Sharma *et al*., 2025). As both an upstream and downstream sector, soybean cultivation sustains economic pillars in many countries, provides employment opportunities, and generates significant industrial benefits. However, soybean production is increasingly challenged by climate change and environmental stresses, particularly in vulnerable coastal regions where soil salinity, low fertility, and structural limitations threaten productivity (Billore *et al*., 2018; Bertham *et al*., 2025; Nyimbo *et al*., 2025). Addressing these challenges requires innovative, adaptive, and sustainable management strategies to secure soybean's role in global food security.

Recent climate change affecting many countries has exerted adverse impacts on the global agricultural sector. Manifestations of climate change, including rising temperatures, unstable rainfall patterns, flooding and erosion, seawater intrusion, and related phenomena, have disrupted the stability of global soybean production (Hasegawa *et al*., 2022). Elevated temperatures influence groundwater conditions, which subsequently affect planting seasons and the distribution of soybean cultivation areas. Lands once suitable for soybean production are becoming unsuitable, thereby necessitating technological interventions to meet water requirements. Rainfall instability, often accompanied by extreme precipitation events, has negative consequences for soybean growth and productivity, threatening both food security and farmers' livelihoods. Higher temperatures and humidity may also enhance the proliferation and severity of pest and disease attacks, leading to increased reliance on pesticides and/or more intensive biological control measures (Ullah *et al*., 2021). Furthermore, rising temperatures coupled with reduced rainfall intensify evaporation, which increases surface soil salinity and ultimately diminishes soybean productivity. A salinity level equivalent to 2000 ppm NaCl can reduce soybean pod numbers by up to 65% (Nasution *et al*., 2024). Overall, climate change has introduced multiple stressors that adversely affect soybean productivity.

Indonesia, an archipelagic nation with the world's second-longest coastline, possesses vast coastal land resources with significant yet underutilized potential. Historically, these areas have received limited attention due to the availability of fertile inland agricultural land. However, coastal soils are characterized by multiple stress factors, including high salinity, low organic matter, sandy texture, lack of structure, and poor nutrient content (Gunadi, 2002; Piñeiro-Juncal *et al*., 2022). Elevated salinity levels can induce ionic and osmotic stress, trigger osmolysis, and increase the production of reactive oxygen species, thereby predisposing plants to drought stress and impairing nutrient uptake (Lu and Fricke, 2023; Trejo-Téllez, 2023). Such conditions ultimately constrain optimal plant growth and reduce crop productivity (Tahjib-Ul-Arif *et al*., 2023).

Furthermore, the combination of low organic matter, sandy texture, and weak soil structure reduces water-holding capacity and fertilizer efficiency. These challenges are compounded by strong coastal winds, which accelerate the spread of pests and diseases. Consequently, managing coastal soils parallels the challenges of farming under climate change conditions and highlights the urgency of preparing future generations for greater resilience in the face of environmental change.

The management of problematic soils, such as coastal lands that resemble those affected by climate change, demands innovative, adaptive, and environmentally sustainable approaches. Key strategies include the use of adaptive soybean varieties; organic amendments and biofertilizer inoculation, complemented by appropriate irrigation and fertilization practices, to sustain soybean productivity (Acharya *et al*., 2024; Amanullah *et al*., 2025; Bertham *et al*., 2019; Hasegawa *et al*., 2022; Nasution *et al*., 2024; Xiao *et al.,* 2025). Organic fertilizers improve water retention, nutrient-holding capacity, and provide substrates for beneficial soil microorganisms, while biofertilizers supply functional microbes such as nitrogen fixers, arbuscular mycorrhizal fungi, and nutrient-solubilizing bacteria, which enhance nutrient-use efficiency and soil health. Their combined application fosters stable soil aggregates, improves porosity, and strengthens plant resilience to environmental stress. This synergy enhances soil fertility without contaminant buildup, preserves ecosystem integrity, and supports long-term sustainable agriculture (Ammar *et al*., 2023; Kumar *et al*., 2021).

Climate change presents complex challenges to global soybean production, particularly in vulnerable coastal regions where soil salinity, low fertility, and structural limitations exacerbate environmental stresses. Innovative, adaptive, and sustainable management practices are therefore essential to safeguard productivity and resilience (Futa *et al*., 2024; Majidian *et al*., 2024). The integration of organic and biofertilizers offers a promising pathway, not only improving soil fertility and water-holding capacity but also enhancing microbial functions that support plant growth under adverse conditions (Ammar *et al*., 2023; Mthiyane *et al*., 2024; Samantaray *et al*., 2024). By reducing dependence on chemical inputs and maintaining ecosystem integrity, these practices align with long-term strategies for climate change adaptation. Developing and scaling the application of organic and biofertilizer technologies should thus be prioritized as a key component of sustainable agriculture in coastal areas that are highly vulnerable (Tarolli *et al*., 2024). With such approaches, the agricultural sector can strengthen its resilience to climate change while continuing to play a vital role in ensuring global food security.

The objective was to develop an optimal fertilizer management strategy by integrating biofertilizers and liquid organic fertilizers with chemical fertilizers, in order to enhance soybean productivity on coastal soils.

Materials and methods

Site description

The study was conducted from April to December 2024 in Beringin Raya Subdistrict, Muara Bangkahulu District, Bengkulu City, Indonesia (S03˚45’23’’ E102˚15’41’’). Biofertilizer inoculant preparation, soil characterization, and plant nutrient analyses were carried out at the Soil Biology Laboratory, Faculty of Agriculture, University of Bengkulu.

Experimental design

The experiment was arranged in a Split Plot Design with two soybean varieties as the main plots: Anjasmoro (V1) and Dering I (V2). Subplots consisted of four fertilizer treatments: P_1: Recommended inorganic fertilizer; P_2: AMF + (*Bradyrhizobium*) + K-solubilizer, P_3: (*Bradyrhizobium*) + phosphate-solubilizer + K-solubilizer, P_4: Bioenzyme (liquid organic fertilizer prepared from vegetable residues). The combination of these two factors resulted in eight treatment combinations, replicated four times, for a total of 32 experimental units.

Soil preparation and plot layout

The site was cleared of shrubs and grasses before soil sampling. Composite soil samples were taken from five points in the field for soil characterization. Each experimental plot measured 1.5 m × 3 m, with 50 cm spacing between plots and 100 cm between replications. The coastal soil used in this experiment was characterized by the following properties: total N of 0.20%, organic C of 1.39%, exchangeable K of 0.18 $\text{me}\cdot 100\ \text{g}^{-1}$ soil, available P of 4.79 ppm (low), pH (H_2O) of 6.05, cation exchange capacity (CEC) of 14.67 $\text{me}\cdot 100\ \text{g}^{-1}$ soil, and electrical conductivity (EC) of 2.2 dS/m. These properties indicate low levels of organic matter and nutrients, low nutrient retention capacity, slightly acidic pH, and moderate salinity, suggesting that the soil has low fertility.

Fertilizer application

Basal fertilizers applied included 10 t ha^{-1} coffee husk compost, 200 kg ha^{-1} dolomite [$CaMg(CO_3)_2$], and 25% of the recommended inorganic fertilizer dose (50, 25, and 25 kg ha^{-1} of urea, TSP, and KCl, respectively). Urea was applied in two splits: half at planting and the remainder one month after planting, while TSP and KCl were applied entirely at planting. Bioenzyme was evenly sprayed on the soil surface two days prior to planting.

Planting and crop management

Soybean seeds were inoculated with biofertilizers containing phosphate-solubilizing bacteria, potassium-solubilizing microbes, *Rhizobium*, and arbuscular mycorrhizal fungi (AMF). Seeds were sown in 5 cm deep holes using a wooden dibber at a spacing of 30 cm × 30 cm, resulting in 50 planting holes per plot. Crop management included irrigation, replanting, weeding, and organic pest and disease control.

Harvesting and data collection

Harvesting was conducted twice: (i) at the vegetative stage (40 days after planting) and (ii) at the generative stage, when pods were dry and brown. Plant and soil samples were collected at each harvest. Dry seed weight per plot was calculated from the dry seed weight of sampled plants plus the assumed average seed weight from vegetative samples. Potential yield was estimated based on an effective land use assumption of 80%.

Data analysis

Data were analyzed using analysis of variance (ANOVA) at the 5% significance level, followed by Duncan's Multiple Range Test (DMRT) at the 5% level for mean separation. Data that did not meet the assumption of error normality were transformed using the Box-Cox method.

Results

Soybean variety significantly affected ($p < 0.05$) P and K uptake, the number of effective root nodules, and plant dry weight (Table 1). The Anjasmoro variety exhibited superior performance compared with Dering I, particularly in P and K uptake and plant dry weight.

Table 1. Effect of soybean varieties on P and K uptake, effective root nodule number, and plant dry weight

Plant variety	Phosphorus uptake (mg)	Potassium uptake (mg)	Number of effective root nodules	Plant dry weight (g)
Anjasmoro	0.11 a	0.56 a	23 b	28.63 a
Dering I	0.08 b	0.42 b	35 a	24.82 b

Values followed by different letters within the same column are significantly different at $p < 0.05$ according to the LSD test.

Fertilizer application had a significant significant effect on nutrients (N, P, and K) uptake, effective root nodulation, plant dry weight, number of filled pods, and soil pH the number and dry weight of effective root nodules; plant dry weight; number of filled pods; and soil pH (H_2O) (Table 2). Artificial fertilizer (P_1) produced lower plant performance than biofertilizers (P_2, P_3) and Bioenzyme (P_4). Among treatments, AMF + *Bradyrhizobium*) (P_2) consistently showed the best performance, particularly in N uptake, plant dry weight, filled pod number, and rhizosphere pH (H_2O). (Table 2). Chemical fertilizer (P_1) produced lower plant performance than biofertilizers (P_2 and P_3) and Bioenzyme (P_4). Among treatments, AMF + (*Bradyrhizobium*) (P_2) consistently showed the best performance, particularly in N uptake, plant dry weight, filled pod number, and rhizosphere pH (H_2O).

Table 2. Effects of fertilizer treatments on nutrient uptake, effective root nodulation, plant dry weight, filled pod number, seed dry weight and rhizosphere soil pH (H_2O)

Pupuk	N uptake (mg)	P uptake (mg)	K uptake (mg)	Number of effective root nodules	effective root nodules dry weight (g)	Plant dry weight (g)	Number of filled pod	Seed dry weight per plot (kg)	Soil rhizosphere pH (H_2O)
P_1	0.33 b	0.07 b	0.36 b	11 b	0.18 b	23.94 b	281 ab	1.41 b	6.09 b
P_2	0.49 a	0.11 a	0.57 a	26 a	0.55 a	30.74 a	380 a	1.76 a	6.33 a
P_3	0.36 b	0.10 a	0.50 a	25 a	0.34 a	26.18 b	319 a	1.88 a	6.27 ab
P_4	0.56 a	0.10 a	0.50 a	52 a	0.93 a	26.04 b	206 b	1.66 a	6.37 a

Values followed by different letters within the same column are significantly different at $p < 0.05$ according to the DMRT.

Soybean variety and fertilizer showed a significant interaction effect on N, P, and K uptake; dry weight of effective root nodules; plant dry weight; and root dry weight (Table 3). The Anjasmoro variety supplied with biofertilizer AMF + *Bradyrhizobium* + K-solubilizer (P_2) exhibited the highest N uptake (0.67 mg), P uptake (0.14 mg), K uptake (0.70 mg), and plant dry weight (36.55 g)However, when Anjasmoro was supplied with fertilizer *Bradyrhizobium*) +

phosphate solubilizer + K-solubilizer (P_3), it showed only moderate P (0.13 mg) and K uptake (0.68 mg), but recorded the highest root dry weight (3.81 g) (Table 3).

Table 3. Interaction effects of soybean variety and fertilizer on nutrient uptake, nodulation, and biomass accumulation

Varietty	Fertilizer	Uptake of (mg)			Dry weight of (g)		
		N	P	K	Effective root nodules	Plant	Plant root
Anjasmoro (V_1)	P_1	0.29 c	0.06 c	0.32 c	0.19 cd	23.25 b	2.33 d
	P_2	0.67 a	0.14 a	0.70 a	0.35 bcd	36.55 a	3.13 bc
	P_3	0.39 bc	0.13 a	0.68 a	0.40 bc	28.35 b	3.81 a
	P_4	0.51 ab	0.10 ab	0.53 ab	0.11 d	26.35 b	3.25 ab
Dering I (V_2)	P_1	0.36 bc	0.08 bc	0.39 bc	0.16 d	24.63 b	2.61 cd
	P_2	0.32 c	0.08 bc	0.43 bc	0.76 ab	24.93 b	2.36 d
	P_3	0.33 c	0.08 bc	0.39 bc	0.28 cd	24.00 b	2.39 d
	P_4	0.61 a	0.09 bc	0.47 bc	1.75 a	25.73 b	2.48 d

P_1 = artificial fertilizer, P_2 = AMF + *Bradyrhizobium* + K solubilizer, P_3 = *Bradyrhizobium* + P and K solubilizers K, P_4 = Bioenzym.

Values followed by different letters within the same column are significantly different at $p < 0.05$ according to the DMRT.

Discussion

Environmental changes, such as reduced water availability, nutrient levels, and soil temperature, have a major impact on root life and directly affect water and nutrient uptake (Lynch, 2022). Under such conditions, plants optimize resource utilization and enhance tolerance to stress (Calleja-Cabrera *et al.*, 2020). This is reflected in changes in root architecture, including root length, lateral and adventitious root density, as well as the formation of specialized structures such as aerenchyma (Vives-Peris *et al.,* 2020). An increased flow of photosynthates to the roots is required for adventitious root formation (Tripathi *et al.,* 2024). Root dry weight reflects photosynthate translocation to the roots. A higher root dry weight indicates greater allocation of photosynthates, whereas values exceeding shoot dry weight often signal environmental stress. In this study, no stress symptoms were observed (Table 3), suggesting that both Anjasmoro and Dering I varieties adapted well to coastal soils. Anjasmoro showed increased root dry weight under *Bradyrhizobium* + P- and K-solubilizers (P_3) and Bioenzyme (P_4) treatments compared to AMF + *Bradyrhizobium* (P_2). This effect was likely due to enhanced microbial populations in the rhizosphere, which facilitated higher photosynthate flow to the roots.

In contrast, Dering I responded positively only to Bioenzym (P_4), showing higher N uptake (0.61 mg) and effective nodule dry weight (1.75 g). The Bioenzyme application increased root nodule formation (Table 2), improving nitrogen fixation and uptake. As a liquid organic fertilizer derived from vegetable residues, Bioenzyme has been reported to improve soil physical properties (Mekonnen *et al*., 2020) and stimulate nodule-forming bacteria (Mu'min *et al*., 2022). Increased nodulation enhances the plant's ability to fix atmospheric N and supports more efficient N absorption, contributing to higher tissue N content (Tables 2 and 3). The tolerance of the Anjasmoro variety to coastal soil conditions has previously been reported by Bertham *et al*. (2020a).

The combination of biofertilizers applied AMF + *Bradyrhizobium* + phosphate-solubilizing microbes + potassium-solubilizing microbes provided significant synergistic benefits for plant growth. *Bradyrhizobium* inoculation supported soybean nodule formation and atmospheric N_2 fixation, with the assimilated nitrogen subsequently used in metabolic processes that promote healthy plant growth (DelPercio *et al*., 2025; Kajić *et al*., 2025). AMF enhanced nutrient uptake efficiency, particularly phosphorus, through hyphal networks that expand the root exploration zone for nutrients and water, while also improving soil structure (Boyno *et al*., 2025; Peng *et al*., 2025). Phosphate-solubilizing microbes converted insoluble forms of phosphorus into available forms that can be absorbed directly by roots or via AMF hyphae, supporting plant growth and pod formation (Vey *et al*., 2025;). The synergistic interaction between *Bradyrhizobium* and phosphate-solubilizing microbes has been reported to increase 100-seed weight, seed weight per plant, and seed weight per plot in soybean (Salman and Dani, 2021; Aldrighi *et al*., 2025). Potassium-solubilizing microbes played a role in osmotic regulation and ion balance within plant cells, improving stress tolerance and supporting more efficient photosynthesis (Olaniyan *et al*., 2022; Sharma *et al*., 2024). The role of AMF, both independently and in combination with other microbes, in enhancing plant growth and yield has been widely documented (Bertham *et al*., 2020b; Shi *et al*., 2023; Martin *et al*., 2024; Peng *et al*., 2025). Through the integration of these biofertilizers, the Anjasmoro soybean variety benefited from improved nutrient availability and uptake efficiency, ultimately resulting in higher plant dry weight.

Bioenzyme is a liquid organic material mixed with microorganisms. Such a mixture has been reported to enhance enzymatic activity in the soil as a result of improved microbial life (Wu *et al*., 2024; Wang *et al*., 2025) and to increase the population of phosphate-solubilizing microbes (Prado *et al*., 2016; Lumactud *et al*., 2022). In addition, bioenzyme is thought to function as a biocatalyst in the biochemical degradation of organic matter, mineralization, and nutrient cycling (Selvakumar *et al*., 2018). By enhancing soil microbial activity, bioenzyme plays an important role in improving nutrient supply efficiency and supporting greater nutrient availability for plants (Nugroho *et al*., 2021; Song *et al*., 2023). These improvements in soil characteristics positively influenced the increase in root nodules (Tables 2 and 3). The increase in nodules, which reflects higher activity of N_2-fixing microbes, further enhanced the ability of soybean plants to acquire atmospheric N_2 and likely improved nutrient availability as well (Savita *et al.,* 2019; Martins *et al*., 2022). The nitrogen obtained is then used for protein synthesis and vegetative growth (Marques *et al*., 2023). Liquid organic fertilizers, similar to Bioenzyme, have been reported to increase the number of branches, root nodules, and pods in soybean plants (Bengkal *et al*., 2023), soil physical propertis (Mekonnen *et al*., 2020), and to improve soybean productivity more effectively than synthetic fertilizers (Herawati *et al*., 2017). By improving rhizosphere conditions, bioenzyme enables plants to absorb nitrogen more efficiently from the soil, thereby contributing to higher nitrogen uptake within plant tissues. Thus, bioenzyme represents an alternative to biofertilizers for enhancing soybean productivity in coastal soils.

The study demonstrates that soybean varieties differ in their adaptability to coastal soils, with biofertilizers and bioenzyme outperforming chemical fertilizers. The application of these inputs effectively enhanced growth and yield, highlighting their potential as sustainable strategies for soybean cultivation in coastal environments. Anjasmoro treated with AMF + *Bradyrhizobium* + K-solubilizer (P_2) showed the best growth. Biofertilizers (P_2 and P_3) and Bioenzyme produced similar yields in both varieties, all exceeding those of chemical fertilizer. Biofertilizer application thus represents a viable strategy for mitigating the impacts of climate change on vulnerable soils.

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Conflicts of interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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