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# Effectiveness of Organic Fertilizer and Rhizobium Biofertilizer in Improving Soybean Growth and Yield (*Glycine max* L. Merrill)

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**Abstract**

Soybean productivity in Indonesia remains constrained by declining soil fertility and inefficient nutrient management. This study evaluated the effectiveness of Sokom organic fertilizer and Rhizobium biofertilizer, applied individually and in combination, on the growth and productivity of soybean (*Glycine max* L. Merrill). The experiment was conducted from October to December 2024 at the experimental field of the Faculty of Agriculture, Islamic University of North Sumatra, Medan, Indonesia, using a factorial randomized block design with four organic-fertilizer rates (0, 20, 25, and 30 tons/ha) and three Rhizobium application methods (control, seed soaking, and soil application). Observed parameters included plant height, flowering age, filled and empty pods, seeds per plant, and yield per plot. Organic fertilizer significantly affected yield, with the highest mean yield of 3.16 kg/plot at 20 tons/ha. Rhizobium seed soaking significantly accelerated flowering to 27.33 days. The interaction between organic fertilizer and Rhizobium significantly affected seeds per plant and yield, and the combination of 20 tons/ha Sokom with soil-applied Rhizobium produced the highest observed yield of 3.43 kg/plot. The principal advantage of this treatment was its ability to combine a moderate organic-fertilizer rate with biological nitrogen fixation, providing a practical option for reducing dependence on synthetic nitrogen fertilizer. For farmers under similar agroecological conditions, 20 tons/ha Sokom combined with soil-applied Rhizobium is recommended as the most promising treatment, subject to local validation and economic assessment.

**Keywords:** Edamame, Inoculation, Nutrient Management, Soil Fertility, Sustainable Agriculture

## 1. Introduction

Soybean (*Glycine max* L. Merrill) is one of the most strategic food commodities in Indonesia, playing a vital role in meeting the nutritional needs of the population and supporting the national food industry. This legume is recognized as a high-quality source of vegetable protein, containing nine essential amino acids, and is also rich in fats, carbohydrates, vitamins, and minerals. Consequently, it is widely used as a raw material for various food products, including tofu, tempeh, soy sauce, soy milk, and numerous processed goods, ranging from household to industrial scales (BPS, 2015). The demand for soybeans continues to rise annually; however, domestic production has consistently failed to meet national requirements. Currently, Indonesia needs approximately 2.7 million tons of soybeans per year, while domestic production is only around 355,000 tons, resulting in a persistent high dependence on imports (Nugroho, 2023). This disparity between production and consumption underscores the urgent need to enhance soybean productivity as a key agenda for supporting national food security (Kebede, 2021).

One of the fundamental causes of low soybean productivity is the progressive deterioration of soil fertility caused by nutrient imbalance, declining soil organic matter, reduced biological activity, and inefficient nutrient-use practices. In soybean fields, these constraints can reduce root development, biological nitrogen fixation, pod filling,

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and ultimately seed yield. Continuous reliance on inorganic fertilizers without adequate organic inputs may also accelerate nutrient imbalance and weaken the soil biological environment. Therefore, the productivity problem is not only a matter of insufficient nutrient quantity, but also of synchronizing nutrient availability with soybean demand while maintaining soil biological function (Triyono, 2013; Fageria & Moreira, 2021).

The use of organic fertilizers presents an environmentally friendly alternative capable of improving soil quality and providing nutrients more steadily. Organic fertilizers function to enhance soil structure, increase cation exchange capacity, improve aeration, boost water-holding capacity, and support root development (Laili, 2022; Agegnehu et al., 2020). Additionally, organic matter can stimulate the activity of microorganisms involved in nutrient mineralization. According to Agnes (2024), organic fertilizers can be made from various materials such as straw, market waste, livestock manure, and other agricultural residues, with the quality of the fertilizer being greatly influenced by the constituent materials. In this study, Sokom organic fertilizer was used—a mixture of cow dung, biocar, topsoil, and EM4 activator—which has the potential to increase soil organic matter content and improve the physical and chemical properties of the soil. As reported by Lazcano et al. (2021), organic amendments not only supply nutrients but also enhance soil biological activity, which is critical for long-term soil health.

In addition to organic fertilizers, the application of biological fertilizers such as Rhizobium can significantly enhance soybean growth. Rhizobium is a nitrogen-fixing bacterium that forms a symbiotic relationship with the roots of leguminous plants, developing root nodules that convert atmospheric nitrogen into a form available to plants (Allen & Allen, 1981; Lindström & Mousavi, 2020). Nitrogen is a primary nutrient for plant growth, particularly influencing the development of leaves, stem tissues, and pod formation. According to Purwani and Sucahyono (2020) and Thilakarathna & Raizada (2020), the success of Rhizobium inoculation is greatly influenced by bacterial population, application method, and soil environmental conditions. Proper application of Rhizobium can improve pod formation and crop yields while reducing the need for synthetic nitrogen fertilizers, thus contributing to more sustainable agricultural systems (Herridge et al., 2022; Koskey et al., 2021).

Although the benefits of organic fertilizers and biofertilizers have been widely documented, previous studies have used different fertilizer sources, rates, inoculant doses, soybean genotypes, and application methods, making their results difficult to transfer directly to the present system. For example, Lumban Gaol et al. (2025) evaluated banana-corm liquid organic fertilizer at 0, 500, 600, and 700 mL/L combined with SP-36 at 150, 200, and 250 kg/ha; the best combination was 600 mL/L LOF + 200 kg/ha SP-36, which improved several vegetative and reproductive traits but did not significantly increase seed weight per plant or per hectare. Pardede et al. (2025) tested Rhizobium at 0, 10, and 15 g/kg seed in Anjasmoro and Dega 1 soybean and found 15 g/kg seed to be effective for root nodules and pod number. The present study differs fundamentally by evaluating a solid Sokom organic fertilizer at 20–30 tons/ha together with two practical Rhizobium delivery methods—seed soaking at 50 g/L and soil application at 50 g/L—using Edamame soybean. This design directly evaluates whether a locally formulated organic amendment and inoculation method can be integrated to improve productivity under the specific soil and environmental conditions of Medan.

Based on this background, this study was conducted to examine the effect of Sokom organic fertilizer dosage and Rhizobium biofertilizer, both singly and in interaction, on the growth and productivity of soybean plants. This research is expected to provide recommendations for soybean cultivation technology based on organic-biological fertilization that is environmentally friendly, low-cost, and applicable by farmers. The results will contribute scientifically to the development of sustainable agricultural systems and support the increase in national soybean production to reduce import dependence. Thus, this research is important as it addresses the need to enhance soybean productivity through innovative fertilization strategies based on local resources and biotechnology (Mukhtar et al., 2023; Sharma et al., 2024).

## 2. Material and Methods

### 2.1. Study Site and Period

The research was conducted from October to December 2024 at the experimental field of the Faculty of Agriculture, Islamic University of North Sumatra, Jalan Karya Wisata, Medan Johor District, Medan, Indonesia. The site is located at approximately 03°30′24″ N and 98°26′00″ E, at an elevation of approximately 25 m above sea level, with flat topography. The area has a tropical rainforest climate, with average annual rainfall of about 2,200 mm and average temperatures of 24–32 °C.

### 2.2. Tools and Materials

The tools used included hoes, measuring tapes, sprayers, documentation cameras, jerry cans, marking stakes, and laboratory analysis equipment. The research materials consisted of soybean seeds of the Edamame variety, Sokom organic fertilizer (a mixture of cow manure, biocar, topsoil, and EM4 activator), Rhizobium sp. biofertilizer, basic NPK fertilizer (15-15-15), and water.water.

### 2.3. Experimental Design

The study employed a factorial randomized block design with two factors. The first factor was Sokom organic

fertilizer dosage, consisting of 0 tons/ha (control), 30 tons/ha (9 kg/plot), 25 tons/ha (7.5 kg/plot), and 20 tons/ha (6 kg/plot). The second factor was Rhizobium biofertilizer application, consisting of no biofertilizer, seed soaking in 50 g/L Rhizobium solution for 15 minutes, and soil application of a 50 g/L Rhizobium solution at 20 days after planting. The 12 treatment combinations were replicated three times, resulting in 36 experimental plots. Each plot measured 200 cm × 200 cm (4 m²), with a spacing of 20 cm × 40 cm and 50 plants per plot. Five plants per plot were selected as sample plants. Organic fertilizer dosage (O) with four levels: 0 tons/ha (control, no organic fertilizer), 30 tons/ha (equivalent to 9 kg per plot), 25 tons/ha (equivalent to 7.5 kg per plot), 20 tons/ha (equivalent to 6 kg per plot). Rhizobium biofertilizer application (R) with three levels: no biofertilizer (control), seed soaking in 50 g/L Rhizobium solution for 15 minutes, soil application of Rhizobium solution at 20 days after planting (DAP) The combination of treatments resulted in 12 treatment combinations (4 × 3). Each combination was replicated three times, giving a total of 36 experimental units (plots). Plot size was 200 cm × 200 cm (4 m²), with a planting distance of 20 cm × 40 cm, resulting in 50 plants per plot. Five plants per plot were randomly selected as sample plants for data collection.

### 2.4. Research Procedure

The research workflow consisted of the following sequential stages (Figure 1).

#### 2.4.1. Initial Soil Analysis

Before treatment application, composite soil samples were collected from the experimental site at a depth of 0–20 cm. The samples were air-dried, ground, and sieved through a 2 mm mesh. Soil analysis included the following parameters: total nitrogen (Kjeldahl method), available phosphorus (Bray I method), exchangeable potassium (flame photometry), soil pH (1:2.5 soil-water suspension using a pH meter), and organic carbon (Walkley and Black method). These analyses were performed at the Soil Science Laboratory, Faculty of Agriculture, Islamic University of North Sumatra, to determine the initial fertility status of the soil and to serve as a basis for interpreting the research results (Fageria & Moreira, 2021).

#### 2.4.2. Land Preparation and Tillage

The land was cleared of weeds, plant residues, and other debris. Primary tillage was carried out by hoeing to a depth of 20–25 cm to loosen the soil and improve its structure. Secondary tillage involved harrowing and leveling to create a fine seedbed. This stage aimed to facilitate root penetration, improve soil aeration, and prepare the land for bed and plot formation (Agegnehu et al., 2020).

#### 2.4.3. Plot Establishment

The experimental area was divided into 36 plots, each measuring 200 cm × 200 cm. The distance between plots within the same replication was 50 cm, and the distance between replications was also 50 cm. A 20 cm border was left from the edge of the bed to the first plant row. Each plot contained 50 planting holes arranged in a 5 × 10 pattern, with a spacing of 20 cm × 40 cm. Five plants per plot were selected systematically (every 10th plant) as sample plants for non-destructive observations.

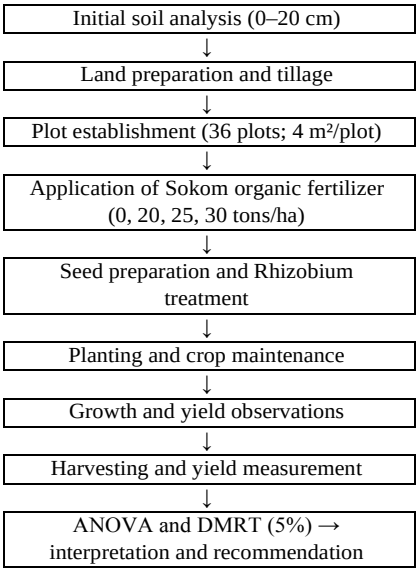



**Figure 1.** Research flow diagram

#### 2.4.4. Application of Sokom Organic Fertilizer

Sokom organic fertilizer was applied one week before planting according to the treatment doses. The fertilizer was spread evenly over the plot surface and then incorporated into the top 10 cm of soil by light hoeing. This timing allowed partial decomposition and nutrient release before planting (Zhang et al., 2023). The doses were: O0 = 0 kg/plot; O1 = 9 kg/plot (30 tons/ha); O2 = 7.5 kg/plot (25 tons/ha); O3 = 6 kg/plot (20 tons/ha).

#### 2.4.5. Seed Preparation

Soybean seeds of the Edamame variety were selected for uniformity, health, and freedom from pests and diseases. Only seeds with good physical appearance and no visible damage were used. The seeds were not treated with any chemical fungicide or insecticide to avoid interference with *Rhizobium* inoculation. The estimated seed requirement was 40–50 kg/ha, with two seeds planted per hole (Kumawat et al., 2020).

#### 2.4.6. Application of Rhizobium Biofertilizer

*Rhizobium* sp. biofertilizer was applied according to the treatment levels: R0 (control) – no biofertilizer; R1 (seed soaking) – seeds were soaked in a solution containing 50 g of *Rhizobium* powder per liter of tap water for 15

minutes at room temperature, then air-dried under shade for 30 minutes before planting (Koskey et al., 2021); R2 (soil application) – *Rhizobium* solution (50 g/L water) was applied directly to the soil around the root zone of each plant at 20 DAP, with volume adjusted to approximately 2 L per plot (equivalent to 500 L/ha). The concentration and application methods followed standard recommendations for legume inoculation (Lindström & Mousavi, 2020; Thilakarathna & Raizada, 2020).

#### 2.4.7. Planting

Planting was done using a hand drill (tugal) to create holes 2–3 cm deep. Two seeds were placed in each hole, then covered with fine soil. Planting was carried out uniformly across all plots on the same day to ensure synchronous growth. Germination occurred within 5–7 days, and thinning to one plant per hole was performed at 10 DAP, leaving a final population of 50 plants per plot (Ulzen et al., 2020).

#### 2.4.8. Crop Maintenance

Watering was provided twice daily (07:00–09:00 AM and 04:00–05:30 PM) using a hose or watering can, except on days with sufficient rainfall (>20 mm), to maintain soil moisture at field capacity (Salvagiotti et al., 2020). Manual weeding was performed at 20 and 40 DAP to minimize competition (Mbah & Nwite, 2021). Pest and disease control was carried out using integrated pest management, including field sanitation and manual removal of infected plants; when necessary, selective insecticides (e.g., abamectin) and fungicides (e.g., mancozeb) were applied at recommended doses (Raimi et al., 2022).

#### 2.4.9. Harvesting

Soybean plants were harvested at approximately 75 DAP, when leaves turned yellow and began to fall, and pods dried and turned brown (physiological maturity). Harvesting was done manually by cutting stems at ground level using a sickle. The harvested plants were sun-dried for 3–5 days until moisture content reached approximately 12–14%. Threshing was done manually to separate seeds from pods. Seeds were cleaned and weighed for yield determination (Sharma et al., 2024).

### 2.5. Observed Parameters

The following growth and yield parameters were recorded:

1. **Plant height (cm)**: Measured from the base of the stem at ground level to the highest growing point (apical meristem) of the sample plant. Measurements were taken weekly from 3 weeks after planting (WAP) until harvest (5 times total). A meter stick was used, and each sample plant was marked to ensure consistent measurement (Kumawat et al., 2020).
2. **Flowering age (days)**: Recorded as the number of days from planting until the first flower appeared on the sample plant (when at least one flower was fully open on the main stem) (Ferguson et al., 2019).
3. **Number of filled pods per plant**: Counted by harvesting all pods that contained at least one normally developed seed (both mature and immature seeds) from each sample plant (Mukhtar et al., 2023).
4. **Number of empty pods per plant**: Counted as the number of pods that contained no seeds or only aborted seeds (Ndakidemi et al., 2022).
5. **Number of seeds per plant**: After threshing, all seeds from the sample plants were counted individually (Tewari et al., 2020).
6. **Yield per plot (kg)**: The total weight of dry seeds harvested from each plot (excluding border plants) was measured using a digital scale (accuracy ±1 g). Yield was expressed in kilograms per plot (4 $m^2$) and can be converted to tons per hectare by multiplying by 2.5 (Raimi et al., 2022; Sharma et al., 2024).

### 2.6. Data Analysis

All data were tested for normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) before analysis. Data that met the assumptions were analyzed using analysis of variance (ANOVA) for a factorial randomized block design. When significant differences were detected ($p < 0.05$), means were separated using Duncan's Multiple Range Test (DMRT) at the 5% significance level. Statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA) (Gomez & Gomez, 1996).

## 3. Results and Discussion

### 3.1. General Overview

This study evaluated the single and interactive effects of organic fertilizer (Sokom) and *Rhizobium* biofertilizer on the growth and yield of soybean (*Glycine max* L. Merrill). The results showed that the two factors produced different responses across the observed parameters. In general, organic fertilizer significantly affected yield per plot, while biofertilizer significantly accelerated flowering age. Their interaction significantly influenced the number of seeds per plant and yield per plot. These findings are consistent with the growing body of literature that emphasizes the importance of integrated nutrient management in legume crops (Herridge et al., 2022; Thilakarathna & Raizada, 2020).

### 3.2. Plant Height

The average plant height at 4 weeks after planting (WAP) ranged from 33.73 to 38.67 cm (Table 1). Analysis of variance (ANOVA) revealed that neither organic fertilizer, biofertilizer, nor their interaction had a significant effect on plant height ($p > 0.05$). This indicates that the initial soil fertility level was sufficient to support early

vegetative growth, and the additional nutrient inputs did not produce a measurable increase in vertical growth.

**Table 1.** Average plant height of soybean (cm) at 4 weeks after planting

| Fertilizer Treatment | R0 (control) | R1 (soaking) | R2 (soil application) | Mean |
|---|---|---|---|---|
| (0 kg) | 36.10 ± 2.21 | 38.67 ± 2.15 | 35.80 ± 2.30 | 36.86 |
| (9 kg) | 37.27 ± 2.05 | 33.73 ± 2.40 | 37.53 ± 2.10 | 36.18 |
| (7.5 kg) | 36.53 ± 2.18 | 35.67 ± 2.25 | 36.67 ± 2.12 | 36.29 |
| (6 kg) | 36.73 ± 2.10 | 35.10 ± 2.32 | 38.03 ± 2.08 | 36.62 |
| **Mean** | 36.66 | 35.79 | 37.01 | - |

Remarks: No significant differences among treatments ($p > 0.05$).

The absence of a significant response in plant height indicates that the treatments did not materially change early vegetative elongation under the conditions of this experiment. The means varied from 33.73 to 38.67 cm, a range of 4.94 cm (14.6% relative to the minimum), but ANOVA detected no significant treatment effect. In contrast, Lumban Gaol et al. (2025) reported a significant interaction of banana-corm LOF and SP-36 on soybean plant height at 42 days after planting using 0–700 mL/L LOF and 150–250 kg/ha SP-36. The different response likely reflects differences in fertilizer form, nutrient composition, genotype, and phosphorus supply rather than a contradiction between studies. Sutanto (2012) emphasized that plant response to organic fertilizer is strongly influenced by the initial soil fertility status. In soils with adequate organic matter and nitrogen, the addition of organic fertilizer often does not produce a significant increase in plant height, as observed in this study. Similar results were reported by Ulzen et al. (2020) in northern Ghana, where organic manure alone did not improve soybean height unless combined with rhizobia inoculant and phosphorus. A limitation of this study is the absence of soil nutrient analysis during each growth phase, which would have provided a clearer understanding of nutrient dynamics and plant uptake patterns (Fageria & Moreira, 2021).

### 3.3. Flowering Age

In contrast to plant height, the application of *Rhizobium* biofertilizer significantly affected flowering age ($p < 0.05$). The fastest flowering (27.33 days) was observed in the R1 treatment (seed soaking), followed by R0 (28.00 days) and R2 (28.25 days) (Table 2). The R1 treatment was significantly different from both R0 and R2, indicating that seed inoculation with *Rhizobium* effectively accelerated the transition from vegetative to generative phase.

**Table 2.** Average flowering age of soybean (days)

| Organic fertilizer (kg/plot) | R0 | R1 | R2 | Mean |
|---|---|---|---|---|
| **O0 (0)** | 36.10 ± 2.21 | 38.67 ± 2.15 | 35.80 ± 2.30 | 28.33 |
| **O1 (9)** | 37.27 ± 2.05 | 33.73 ± 2.40 | 37.53 ± 2.10 | 27.89 |
| **O2 (7,5)** | 36.53 ± 2.18 | 35.67 ± 2.25 | 36.67 ± 2.12 | 27.33 |
| **O3 (6)** | 36.73 ± 2.10 | 35.10 ± 2.32 | 38.03 ± 2.08 | 27.89 |
| **Mean** | 36.66 ± 2.05 | 35.79 ± 2.20 | 37.01 ± 2.15 | |

Remarks: Means followed by the same letter in the same row are not significantly different at $p < 0.05$ (DMRT). a = fastest flowering.

The acceleration of flowering by Rhizobium seed soaking can be explained by the early establishment of symbiotic nitrogen fixation. When seeds are soaked in a Rhizobium solution, the bacteria colonize the emerging root system immediately after germination, leading to rapid nodule formation and biological nitrogen fixation (BNF) (Lindström & Mousavi, 2020). Increased nitrogen availability during the early vegetative stage promotes the synthesis of flowering-related hormones such as florigen, thereby shortening the time to first anthesis (Ferguson et al., 2019). Lestari et al. (2025) reported similar findings, noting that inoculation effectiveness is highly dependent on the proximity of contact between bacteria and young roots. Seed soaking provides this intimate contact, whereas soil application (R2) may result in delayed or reduced root colonization due to competition with native soil microbes (Koskey et al., 2021). This is consistent with Tewari et al. (2020), who found that seed inoculation with Rhizobium reduced days to flowering by 5–7 days compared to control in soybean. The lack of a significant effect from organic fertilizer on flowering age suggests that the organic matter applied did not release sufficient mineral nitrogen quickly enough to influence reproductive timing. This is consistent with the slow-release nature of organic fertilizers, which primarily affect soil properties over longer periods (Agegnehu et al., 2020). A limitation of this study is the absence of direct quantification of root nodules and their nitrogen-fixing activity. Future research should include nodule count, leghaemoglobin content, and nitrogenase activity to better correlate BNF with phenological changes (Ndakidemi et al., 2022).

### 3.4. Number of Seeds per Plant

The number of seeds per plant was significantly influenced by the interaction between organic fertilizer and *Rhizobium* biofertilizer ($p < 0.05$). The highest seed

numbers were recorded in O2R0 (60.80 seeds/plant) and O3R0 (59.67 seeds/plant), while the lowest was in O2R1 (45.73 seeds/plant) (Table 3). This non-linear response indicates that the combined effect of organic and biological fertilizers is not simply additive; rather, it depends on specific dosage combinations and application methods.

**Table 3.** Average number of seeds per soybean plant (interaction effect)

| Organic fertilizer (kg/plot) | R0 | R1 | R2 | Mean |
|---|---|---|---|---|
| **O0 (0)** | 46.53 a ± 2.11 | 59.87 b ± 2.45 | 52.40 ab ± 2.23 | 52.93 ± 1.98 |
| **O1 (9)** | 52.60 ab ± 2.30 | 56.20 ab ± 2.18 | 55.67 ab ± 2.35 | 54.82 ± 2.02 |
| **O2 (7,5)** | 60.80 b ± 2.50 | 45.73 a ± 2.05 | 58.87 b ± 2.40 | 55.13 ± 2.10 |
| **O3 (6)** | 59.67 b ± 2.42 | 57.00 ab ± 2.28 | 46.67 a ± 2.15 | 54.44 ± 2.05 |
| **Mean** | 54.90 ± 2.33 | 54.70 ± 2.24 | 53.40 ± 2.28 | - |

Remarks: Means followed by the same letter in the same column and row are not significantly different at $p < 0.05$ (DMRT). Letters compare interaction combinations across the whole table.

The interaction pattern demonstrates that seed number responded to the specific fertilizer combination rather than to either input alone. The highest values were 60.80 seeds/plant in O2R0 (25 tons/ha organic fertilizer without Rhizobium) and 59.67 seeds/plant in O3R0 (20 tons/ha without Rhizobium), while O2R1 produced only 45.73 seeds/plant. Thus, the difference between the highest and lowest treatment combinations was 15.07 seeds/plant, equivalent to 33.0% of the lowest value. This non-linear response indicates that the contribution of organic fertilizer and Rhizobium cannot be assumed to be additive and reinforces the need to identify treatment combinations rather than relying on a single-input recommendation. Another possible explanation is that the Edamame variety used in this study has a high sensitivity to excess nitrogen during the pod-filling stage. While nitrogen is essential for seed formation, excessive nitrogen can delay senescence and reduce the efficiency of assimilate partitioning to seeds (Salvagiotti et al., 2020). The optimal combination for seed number in this study (O2R0) suggests that organic fertilizer alone at 25 tons/ha provided sufficient slow-release nitrogen without overstimulating vegetative growth. A limitation of this study is the lack of organic matter quality analysis (e.g., C/N ratio, lignin content), which would have helped explain the decomposition rate and nutrient release pattern (Lazcano et al., 2021). As noted by Raimi et al. (2022), the quality of organic manure significantly affects its interaction with rhizobia.

### 3.5. Yield per Plot

Soybean seed yield per plot, the most critical parameter for agronomic success, was significantly affected by both organic fertilizer ($p < 0.05$) and its interaction with biofertilizer ($p < 0.05$). The highest yield was obtained in O3R2 (3.43 kg/plot), followed by O3R0 (3.17 kg/plot) and O1R1 (3.10 kg/plot) (Table 4). Notably, the highest organic fertilizer dose (O1 = 30 tons/ha) did not produce the highest yield; instead, the optimal dose was O3 (20 tons/ha). This confirms the existence of an optimal fertilization threshold beyond which yield plateaus or declines.

**Table 4.** Average soybean yield per plot (kg) – interaction effect

| Organic fertilizer (kg/plot) | R0 | R1 | R2 | Mean |
|---|---|---|---|---|
| **O0 (0)** | 2.57 ± 0.19 a | 2.87 ± 0.19 ab | 2.40 ± 0.19 a | 2.61 ± 0.11 a |
| **O1 (9)** | 2.93 ± 0.19 ab | 3.10 ± 0.19 ab | 2.93 ± 0.19 ab | 2.99 ± 0.11 ab |
| **O2 (7,5)** | 3.07 ± 0.19 ab | 2.57 ± 0.19 a | 2.93 ± 0.19 ab | 2.86 ± 0.11 ab |
| **O3 (6)** | 3.17 ± 0.19 b | 2.87 ± 0.19 ab | 3.43 ± 0.19 b | 3.16 ± 0.11 b |
| **Mean** | 2.93 ± 0.11 | 2.85 ± 0.11 | 2.93 ± 0.11 | - |

Remarks: Means followed by the same letter in the same column and row are not significantly different at $p < 0.05$ (DMRT). a = significantly lower; b = significantly higher.

The quadratic response of soybean yield to organic fertilizer dose observed in this study is consistent with the findings of Kumari et al. (2022), who reported that crop response to organic fertilizer follows a diminishing returns curve. At low doses (O0), nutrient availability is insufficient to support high yields. As the dose increases to an optimal level (O3 = 20 tons/ha), yield improves due to enhanced soil water-holding capacity, aeration, and nutrient release (Diacono & Montemurro, 2019). However, beyond this optimum (O1 = 30 tons/ha), excessive organic matter can lead to nutrient immobilization, particularly of nitrogen and phosphorus, as well as the production of phytotoxic compounds such as organic acids and phenols during decomposition (Müller et al., 2020). Furthermore, high organic matter application may increase soil salinity and electrical conductivity, which can reduce root water uptake and seed set (Zhou et al., 2022). Kebede (2021) reviewed that in Ethiopian conditions, the optimal organic fertilizer dose for soybean ranged from 15–25 tons/ha, depending on soil type.

The combination of 20 tons/ha Sokom organic fertilizer with soil-applied Rhizobium produced the highest observed yield, 3.43 kg/plot, compared with 2.57 kg/plot in the untreated control. This represents an increase of 0.86 kg/plot or 33.5%. The treatment was also 8.2% higher than O3R0 (3.17 kg/plot), although the manuscript's DMRT

grouping indicates that these two treatments were not significantly different. Lumban Gaol et al. (2025) identified 600 mL/L banana-corm LOF + 200 kg/ha SP-36 as the most effective combination for plant height, pod number, empty-pod percentage, and fruit set, but seed weight per plant and per hectare were not significantly affected. Pardede et al. (2025) recommended 15 g Rhizobium/kg seed based on effects on root nodules and pod number. The present study is distinct because its primary productivity advantage was demonstrated as a yield response from combining solid organic fertilizer with soil-applied Rhizobium in Edamame soybean.

Interestingly, the treatment O3R0 (organic fertilizer alone at 20 tons/ha) also produced a high yield (3.17 kg/plot), not significantly different from O3R2. This suggests that under the conditions of this study, organic fertilizer alone at the optimal dose was already quite effective, and the addition of Rhizobium provided only a marginal (though significant) increase. However, from a sustainability perspective, the combined treatment O3R2 is preferable because it reduces the need for high doses of organic fertilizer (which may be costly or scarce) and leverages biological nitrogen fixation.

Taken together, the results of this study highlight the importance of integrated nutrient management for soybean production. While organic fertilizer alone improved yield, its effectiveness was maximized when combined with an appropriate Rhizobium application method. The significant interaction on seed number and yield per plot underscores the need to move beyond single-factor fertilization strategies toward holistic soil-plant-microbe management (Fageria & Moreira, 2021).

Several mechanisms may explain the observed synergies. First, organic matter enhances soil aggregation and water retention, creating a more favorable environment for root growth and nodule formation (Lazcano et al., 2021). Second, the slow release of nutrients from organic fertilizer matches the temporal demand of soybean, which requires high nitrogen during pod filling but not excessively early in the season (Salvagiotti et al., 2020). Third, Rhizobium inoculation increases the availability of biologically fixed nitrogen, which is more efficiently utilized for seed protein synthesis than synthetic nitrogen (Herridge et al., 2022). As reported by Sharma et al. (2024), integrated nutrient management combining vermicompost and Rhizobium increased soybean yield by 28–35% compared to control.

### 3.6. Integrated Discussion and Implications

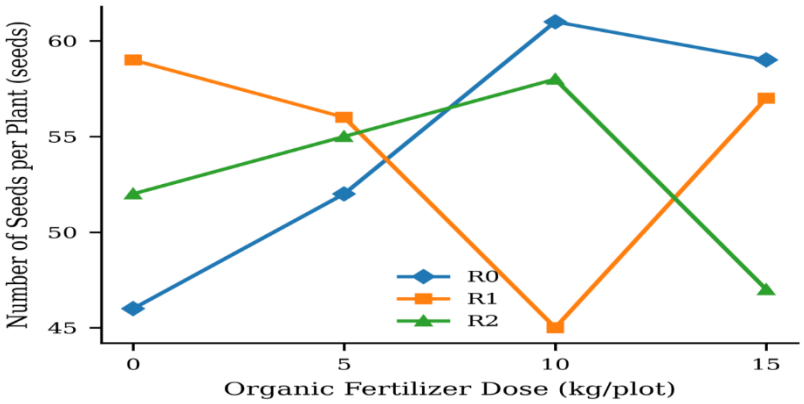



**Figure 2.** Number of seeds per plant (seeds)

The strongest contribution of this study is the identification of a practical treatment combination that produced a 33.5% higher yield than the untreated control while using a moderate organic-fertilizer rate of 20 tons/ha. For users, the findings support prioritizing soil-applied Rhizobium together with 20 tons/ha Sokom under conditions similar to the study site, while avoiding the assumption that increasing organic fertilizer to 30 tons/ha will necessarily increase yield. Because the experiment was conducted at one location and the manuscript lacks economic and replicate-level variance data, the recommendation should be validated through multi-location trials and economic analysis.

A major limitation of this study is the absence of detailed soil biological and chemical analyses at multiple time points. Future studies should measure nodule number, nitrogenase activity, soil microbial biomass, and nutrient mineralization rates to better understand the underlying mechanisms. Additionally, multi-location trials across different soil types and climatic conditions are needed to validate the generalizability of these findings (Ndakidemi et al., 2022). As suggested by Ulzen et al. (2020), the response to rhizobia and organic fertilizer is highly site-specific.

In conclusion, the combination of 20 tons/ha organic fertilizer (Sokom) with soil-applied Rhizobium biofertilizer (R2) is recommended for optimizing soybean yield in similar agroecological conditions. This approach reduces dependence on synthetic fertilizers, promotes soil health, and contributes to sustainable intensification of soybean

production in Indonesia.

## 4. Conclusion

Based on the research results, oil palm frond waste-based biochar demonstrates superiority in reducing heavy metals in soil: cadmium (Cd) decreased from 0.05 ppm to "undetectable" (100% removal efficiency). In comparison, lead (Pb) decreased from 0.34 ppm to 0.29 ppm (14.71% reduction). Based on these findings, oil palm frond biochar is recommended for farmers and plantation operators as an alternative soil conditioner for land contaminated with heavy metals. The main advantage of this biochar lies in its ability to immobilize heavy metals through mechanisms such as adsorption, ion exchange, surface complexation, and increased soil pH, making it an inexpensive and environmentally friendly remediation solution.

Based on the results and discussion, the following conclusions are drawn:

Dosage efficiency: Organic fertilizer at 20 tons/ha (6 kg/plot) is already optimal; increasing the dose to 30 tons/ha did not further increase yield, thus saving fertilization costs.

Highest synergy: The combination of 20 tons/ha organic fertilizer with soil-applied Rhizobium (O3R2) produced the highest yield (3.43 kg/plot), surpassing organic fertilization without Rhizobium (3.16 kg/plot). This confirms a significant synergistic effect.

Eco-friendly: This integrated organic-biofertilizer strategy effectively reduces dependence on chemical fertilizers without compromising productivity.

**References**


Agegnehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2020). Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Agronomy for Sustainable Development, 40*(3), Article 19. https://doi.org/10.1007/s13593-020-00627-w

Allen, O. N., & Allen, E. K. (1981). *The Leguminosae: A source book of characteristics, uses, and nodulation*. The University of Wisconsin Press.

Badan Pusat Statistik. (2015). *Statistik Indonesia 2015*.

Diacono, M., & Montemurro, F. (2019). Long-term effects of organic amendments on soil fertility: A review. *Agronomy, 9*(2), Article 88. https://doi.org/10.3390/agronomy9020088

Egamberdieva, D., Wirth, S., Bellingrath-Kimura, S. D., Mishra, J., & Arora, N. K. (2019). Biochar and manure co-compost improve soybean growth and soil properties. *Journal of Soil Science and Plant Nutrition, 19*(3), 565–574. https://doi.org/10.1007/s42729-019-00055-6

Fageria, N. K., & Moreira, A. (2021). Role of soil organic matter in maintaining sustainability of cropping systems. *Journal of Plant Nutrition, 44*(5), 678–695. https://doi.org/10.1080/01904167.2020.1867579

Ferguson, B. J., Mens, C., Hastwell, A. H., Zhang, M., Su, H., Jones, C. H., & Gresshoff, P. M. (2019). Legume nodulation: The host controls the party. *Journal of Experimental Botany, 70*(2), 441–454. https://doi.org/10.1093/jxb/ery422

Gomez, K. A., & Gomez, A. A. (1996). *Statistical procedures for agricultural research* (2nd ed.). John Wiley & Sons.

Hartman, K., & Tringe, S. G. (2019). Interactions between plants and soil shaping the root microbiome under abiotic stress. *Current Opinion in Microbiology, 49*, 73–80. https://doi.org/10.1016/j.mib.2019.10.003

Herridge, D. F., Giller, K. E., Jensen, E. S., & Peoples, M. B. (2022). Quantifying the contribution of biological nitrogen fixation to agricultural systems: A meta-analysis. *Field Crops Research, 276*, Article 108374. https://doi.org/10.1016/j.fcr.2021.108374

Kebede, E. (2021). Response of soybean to rhizobium inoculation and organic fertilizer in Ethiopia: A review. *Cogent Food & Agriculture, 7*(1), Article 1929735. https://doi.org/10.1080/23311932.2021.1929735

Koskey, G., Mburu, S. W., Njeru, E. M., Kimiti, J. M., Ombori, O., & Maingi, J. M. (2021). Potential of native rhizobia in enhancing nitrogen fixation and yield of soybean in smallholder farming systems. *Frontiers in Microbiology, 12*, Article 628979. https://doi.org/10.3389/fmicb.2021.628979

Kumari, P., Singh, V. K., & Singh, S. K. (2022). Long-term impact of organic and inorganic fertilizers on soybean productivity and soil health. *Archives of Agronomy and Soil Science, 68*(5), 641–655. https://doi.org/10.1080/03650340.2021.1932834

Kumawat, N., Kumar, R., & Singh, I. (2020). Effect of organic nutrient management on growth, yield and quality of soybean (*Glycine max* L.). *Legume Research, 43*(4), 457–465. https://doi.org/10.18805/LR-458

Lazcano, C., Zhu-Barker, X., & Decock, C. (2021). Effects of organic and inorganic amendments on soil microbial activity and nitrogen cycling. *Soil Biology and Biochemistry, 152*, Article 108069. https://doi.org/10.1016/j.soilbio.2020.108069

Lindström, K., & Mousavi, S. A. (2020). Effectiveness of nitrogen fixation in rhizobia. *Applied Soil Ecology, 146*, Article 103370. https://doi.org/10.1016/j.apsoil.2019.103370

Mbah, C. N., & Nwite, J. N. (2021). Response of soybean to organic manure and rhizobium inoculation in an Ultisol. *Communications in Soil Science and Plant Analysis, 52*(8), 891–902. https://doi.org/10.1080/00103624.2021.1872596

Mukhtar, S., Ahmad, M., & Khalid, M. (2023). Synergistic effect of organic fertilizer and rhizobium on nodulation and seed yield of soybean. *Pakistan Journal of Botany, 55*(2), 667–674. https://doi.org/10.30848/PJB2023-2(12)

Müller, T., Rupp, C., & Wiesler, F. (2020). Organic matter decomposition and nutrient release patterns in agricultural soils. *Plant and Soil, 447*(1), 1–25. https://doi.org/10.1007/s11104-019-04399-1

Ndakidemi, P. A., Dakora, F. D., & Nkonya, E. M. (2022). Symbiotic nitrogen fixation and its role in sustainable agriculture. *Symbiosis, 86*(2), 123–137. https://doi.org/10.1007/s13199-022-00830-5

Nugroho, D. (2023). Analysis of national soybean production and needs from the perspective of food security. *Indonesian Food Journal, 8*(1), 55–66.

Nyoki, D., & Ndakidemi, P. A. (2019). Effects of rhizobium inoculation and phosphorus fertilizer on soybean yield. *Journal of Plant Nutrition, 42*(4), 385–396. https://doi.org/10.1080/01904167.2019.1567769

Peoples, M. B., Hauggaard-Nielsen, H., & Jensen, E. S. (2021). The role of biological nitrogen fixation in future agricultural systems. *Plant and Soil, 460*(1), 1–28. https://doi.org/10.1007/s11104-020-04780-5

Raimi, A., Adeleke, R., & Roopnarain, A. (2022). Co-application of cow dung and rhizobium inoculation improves soybean yield and soil fertility. *Sustainability, 14*(8), Article 4567. https://doi.org/10.3390/su14084567

Salvagiotti, F., Specht, J. E., & Cassman, K. G. (2020). Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. *European Journal of Agronomy, 115*, Article 126018. https://doi.org/10.1016/j.eja.2020.126018

Sharma, A., Singh, B., & Kaur, S. (2024). Integrated nutrient management in soybean using rhizobium and vermicompost under rainfed conditions. *Legume Research, 47*(1), 45–51. https://doi.org/10.18805/LR-512

Sutanto, R. (2012). *Organic farming: Towards alternative and sustainable agriculture*. Kanisius.

Tewari, K., Singh, A., & Singh, R. (2020). Combined application of organic manure and rhizobium enhances nodulation, growth and yield of soybean. *Journal of Plant Nutrition, 43*(15), 2273–2285. https://doi.org/10.1080/01904167.2020.1771579

Thilakarathna, M. S., & Raizada, M. N. (2020). A meta-analysis of the effectiveness of rhizobial inoculants in soybean production. *Frontiers in Plant Science, 11*, Article 561234. https://doi.org/10.3389/fpls.2020.561234

Triyono, S. (2013). The impact of the use of chemical fertilizers and efforts to improve soil fertility through the application of organic fertilizers. *Journal of Land Resources, 7*(2), 89–97.

Ulzen, J., Abaidoo, R. C., Ewusi-Mensah, N., & Masso, C. (2020). Organic manure improves soybean response to rhizobia inoculant and P fertilizer in northern Ghana. *Frontiers in Agronomy, 2*, Article 593964. https://doi.org/10.3389/fagro.2020.593964

Wang, X., Li, Y., & Zhang, W. (2021). Soil organic carbon and nitrogen dynamics under long-term organic fertilization. *Science of the Total Environment, 754*, Article 142442. https://doi.org/10.1016/j.scitotenv.2020.142442

Zhang, Y., Chen, X., & Zhang, F. (2023). Organic fertilizer mineralization and its synchronization with crop nitrogen demand. *Nutrient Cycling in Agroecosystems, 125*(2), 189–205. https://doi.org/10.1007/s10705-022-10255-3

Zhou, M., Wang, H., & Zhu, B. (2022). Long-term organic amendments increase soil salinity and reduce crop yield in dryland agriculture. *Agriculture, Ecosystems & Environment, 326*, Article 107798. https://doi.org/10.1016/j.agee.2021.107798