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Comparative Effectiveness of Organic Fertilizer Types on Soybean Growth, Yield, and Soil Health in Sustainable Cultivation Systems

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ABSTRACT

Limitations in productivity and adverse impacts of chemical fertilizers highlight the need for sustainable solutions in soybean cultivation in Indonesia. This study aims to evaluate the effectiveness of organic fertilizers as an alternative to chemical fertilizers in sustainable agriculture-based soybean cultivation. The experimental method employed a Completely Randomized Design (CRD) with six treatments: control (no fertilizer), chemical fertilizer, goat manure, compost, biochar, and a combination of POC + compost. The parameters observed included plant height, number of effective root nodules, yield components (number of pods, weight of 100 seeds, yield per polybag), as well as changes in soil chemistry after harvest. The results showed that the treatment of goat manure (P2) and a combination of POC + compost (P5) gave the best results in improving soybean growth and yield. Both also showed significant improvements in soil pH, C-organic content, total nitrogen, and availability of P and K. In addition to increasing crop yields, organic fertilizers have also been proven to support increased soil microbial activity through the formation of effective root nodules. Thus, organic fertilizers have proven to be an effective and environmentally friendly alternative in replacing chemical fertilizers. The use of organic fertilizers can promote productive, efficient, and sustainable soybean farming.

1. INTRODUCTION

Sustainable agriculture offers a crucial solution to challenges such as land degradation, declining soil fertility, and reliance on synthetic chemical inputs (Bhunia *et al*., 2021; Jin *et al*., 2023; Khan *et al*., 2024). Within this framework, the application of organic fertilizers as an alternative to chemical fertilizers in soybean cultivation is a primary focus for enhancing productivity while preserving environmental integrity (Mayly *et al*., 2022; Ngui *et al*., 2024; Tianigut & Yuriansyah, 2020). In Indonesia, soybeans (*Glycine max* L.) are a strategic commodity, serving as an important source of vegetable protein for the community. However, national soybean production remains insufficient to meet demand, necessitating significant imports.

A key factor contributing to this low production is diminished soil fertility resulting from the excessive application of chemical fertilizers (Abioye *et al*., 2024; Dincă *et al*., 2022; El-Moustaqim *et al*., 2024). The intensive, long-term use of chemical fertilizers can lead to the accumulation of harmful residues, decreased soil microbial activity, and damage to soil structure (Al Tawaha *et al*., 2024; Bijay-Singh & Sapkota, 2023; Singh *et al*., 2021). This consequently impacts crop productivity and quality. Therefore, a more environmentally friendly and sustainable alternative approach is needed.

Organic fertilizers, derived from natural materials such as animal manure, plant residues, and other organic waste, offer significant potential for enhancing soil fertility and increasing crop yields. In addition to providing nutrients, organic fertilizers also boost soil microbial activity, improve soil structure, and increase cation exchange capacity. Several studies have demonstrated the effectiveness of organic fertilizers in soybean cultivation. For instance, research by Rismawan *et al*. (2018) showed that the application of 20 t/ha of goat manure increased the total dry weight of soybean crops at 24 and 34 days after planting (DAP), the number of filled pods, seed weight, and yield per hectare. The application of soybean biochar, municipal waste compost, and Liquid Organic Fertilizer (POC) by Nasa had a significant effect on the number of effective root nodules, the number of pods per plant, the weight of seeds per plant, and the yield per hectare of Anjasmoro variety soybeans (Zahedifar *et al*., 2025). Several studies, (Nurjanah, 2018; Rismawan *et al*., 2018) further indicate that the use of various organic fertilizers can significantly increase soybean yields, although their effectiveness depends on the type of fertilizer, dosage, and local environmental conditions. Therefore, selecting the appropriate type and dosage of organic fertilizer is crucial for achieving optimal results. The application of organic fertilizers also contributes to a reduction in the use of chemical fertilizers, which in turn can reduce production costs and adverse environmental impacts (Jin *et al*., 2023; Rajapaksha *et al*., 2024; Sudirja *et al*., 2023). Moreover, utilizing local organic matter as a fertilizer source can increase added value and farmers' independence (Bellè *et al*., 2022; Rodríguez-Espinosa *et al*., 2023; Schweizer *et al*., 2022). In addition to increasing crop yields, the use of organic fertilizers positively impacts the physical and chemical properties of the soil, such as increasing soil organic matter content, improving soil structure, enhancing cation exchange capacity, and boosting soil microbial activity (Bhatt *et al*., 2019; Pernes-Debuyser & Tessier, 2004; H. Wang *et al*., 2024; J. Wang *et al*., 2024; Zhao *et al*., 2025). This contributes to improving soil fertility and crop productivity in the long term. The use of organic fertilizers can also reduce greenhouse gas emissions resulting from the production and application of chemical fertilizers. Thus, organic fertilizers are an important component of a sustainable and environmentally friendly agricultural system (Gomes *et al*., 2024; Wu *et al*., 2024; Xing *et al*., 2025).

However, the adoption of organic fertilizers in soybean cultivation still faces several challenges, including the availability of raw materials, the quality of organic fertilizers, and farmers' knowledge of proper application techniques. Although comparative data regarding the combined effects of liquid organic fertilizer (LOF) and solid organic fertilizers on soybean performance and soil health under controlled conditions in Indonesia remain limited, several studies provide valuable insights into their individual and combined contributions. For instance, the application of Titocrocoma LOF has been shown to increase soybean dry weight and crude protein content Jamilah *et al.* (2021), while Herawati *et al*. (2021) demonstrated that LOF application can reduce the need for chemical fertilizers. Solid organic fertilizers, such as farmyard manure combined with inorganic inputs, significantly improved soybean growth parameters and enhanced soil physical properties (Bagde *et al*., 2023; Choudhary *et al*., 2018; J. Wang *et al*., 2024). Similarly, compost derived from palm bagasse has proven effective in substituting urea in soybean cultivation (Elashry *et al*., 2025). Regarding soil health, LOF combined with standard NPK fertilizers has been shown to increase soil nitrogen content and nutrient uptake (Sudirja *et al*., 2023), and to enhance microbial activity and overall fertility when used alongside bio-fertilizers (Jin *et al*., 2023). Solid organic inputs like farmyard manure improved soil structure and organic carbon levels (Sunitha-kumari *et al*., 2023), and biochar combined with organic fertilizers helped to increase soil pH and nutrient availability (Ngui *et al*., 2024). Although few studies directly compare different organic fertilizer combinations in soybean systems, integrated nutrient management strategies have consistently demonstrated improved crop performance and soil conditions (Abeje *et al*., 2021; Narkhede *et al*., 2017). This suggests that combining both liquid and solid organic fertilizers may offer synergistic benefits and represent the most effective approach.

Therefore, this study aims to evaluate the comparative effects of different types of organic fertilizers—namely goat manure, compost, biochar, and a combination of liquid organic fertilizer (POC) with compost—on the growth, yield components, and soil chemical properties in soybean cultivation under a sustainable agricultural system. The results of this research are expected to provide empirical evidence that supports the adoption of integrated organic fertilization strategies as a viable alternative to chemical fertilizers, contributing to enhanced productivity, improved soil health, and long-term sustainability in soybean farming.

2. MATERIALS AND METHODS

2.1. Tools and Materials

The main material in this study was Anjasmoro variety soybean seeds which are known to have high adaptability to various environmental conditions and are responsive to organic fertilization treatment. In addition, several types of organic fertilizers and chemical fertilizers were used as a comparison, namely:

1. Organic fertilizer, including goat manure (composted for 3 weeks), household organic waste compost, biochar from soybean cuttings, and molasses-based liquid organic fertilizer (POC), EM4, and rice washing water.
2. Chemical fertilizers (comparator), including Urea (46% N), SP-36 (36% P_2D_5), and KCl (60% K_2O)

The planting medium uses alluvial soil with a sandy clay texture that has been analyzed for macro and micro nutrient content before treatment. An initial analysis of the alluvial soil with a sandy clay texture was conducted to assess its macro- and micronutrient composition—comprising N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu—so as to characterize the baseline fertility conditions prior to the application of treatments. Water for watering uses clean well water and is free of pollutants. The tools used include polybags measuring 40×40 cm, digital scales, soil pH measuring devices, drying ovens, and plant growth measuring devices such as rulers and calipers.

2.2. Methods

This study was conducted using a Completely Randomized Design (CRD) with 6 treatments and 4 replicates, resulting in 24 experimental units. Each experimental unit was represented by one polybag containing 10 kg of planting media. The CRD was chosen due to the controlled and presumably homogenous environmental conditions under which the polybags were maintained, minimizing systematic environmental variability across units. The details of the fertilizer treatments applied in this experiment were presented in Table 1.

Table 1. Tested treatments

Code	Treatment
P0	Control (without fertilizer)
P1	Chemical fertilizers (equivalent to 100 kg Urea, 100 kg SP-36, 75 kg KCl per hectare)
P2	Goat manure (equivalent to 20 tons/ha)
P3	Organic waste compost (equivalent to 15 tons/ha)
P4	Soybean biochar (10 tons/ha)
P5	POC + compost (50:50 each, total equivalent to 20 tons/ha)

Solid organic fertilizer was given one week before planting (incorporated), while liquid organic fertilizer is given in two stages, namely at the age of 15 DAP (day after planting) and 30 DAP. Chemical fertilizers were given according to the recommended dosage at the beginning of planting and subsequent fertilization of 20 DAP.

Soybean seeds were sown at a rate of three seeds per polybag, and thinned to two healthy plants after seven days. Weeding and watering were carried out regularly to maintain optimal growth conditions. The polybags were arranged in a single row with a spacing of 40 cm between polybags and 50 cm between replicates, following a completely randomized layout as recommended for CRD experiments. This arrangement ensured minimal mutual shading and allowed equitable access to environmental resources across all experimental units. The polybags were distributed randomly to ensure that treatments and replicates were not systematically grouped, thereby minimizing bias and maintaining the randomization essential for valid statistical analysis.

2.3. Observed Parameters

The observed parameters in this study encompassed aspects of vegetative growth, root nodule formation, crop yield, and changes in soil chemical properties before and after planting. Vegetative growth parameters included plant height (cm) measured at 15, 30, and 45 days after sowing (DAS), number of leaves, and total dry weight per plant. Root nodule formation was assessed by determining the total number of nodules and the number of effective nodules, which were identified by their pink coloration inside as an indicator of active nitrogen fixation. Crop yield parameters consisted of the number of pods per plant, number of seeds per pod, weight of 100 seeds (g), and total yield per polybag (g). Additionally, the chemical properties of the soil were analyzed both before and after planting, including soil pH, organic carbon (C-organic, %), total nitrogen (N, %), available phosphorus (P, ppm), and available potassium (K, cmol/kg) to determine the effects of each treatment on soil fertility dynamics.

2.4. Data Analysis

The observation data was analyzed using variance analysis (ANOVA) at the level of 5%. If there is a significant difference between treatments, a follow-up test of Duncan's Multiple Range Test (DMRT) is carried out at a significant level of 5% to find out the difference between treatments.

3. RESULTS AND DISCUSSION

This study produced data (Table 2) that showed a significant difference between the treatment of organic fertilizers and chemical fertilizers on the growth, yield, and chemical properties of the soil after harvest. The application of organic fertilizers, especially goat manure and a combination of POC + compost, showed even better competitive results than chemical fertilizers in several parameters.

Table 2. Plant growth and yield under different fertilizer treatments

Treatment	Plant Height (cm)	Effective Root Nodules	Number of Pods	Weight 100 Grains (g)	Yield per Polybag (g)
P0	35.2 ± 1.4 a	4.1 ± 0.9 a	15.1 ± 2.3 A	12.6 ± 0.8 A	22.4 ± 2.1 A
P1	51.7 ± 2.0 b	7.2 ± 1.1 b	25.3 ± 3.1 b	13.9 ± 0.7 b	36.5 ± 3.4 b
P2	53.5 ± 2.3 b	9.3 ± 1.3 c	28.7 ± 3.5 c	14.5 ± 0.6 b	40.1 ± 4.0 C
P3	48.4 ± 1.8 b	7.5 ± 1.2 b	24.5 ± 2.9 b	13.7 ± 0.5 b	34.2 ± 3.1 b
P4	46.9 ± 2.1 b	6.8 ± 1.0 b	23.1 ± 2.8 b	13.4 ± 0.6 b	32.6 ± 3.0 b
P5	54.1 ± 2.5 b	9.7 ± 1.4 c	29.2 ± 3.6 c	14.7 ± 0.6 b	41.3 ± 4.2 c
F-value	27.46	22.81	19.67	16.24	21.55
p-value	0.000 (<0.05)	0.000 (<0.05)	0.000 (<0.05)	0.000 (<0.05)	0.000 (<0.05)
Significance	Significant	Significant	Significant	Significant	Significant

Remarks: Values with different letters show a noticeable difference on the 5% DMRT test

3.1. Soybean Plant Height

Observation of plant height was carried out at the age of 45 days after planting (DAP). Goat manure treatment (P2) and a combination of POC + compost (P5) provides the highest plant height. Table 2 highlights the significant influence of fertilizer treatments on plant height observed 45 days after planting. The unfertilized control group (P0) had the lowest average height (35.2 cm), consistent with previous research showing that limited nutrient supply restricts plant growth. Ghimirey *et al*. (2025), for example, found that control plots had markedly shorter cauliflower plants (50.23 cm) than all organic fertilizer treatments.

All fertilizer treatments (P1–P5) produced significantly taller plants than the control, as shown by distinct letter notations in the 5% DMRT analysis. The tallest plants were observed in P5 (the combination of liquid organic fertilizer and compost, 54.1 cm) and P2 (goat manure, 53.5 cm). These results align with Ghimirey *et al*. (2025), who found poultry manure led to optimal growth in cauliflower (54.24 cm), and with Siregar *et al*. (2025), who demonstrated that a 40% concentration of liquid organic fertilizer produced maximum stem elongation in cucumber (15.46 cm), further supporting the value of appropriately formulated organic treatments.

The strong performance of goat manure (P2) finds support in recent literature as well. Chotimah *et al*. (2022) reported more than double the plant height with NPK compared to controls, while Kebede *et al*. (2023) showed that compost application (15 t/ha) promoted the most vigorous vegetative growth, attributed to improved nutrient and hormone availability. These studies reinforce the view that goat manure, rich in nitrogen and micronutrients, effectively enhances early plant development.

A synergistic effect was also seen in the combination of liquid organic fertilizer and compost (P5). Recent work by Alneyadi *et al*. (2024) shows that liquid organic fertilizers can consistently stimulate plant growth, although their efficacy may depend on crop and site-specific factors. Hapsari & Suparno (2023) further found that optimal concentrations enhance height, leaf density, and plant resilience.

Treatments P1, P3, and P4 resulted in moderate gains in plant height relative to the control, though mean heights were not statistically different from top treatments (P2 and P5) according to DMRT grouping. This observation is consistent with Ma *et al*. (2022), who described variable yet generally positive impacts of alternative fertilizers on nutrient uptake. Moreover, the importance of optimizing fertilizer concentration is emphasized by recent research. Panjaitan *et al*. (2023) found that adjusted doses of liquid organic fertilizer significantly improved vegetative growth and yield indices, while Aditya & Permatasari (2023) showed that applying 15 ml doses maximized lettuce growth, with yields dropping sharply in unfertilized conditions.

In summary, these findings underscore that organic fertilizers, especially goat manure and the combination of liquid organic fertilizer with compost, substantially promote early plant height and are corroborated by a broad scientific literature base. Organic nutrient sources thus offer consistent benefits for growth, soil health, and sustainability across diverse crop systems.

The statistical analysis conducted (F-value: 27.46, $p < 0.05$) confirms that fertilizer type has a significant effect on plant height, with P2 and P5 yielding the highest means. This is mirrored in previous high-impact studies where integrated or optimized fertilization enhanced growth and nutrient efficiency. Collectively, the results affirm the value of tailored fertilizer management in maximizing early vegetative development and support evidence-based recommendations for agricultural practice.

3.2. Number of Effective Root Nodules

Effective root nodules are observed at the age of 30 DAP. Treatment with manure and POC + compost combination results in a higher number of effective nodules than other treatments. Table 2 demonstrates that fertilizer application significantly affected the number of effective root nodules at 30 days after planting, as indicated by the ANOVA results ($F = 22.81$, $p < 0.05$). The untreated control (P0) developed the fewest nodules (4.1 ± 0.9), while goat manure (P2) and the combined treatment of liquid organic fertilizer andcompost (P5) produced the most effective root nodules (9.3 ± 1.3 and 9.7 ± 1.4 per plant, respectively). Statistically, these treatments were clearly separated from the control, as also suggested by distinct group notations.

The response of root nodulation to organic amendments aligns closely with the latest findings in the scientific literature. For example, Dai *et al*. (2024) indicated that applications of phosphorus, potassium, and organic fertilizers significantly promote symbiotic nodule formation and enhance both nitrogen fixation and vegetative growth in legumes. The synergistic effect of combining organic and inorganic inputs is also supported by Adinurani *et al*. (2021), who found that co-application of mycorrhizae and rhizobium substantially boosts both nodule number and major nutrient uptake, thereby increasing peanut yields.

Further, Xu *et al*. (2025) highlighted the critical importance of precise nitrogen management for effective nodule development and function. Their research shows that moderate nitrogen doses can boost nodule quantity and biomass, whereas excessive nitrogen input suppresses nodulation by disrupting rhizobial infection and nodule organogenesis. This supports the present observation of optimal nodule numbers under balanced organic fertilization rather than overtly high synthetic nitrogen input. Additionally, Restiyah *et al*. (2023) demonstrated that synergy between organic fertilizers and soil bioinoculants such as Plant Growth Promoting Rhizobacteria (PGPR) significantly enhances both nodulation and nitrogen assimilation in legumes.

The present findings reinforce contemporary understanding that organic amendments either alone or integrated with biofertilizers play a pivotal role in optimizing root nodule formation and nitrogen fixation. These improvements are crucial for maximizing legume productivity and soil fertility in sustainable cropping systems. The significant differences observed also confirm the need for evidence-based, tailored amendment strategies for different soils and crops, in keeping with rigorous agronomic experimental design.

3.3. Components of Crop Yields

Yield components such as the number of pods, weight of 100 seeds, and yield per polybag are influenced by the type of fertilizer. P2 (goat manure) and P5 (POC + compost) showed the best results. Table 2 presents the effects of various organic fertilizer treatments on key yield components, namely number of pods, weight of 100 seeds, and total yield per polybag. Statistical analysis using ANOVA demonstrated significant differences among treatments for all three variables ($p < 0.05$), as indicated by the distinct superscript letters in each column.

The control (P0) consistently displayed the lowest values for each component, with only 15.1 ± 2.3 pods, 12.6 ± 0.8 g for 100-seed weight, and a yield of 22.4 ± 2.1 g per polybag. In contrast, treatments involving goat manure (P2) and the combination of liquid organic fertilizer and compost (P5) produced the most favorable results. P2 achieved 28.7 ± 3.5 pods, 14.5 ± 0.6 g seed weight, and 40.1 ± 4.0 g yield; P5 recorded the highest values at 29.2 ± 3.6 pods, 14.7 ± 0.6 g for 100 seeds, and 41.3 ± 4.2 g total yield.

These improvements can be attributed to the ability of organic fertilizers to enhance nutrient availability, stimulate root growth, and promote biological activities in the rhizosphere. This supports previous findings by Shah *et al.* (2023), who reported that organic fertilizer sources significantly improve legume yield components and seed quality compared to mineral inputs, largely due to improved nutrient cycling and soil health. Furthermore, Katakula *et al.* (2021) and Hinarti *et al.* (2025) found that goat manure and organic compost amendments specifically increase pod set, seed weight, and overall productivity through sustained nutrient release and greater microbial activity.

While the differences in 100-seed weight between fertilized treatments were less pronounced than for pod number or yield, P2 and P5 consistently provided the highest seed weights, indicating more complete development and higher seed quality. These results are in accord with the findings of Rismawan *et al.* (2018), who observed that the application of goat manure significantly increased soybean pod numbers and seed weight compared to control, and of Mayly *et al.* (2022), who demonstrated that biochar, compost, and POC treatments can significantly boost soybean yield.

Collectively, these results confirm that the strategic use of organic amendments, particularly goat manure and the integration of liquid organic fertilizer (POC) and compost, not only supports vegetative growth and root development but also improves both the quantity and quality of yield components. The adoption of organic nutrient management is thus strongly supported as an effective and sustainable alternative to conventional chemical fertilizers for improving soybean crop performance.

3.4. Changes in soil chemical properties after harvest

After treatment and harvest, there is an increase in nutrient content and soil pH in organic fertilizer treatment, especially in P2 and P5. This shows an improvement in soil quality biologically and chemically. Table 3 shows that organic fertilizer treatments, particularly goat manure (P2) and the combination of liquid organic fertilizer with compost (P5), significantly enhanced soil chemical properties after harvest. Both treatments resulted in higher values for soil pH (6.2–6.3), organic carbon (1.85–1.92%), total nitrogen (0.21–0.22%), available phosphorus (20.2–21.1 ppm), and exchangeable potassium (0.38–0.41 cmol/kg) compared to the unfertilized control (P0). ANOVA results confirmed significant differences among treatments for all measured variables ($p < 0.05$), as indicated in the table.

Table 3. Effect of organic fertilizer treatments on soil chemical properties after harvest

Treatment	pH (H_2O)	C-Organic (%)	N-Total (%)	P-Available (ppm)	K-Available (cmol/kg)
P0	5.2 ± 0.1 a	1.13 ± 0.09 a	0.12 ± 0.01 a	8.1 ± 1.1 a	0.18 ± 0.02 a
P1	5.5 ± 0.1 ab	1.34 ± 0.10 ab	0.15 ± 0.01 ab	15.4 ± 1.3 b	0.27 ± 0.03 b
P2	6.2 ± 0.1 c	1.85 ± 0.12 d	0.21 ± 0.02 d	20.2 ± 1.7 c	0.38 ± 0.03 c
P3	5.9 ± 0.1 bc	1.74 ± 0.11 cd	0.19 ± 0.02 cd	17.6 ± 1.2 bc	0.34 ± 0.03 c
P4	5.7 ± 0.1 ab	1.68 ± 0.09 c	0.18 ± 0.01 c	16.3 ± 1.4 bc	0.31 ± 0.03 bc
P5	6.3 ± 0.1 c	1.92 ± 0.10 d	0.22 ± 0.02 d	21.1 ± 1.6 c	0.41 ± 0.03 c
F-value	31.22	28.47	25.68	29.53	27.14
p-value	0.000 (<0.05)	0.000 (<0.05)	0.000 (<0.05)	0.000 (<0.05)	0.000 (<0.05)
Significance	Significant	Significant	Significant	Significant	Significant

These improvements are attributable to the direct addition and gradual mineralization of nutrients from organic amendments, which also strengthen long-term soil health and biological function. The marked increase in pH and nutrient availability reflects greater microbial activity and improved cation exchange capacity, supporting crop productivity and nutrient uptake. Notably, manure and compost application have been shown to enrich soil organic matter and maintain balanced macronutrient availability over multiple cropping cycles.

These results are strongly consistent with previous research. For example, Katakula *et al*. (2021); Shah *et al*. (2023); Zhou *et al*. (2022) demonstrate that organic fertilizers reliably improve soil pH, macronutrient status, and biological activity relative to inorganic fertilization. Supporting studies on peanut and soybean cropping systems also find that organic amendments optimize soil chemical and physical properties, enhance plant growth, and sustain yield under field conditions (Puspitasari *et al*., 2024; Nurrahmah, 2022; Rusdani, 2021). The synergy between liquid and solid forms, as seen in P5, further amplifies soil fertility and crop performance (Supartha *et al*., 2012).

In summary, the evidence confirms that applying organic fertilizers especially goat manure and combinations of liquid organic fertilizer and compost effectively improves and sustains critical soil chemical parameters, aligning closely with contemporary research in legume cropping and broader agroecosystem management.

4. CONCLUSION

This study demonstrates that organic fertilizers, particularly goat manure and a combination of liquid organic fertilizer with compost, significantly enhance growth, yield, and soil quality in soybean cultivation. These organic inputs consistently produced superior outcomes across plant height, effective root nodulation, yield components, and post-harvest soil chemical properties, outperforming even chemical fertilizer treatments. Specifically, the application of goat manure (P2) and the POC-compost combination (P5) markedly improved soybean yields, underscoring the capacity of organic fertilizers to provide balanced macro- and micronutrients, support soil structure, and stimulate microbial activity, thereby sustaining soil fertility.

Enhanced root nodulation under organic treatments also reflects a more favorable soil environment for rhizobial symbiosis, which improves nitrogen fixation and nutrient uptake efficiency. Furthermore, organic fertilizer application improved key soil parameters such as pH, organic carbon, nitrogen, phosphorus, and potassium availability—factors critical for maintaining soil health and resilience.

These findings support organic fertilizers, especially manure and POC-compost blends, as viable and sustainable alternatives to chemical fertilizers in soybean systems. Adopting these practices not only boosts productivity but also advances environmental sustainability and farmer welfare. Future research should focus on optimizing application rates and strategies across diverse field conditions, and on strengthening extension programs to facilitate wider adoption of sustainable nutrient management.

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