

ORIGINAL RESEARCH ARTICLE

Integrating organic manure and natural phosphate for sustainable long bean (*Vigna sinensis* L.) cultivation on marginal soilsIndra Purnama^{1,2,3*} , Rahmad Abdul Azis¹, and Muhammad Rizal¹¹Department of Agrotechnology, Faculty of Agriculture, Universitas Lancang Kuning, Pekanbaru, Riau, Indonesia²Graduate School of Agricultural Sciences, School of Graduate Studies, Universitas Lancang Kuning, Pekanbaru, Riau, Indonesia³Center for Sustainable Tropical Agricultural Research, Universitas Lancang Kuning, Pekanbaru, Riau, Indonesia

Abstract

Long bean (*Vigna sinensis* L.) is a legume widely cultivated for its high nutritional value and economic importance. However, marginal podzolic soils in regions such as Riau, Indonesia, pose challenges for sustainable agriculture due to low nutrient availability and high acidity. This study evaluates the integration of quail manure and natural phosphate fertilizers as a sustainable soil management strategy to enhance soil health and crop productivity. A factorial randomized complete block design was implemented with three levels of quail manure (0, 1.5, and 3 kg/plot) and natural phosphate (0, 12.5, and 25 g/plant) across 27 experimental plots. The effects of these amendments on soil properties, plant growth, and yield components were assessed using analysis of variance and Duncan's multiple range test. Results demonstrated that the combined application of quail manure and natural phosphate significantly improved plant growth parameters and soil fertility. The findings suggest that integrating organic and natural fertilizers enhances crop productivity while reducing dependence on synthetic inputs, offering a promising approach for sustainable agriculture on degraded soils.

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1. Introduction

Long bean (*Vigna sinensis* L.) is an essential legume crop widely cultivated for its nutritional value and economic importance, particularly in tropical and subtropical regions. It is a significant source of protein, vitamins (A, B, C), minerals (iron, potassium, magnesium), and antioxidants, contributing to food security and dietary diversity.^{1,2} However, despite its adaptability, long bean cultivation is often constrained by soil degradation, particularly in marginal podzolic soils. These soils, characterized by low organic matter content, high acidity, and limited phosphorus availability due to fixation by aluminum (Al) and iron (Fe), pose a critical challenge to achieving sustainable agricultural productivity.³ Soil degradation is a global issue, affecting over 33% of the

world's arable land, and is exacerbated by unsustainable farming practices, climate change, and deforestation.⁴ Addressing soil fertility in such degraded ecosystems is crucial for ensuring food security, especially in regions where agriculture is the primary livelihood.⁵

Efforts to address soil fertility issues in marginal soils have traditionally relied on synthetic fertilizers. While effective in boosting yields, the overuse of synthetic fertilizers has led to significant environmental issues, including nutrient runoff, water pollution, and increased greenhouse gas emissions.^{6,7} The environmental costs of synthetic fertilizers are substantial, with nitrogen-based fertilizers alone contributing to approximately 2.4% of global greenhouse gas emissions.⁸ Recognizing these limitations, there is growing interest in exploring sustainable alternatives that improve soil fertility while minimizing environmental impacts.⁹ Organic amendments, such as manure and compost, have gained attention for their ability to enhance soil structure, increase microbial activity, and provide essential nutrients in a slow-release manner.¹⁰ Among these, quail manure stands out as a rich source of organic carbon, nitrogen, and phosphorus, which are critical for soil fertility.¹¹ Recent studies have demonstrated that quail manure not only improves soil health but also enhances crop resilience to environmental stressors, making it a promising option for sustainable agriculture.¹²

The potential of organic fertilizer to improve crop yields and soil health has been highlighted in recent reports. For instance, Ma *et al.*¹³ demonstrated that organic manure application significantly increased soil organic carbon and microbial activity, resulting in better nutrient cycling. Similarly, Manono *et al.*¹⁴ found that the application of organic amendments significantly reduced soil bulk density, which in turn improved water infiltration, retention, and aeration, thereby promoting root development and nutrient uptake. However, organic amendments alone may not address phosphorus deficiencies prevalent in acidic podzolic soils.¹⁵ Natural phosphate fertilizers, derived from sedimentary rocks, offer a sustainable alternative by providing a slow-release source of phosphorus, which is essential for root and shoot development.¹⁶ Studies by Timofeeva *et al.*¹⁷ and Mardamootoo *et al.*¹⁸ have demonstrated that natural phosphates are particularly effective in acidic soils, where their dissolution is enhanced, ensuring sustained phosphorus availability to crops. In addition, the integration of organic and inorganic amendments has reportedly improved the efficiency of phosphorus use, reducing the need for synthetic inputs.¹⁹

While the benefits of organic and natural phosphate fertilizers are well-documented, research integrating these

amendments for marginal soil improvement, specifically for long bean cultivation, remains limited. Most studies focus either on organic or chemical fertilizers, with few exploring the synergistic effects of combining organic manure with natural phosphates. For example, Zhen *et al.*¹⁰ evaluated organic amendments on sandy soils but did not consider their interaction with natural phosphate fertilizers. Similarly, Talboys *et al.*²⁰ examined phosphorus management in acidic soils but overlooked the potential of combining organic amendments to further enhance nutrient availability. Recent research by Cen *et al.*²¹ demonstrated that combining organic and inorganic fertilizers significantly improved soil health and crop yields in temperate regions, suggesting a similar potential for tropical marginal soils.

This research aims to address these gaps by investigating the combined application of quail manure and natural phosphate fertilizers for long bean cultivation on podzolic soils. The study evaluates their effects on key agronomic parameters, including plant growth, pod production, and soil health. By integrating these sustainable fertilization strategies, this study contributes to the broader discourse on sustainable agriculture, particularly for regions with degraded soils. The findings aim to provide actionable insights for optimizing land use while promoting environmental resilience, aligning with global efforts to achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).²²

2. Methods

2.1. Study location

The study was conducted in a controlled greenhouse environment at the Faculty of Agriculture, Universitas Lancang Kuning, Riau, Indonesia (0°34'37.2"N 101°25'30.3"E). The greenhouse conditions were regulated to simulate the tropical climate of the region, with temperatures maintained at 28 – 32°C, relative humidity at 70 – 80%, and a photoperiod of 12 h of light per day. These conditions were chosen to mimic the natural growing environment of long beans in tropical regions. The soil used for the experiment was podzolic, representative of marginal soils in tropical regions, characterized by low fertility, high acidity (pH 5.2), and poor phosphorus availability due to Al and Fe fixation,³ as displayed in Figure 1.

2.2. Experimental design

A factorial randomized complete block design was employed to assess two factors: quail manure (P) and natural phosphate fertilizer (R). Quail manure was tested

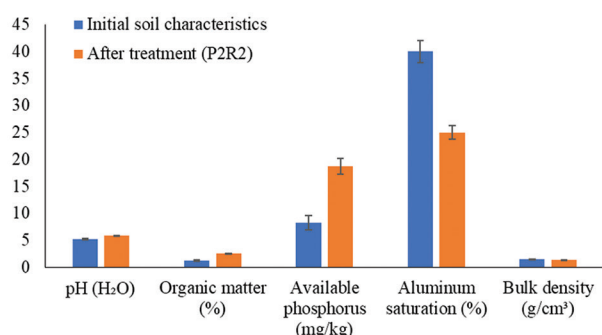


Figure 1. Changes in soil properties following application of quail manure and natural phosphate (P2R2 treatment; $n = 3$)

at three levels: no application (P0), 1.5 kg/plot (P1), and 3.0 kg/plot (P2). Natural phosphate was tested at three levels: no application (R0), 12.5 g/plant (R1), and 25 g/plant (R2). Each treatment combination was replicated 3 times, resulting in 27 experimental units, each containing four plants. This design ensured robust statistical analysis of the main and interaction effects of the treatments.²³ The experiment was conducted over a period of 7 weeks, from seed germination to final harvest, to capture the full growth cycle of long beans.

2.3. Plant materials and soil preparation

The experiment utilized *V. sinensis* L. (variety Parade Tavi), which is well-suited to tropical climates. Soil samples were collected from agricultural fields in Riau at a depth of 0 – 20 cm, homogenized, and sieved through a 2-mm mesh to remove debris and large particles. The soil was classified as podzolic with an initial pH of 5.2, low organic matter (1.25%), and high aluminum saturation (40%). These characteristics necessitate amendments to improve fertility.^{3,24} Before planting, the soil was air-dried and thoroughly mixed to ensure uniformity across all experimental units.

2.4. Fertilizer application

Quail manure was air-dried, pulverized, and applied as a basal amendment 1 week before planting. The manure composition included 1.8% nitrogen, 0.4% phosphorus, and 0.6% potassium, consistent with previous studies on organic amendments.⁶ Natural phosphate, containing 32% P_2O_5 , was sourced locally and applied 3 days before planting to the soil surface, then thoroughly mixed with the top 15 cm of soil to ensure even distribution. This timing was selected to allow for the gradual release of nutrients and improve phosphorus availability at the time of seedling establishment. Long bean seeds were sown in planting holes of 3 cm depth, ensuring uniform germination and optimal root development. The combination of these amendments

provided an integrated approach to enhancing soil fertility while minimizing synthetic inputs.^{10,11,25} The fertilizer application rates were predetermined according to the experimental treatments.

2.5. Plant cultivation

Pre-germinated seeds of *V. sinensis* L. were transplanted into the prepared soil at a spacing of 40 × 60 cm, with each plot containing four plants. Transplantation was conducted simultaneously across all experimental units to ensure uniform growth conditions. Plants were monitored for 1 week post-transplantation to assess seedling establishment and minimize transplant shock before further data collection. Irrigation was provided daily to maintain field capacity, and pest control was achieved using mancozeb fungicides (Dithane® M-45; Corteva, Indonesia) and deltamethrin insecticides (Decis® 25 EC; Bayer, Indonesia) as required. Weed management was performed manually to ensure no competition for nutrients or space. The plants were monitored daily for growth and any signs of stress or disease.

2.6. Measured parameters

The study assessed the impact of quail manure and natural phosphate fertilizers on the growth and yield of long beans through a series of agronomic measurements, chosen to reflect both vegetative growth and reproductive performance. All parameters were measured from three sample plants per experimental unit to ensure statistical reliability.

Flowering is a critical phenological stage in plant development, and the days to flowering were recorded as the number of days from planting until the first flower appeared. This parameter provides insights into the plant's response to nutrient availability and its ability to reach reproductive maturity under the applied treatments.^{26,27} The stem diameter, measured 1 week before harvest using a digital caliper at 5 cm above the soil surface, served as an indicator of the plant's structural robustness. Stem diameter is directly associated with the plant's ability to transport water and nutrients efficiently, a key determinant of overall plant health.²⁸

To evaluate reproductive performance, the number of pods per plant was counted at the end of the harvest period. This metric reflects the reproductive success of the plant, which is influenced by the nutrient supply and soil conditions.²⁹ In addition, pod length was measured for the longest pod harvested from each plant using a measuring tape. Pod length is a vital yield component that indicates the effectiveness of the treatments in promoting pod development.³⁰

Finally, the pod weight per plant was determined by weighing all harvested pods from each sample plant using a digital balance. Harvesting was conducted 7 weeks after transplantation when the pods reached full maturity. Pod weight, expressed in grams (g), represents the culmination of the plant's growth and reproductive processes, offering a comprehensive indicator of yield potential.³⁰ By analyzing these parameters, the study aimed to capture the full spectrum of plant responses to the integrated application of quail manure and natural phosphate fertilizers, providing robust evidence for the effectiveness of these sustainable soil amendments.

2.7. Data analysis

The collected data were analyzed using analysis of variance (ANOVA) to determine the significance of the main and interaction effects of quail manure and natural phosphate fertilizers. ANOVA was chosen because it allows for the simultaneous comparison of multiple treatment groups and their interactions. Treatments with significant effects ($P < 0.05$) were further analyzed using Duncan's New Multiple Range Test (DNMRT) at a 5% significance level to identify specific differences between treatment means. DNMRT was selected for its ability to control type I errors while providing a clear comparison of treatment effects. Statistical analyses were performed using the Statistical Package for the Social Sciences software (version 25.0; IBM Corp., USA).³¹

2.8. Environmental and soil analysis

Soil samples were collected before treatment application (week 0) and after harvesting (week 7) to assess the initial fertility status and the effects of the amendments. For each experimental plot, three subsamples were taken at a depth of 0 – 20 cm and then composited into one representative sample per plot. This approach ensured a homogenous representation of soil conditions across treatments. Soil pH was measured in a 1:2.5 soil-water suspension using a pH meter (HI98128; Hanna Instruments, Romania). Organic matter content was determined using the Walkley-Black method, while phosphorus availability was quantified using the Bray-1 extraction method and a spectrophotometer (Shimadzu ultraviolet-1800; Shimadzu Corp., Japan). Aluminum saturation was determined using the 1 M KCl extraction method, and total nitrogen was measured using the Kjeldahl method. These analyses provided baseline and post-treatment soil characteristics essential for evaluating the amendments' efficacy.³¹ Soil bulk density was measured using the core method at a depth of 0 – 10 cm and 10 – 20 cm to assess changes in soil structure and porosity. Measurements were taken before treatment application (week 0) and after harvesting

(week 7) to evaluate the effects of the amendments on soil compaction and aeration.

3. Results and discussion

3.1. Soil characteristics and their transformation

The podzolic soils used in this study were initially characterized by low fertility and high acidity, conditions that pose significant challenges to sustainable crop production. These soils exhibited a pH of 5.2, low organic matter content (1.25%), and high aluminum saturation (40%), which limits the availability of essential nutrients such as phosphorus.¹ These properties are typical of tropical marginal soils and are often associated with poor agricultural productivity due to their compact structure and low capacity for nutrient retention.^{3,24,32}

The application of quail manure significantly improved soil characteristics by increasing organic matter content ($P < 0.01$), as illustrated in Figure 1, which displays notable enhancements in organic matter percentage ($P < 0.01$), phosphorus availability ($P < 0.01$), and reduced aluminum saturation ($P < 0.05$). Organic matter plays a crucial role in improving soil aggregation, enhancing water infiltration, and creating a more favorable environment for root growth. In addition, as organic material decomposes, microbial activity is stimulated, leading to the mineralization of nitrogen into plant-available forms (NH_4^+ and NO_3^-).³³ This process not only increases nitrogen availability but also enhances soil microbial diversity, accelerating the breakdown of organic residues and further improving soil structure.^{10,13} Moreover, the carbon-rich nature of quail manure promotes soil aggregate stabilization, reducing the risk of erosion, improving porosity, and enhancing aeration.³⁴ These improvements create a more stable and resilient soil environment, ensuring optimal conditions for plant growth by facilitating root penetration, improving nutrient exchange capacity, and maintaining sufficient oxygen supply for root respiration. The combined effects of these transformations highlight the vital role of organic amendments in improving the fertility and structure of degraded soils.

Natural phosphate fertilizer further improved soil fertility by supplying a slow-release source of phosphorus, an essential nutrient often deficient in acidic soils. The amendments reduced the chemical fixation of phosphorus by aluminum and iron, thereby increasing its availability for plant uptake.³⁵ In addition, the combined application of quail manure and natural phosphate resulted in a slight increase in soil pH, which mitigated the toxicity effects of aluminum and improved overall nutrient availability.³⁶ These transformations highlight the synergistic effects of organic and inorganic amendments in enhancing

soil properties. The increase in soil pH from 5.2 to 5.8 is particularly noteworthy, as it suggests a reduction in soil acidity, which is critical for improving nutrient availability and reducing toxicity from aluminum ions. The organic matter content doubled from 1.25% to 2.50%, reflecting the contribution of quail manure in enriching the soil with organic carbon and enhancing its physical properties.^{10,13}

The available phosphorus concentration increased from 8.3 to 18.7 mg/kg, demonstrating the synergistic effect of organic manure and natural phosphate. Organic manure enhances microbial activity, which facilitates phosphorus solubilization from natural phosphate, thereby improving phosphorus availability in acidic soils, where fixation is a major constraint.¹⁷ These findings align with previous studies demonstrating that natural phosphate amendments can sustain phosphorus release in acidic conditions, preventing fixation and ensuring long-term nutrient availability to plants.^{35,36} Similarly, Manono *et al.*¹⁴ observed that organic amendments contributed to increased phosphorus availability in acidic soils, likely due to their role in enhancing microbial activity and facilitating phosphorus solubilization. The reduction in aluminum saturation from 40% to 25% further underscores the effectiveness of these amendments in mitigating the adverse effects of soil acidity.³⁷ Lower aluminum levels reduce phosphorus fixation in the soil matrix, thereby enhancing phosphorus availability and uptake by plants.³⁸

In addition, bulk density decreased from 1.45 to 1.30 g/cm³, indicating improved soil structure and porosity ($P = 0.027$). This finding aligns with Manono *et al.*,¹⁴ who reported that the application of organic amendments significantly reduced bulk density, improving water infiltration, retention, and aeration, thereby enhancing root penetration and overall soil quality. These changes collectively demonstrate the potential of integrating organic and natural fertilizers to transform marginal soils into productive agricultural systems, offering a sustainable solution for improving soil health in tropical regions.

3.2. Effect of treatments on plant growth parameters

The application of quail manure and natural phosphate fertilizers significantly influenced the growth parameters of long beans, particularly days to flowering and stem diameter (Figure 2). The treatments resulted in a notable reduction in days to flowering, with the shortest flowering time observed under the P2R2 treatment (27.00 ± 0.85 days). In contrast, the control (P0R0) exhibited the longest time to flowering (34.66 ± 1.20 days). The reduction in days to flowering under the P2R2 treatment indicates that the combined application of quail manure and natural phosphate provided optimal nutrient availability,

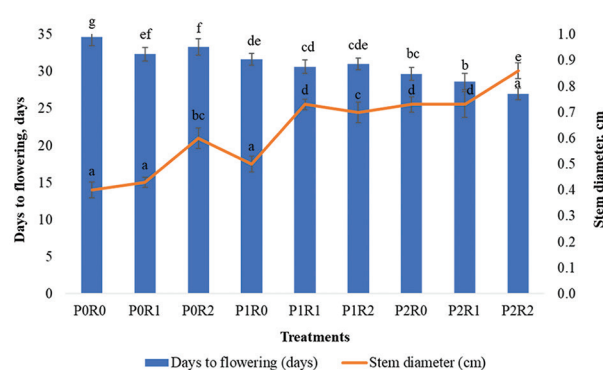


Figure 2. Effect of treatments on plant growth parameters (days to flowering and stem diameter; $n = 3$). Different letters (a-f) indicate significant differences at $P < 0.05$ according to Duncan's New Multiple Range Test. Treatments sharing the same letter are not significantly different from each other.

particularly nitrogen and phosphorus. These nutrients are essential for vegetative growth and accelerating the transition to reproductive phases.³⁰

The enhanced availability of phosphorus likely supported critical metabolic processes, including adenosine triphosphate production, which is necessary for flowering initiation.³⁹ Nitrogen supplied by quail manure further promoted vigorous vegetative growth, enabling the plants to transition to reproductive development more rapidly. These findings are consistent with those of Míguez-Montero *et al.*,⁴⁰ who reported that balanced nitrogen and phosphorus inputs significantly reduced the time to flowering in legumes.

Stem diameter, an indicator of plant robustness and nutrient transport efficiency, was significantly affected by the treatments. The P2R2 treatment yielded the largest stem diameter (0.86 ± 0.03 cm), which was significantly higher than all other treatments ($P < 0.05$). In contrast, the control treatment (P0R0) exhibited the smallest stem diameter (0.40 ± 0.03 cm), with statistically significant differences from all fertilized treatments. The increase in stem diameter under the P2R2 treatment can be attributed to the synergistic effects of organic matter and phosphorus in enhancing soil structure and nutrient availability.⁴¹ Organic matter provided by quail manure increased soil carbon content, which in turn stimulated microbial activity and improved soil aggregate stability. This enhancement likely facilitated better root penetration and moisture retention, allowing for more efficient nutrient uptake.⁴²

The slow-release phosphorus from natural phosphate contributed to sustained nutrient availability, which supported cell division and elongation, resulting in thicker and sturdier stems.⁴³ The microbial solubilization of phosphorus further enhanced its bioavailability, improving

root elongation and branching, which facilitated greater nutrient uptake.^{17,20} In addition, the increased nitrogen mineralization from quail manure decomposition provided a steady supply of essential nitrogen, which is crucial for chlorophyll synthesis and overall vegetative growth.^{33,44}

These findings align with previous research by De Prato *et al.*,⁴³ who reported similar improvements in stem diameter in hemp crops when organic amendments were integrated with phosphorus-based fertilizers. Furthermore, the reduction in aluminum saturation (40% to 25%) observed in the soil analysis likely contributed to an improved root environment, minimizing toxicity and enhancing nutrient absorption efficiency. The effectiveness of the P2R2 treatment in improving plant growth parameters on podzolic soils highlights its potential as a sustainable soil amendment strategy. The integration of quail manure and natural phosphate not only enhanced nutrient availability but also improved soil physical properties, creating a more conducive environment for root development and nutrient transport. The consistent superiority of the P2R2 treatment across all measured growth parameters suggests that a balanced combination of organic matter and slow-release phosphorus is essential for optimizing plant development in acidic, nutrient-deficient soils.

3.3. Effect on yield components

The yield components of long beans, including pod length, number of pods per plant, and pod weight per plant, exhibited significant improvements with the application of quail manure and natural phosphate fertilizers. The combination of these amendments consistently outperformed the control treatment across all measured parameters, as displayed in Table 1. The pod length varied significantly among treatments, with the longest pods

(96.66 cm) observed under the P2R2 treatment (3 kg quail manure per plot and 25 g natural phosphate per plant). In contrast, the control treatment (P0R0) produced the shortest pods (60.66 cm). The enhanced pod length under the P2R2 treatment can be attributed to improved nutrient availability, particularly phosphorus, which is essential for cell elongation and pod development.⁴⁵ The slow-release nature of phosphorus in natural phosphate ensured a consistent supply of this critical nutrient throughout the pod growth phase. These results align with findings by Rahaman *et al.*,³⁰ who demonstrated that phosphorus availability significantly increased pod elongation in legumes.

The number of pods per plant also increased significantly with the treatments. The P2R2 treatment produced the highest number of pods (36.66/plant), while the control recorded the lowest (12.00/plant). This increase reflects the improved soil fertility and nutrient availability provided by the combined amendments, which supported robust reproductive growth.⁴⁶ Organic matter supplied by quail manure likely enhanced soil structure and microbial activity, facilitating efficient nutrient uptake.¹³ These findings are consistent with those of Fekadu *et al.*,⁴⁶ who reported significant increases in pod production of faba bean with organic amendments.

Pod weight per plant was the most significantly impacted yield parameter, with the P2R2 treatment producing the highest weight (2850.66 g/plant) compared to the control (802.33 g/plant). This substantial increase highlights the effectiveness of integrating quail manure and natural phosphate fertilizers in enhancing nutrient availability, improving soil structure, and optimizing resource allocation to reproductive growth.^{41,47} The high nutrient supply from these amendments likely boosted photosynthetic efficiency, increased biomass accumulation, and facilitated better assimilate partitioning toward pod development.^{44,48} The P2R2 treatment also resulted in the longest pods (96.66 cm) and the highest number of pods per plant (36.66), indicating that the combined application of organic and phosphate fertilizers not only promoted individual pod development but also enhanced overall reproductive capacity. The increase in phosphorus availability from 8.3 to 18.7 mg/kg contributed to stronger root development, improved nutrient uptake, and enhanced energy metabolism, which are critical for fruit formation and filling.⁴⁷

The observed yield improvements may be directly linked to microbial activity, particularly phosphate-solubilizing bacteria that facilitated the release of inorganic phosphorus from natural phosphate sources.^{10,17} Furthermore, the enhanced nitrogen mineralization improved nitrogen uptake, optimizing the synthesis of

Table 1. Effect of treatments on yield components

Treatment	Pod length (cm)	Number of pods per plant	Pod weight per plant (g)
P0R0 (Control)	60.66±1.50 ^a	12.00±1.00 ^a	802.33±20.00 ^a
P0R1	67.16±2.00 ^b	13.33±1.10 ^{ab}	852.00±25.00 ^a
P0R2	67.66±1.80 ^b	16.33±1.50 ^{bc}	859.00±30.00 ^{ab}
P1R0	69.33±2.10 ^a	18.66±1.75 ^c	1021.66±35.00 ^b
P1R1	76.50±2.50 ^b	23.00±2.00 ^d	1331.00±40.00 ^c
P1R2	75.16±2.00 ^b	23.66±2.10 ^d	1442.00±45.00 ^c
P2R0	78.33±2.50 ^b	25.66±2.20 ^d	1732.66±50.00 ^d
P2R1	84.33±2.80 ^b	31.00±2.50 ^e	2732.00±60.00 ^e
P2R2	96.66±3.00 ^c	36.66±2.80 ^f	2850.66±70.00 ^e

Note: Values are presented as the mean±standard error ($n=3$). Different letters (a-f) indicate significant differences at $P<0.05$ according to Duncan's New Multiple Range Test. Treatments sharing the same letter are not significantly different from each other.

amino acids and proteins, which are essential for pod filling and biomass accumulation.⁴⁹ In addition, the reduction in aluminum saturation (40% – 25%) created a more favorable rhizosphere environment, mitigating potential root stress and supporting optimal nutrient absorption. These findings align with those of Islam *et al.*,⁴⁷ who reported significant improvements in pod weight when organic and phosphate fertilizers were applied in tropical legumes. Similarly, Manono *et al.*¹⁴ demonstrated that phosphorus amendments in combination with organic matter can increase the efficiency of phosphorus use, enhance microbial activity, and improve soil aeration, all of which contribute to increased crop productivity.

The observed improvements in pod length, number of pods per plant, and pod weight per plant in the P2R2 treatment (3 kg quail manure + 25 g natural phosphate) underscore the interactive effects of organic and phosphate-based fertilization in enhancing crop productivity. Organic manure supplies essential macronutrients and improves soil moisture retention, while natural phosphate ensures a steady phosphorus supply, which is crucial for reproductive growth.⁴⁷ This interaction optimizes the efficiency of nutrient use, making the combined application more effective than either amendment alone. This integrated

fertilization strategy not only enhances nutrient availability but also improves soil physical properties, leading to more sustainable crop production. These results are particularly relevant for tropical regions with inherently low soil fertility, where conventional chemical fertilizers may not be a long-term solution due to economic and environmental constraints.

The effectiveness of integrating organic amendments and phosphate fertilizers has been widely demonstrated across different cropping systems and regions, as summarized in Table 2. Studies on tropical legumes⁴⁷ and soybean-wheat rotations⁵⁰ consistently highlight the benefits of organic amendments in improving soil structure, enhancing phosphorus availability, and boosting overall crop productivity. In tropical legume cultivation, Islam *et al.*⁴⁷ found that vermicompost application improved soil structure and water retention, leading to increased plant height and pod production. Similarly, in soybean-wheat systems, Choudhary *et al.*⁵⁰ reported that long-term application of manure combined with nitrogen, phosphorus, and potassium increased soil organic matter, nitrogen availability, and overall grain yield.

For phosphorus-deficient soils, Namakka *et al.*⁴⁵ investigated the effect of single superphosphate

Table 2. Comparative studies on the use of organic amendments and phosphate fertilizers in different cropping systems

Study	Crop (region)	Fertilizer type	Main findings	References
Purnama <i>et al.</i>	Long beans (Indonesia)	Quail manure+natural phosphate ^a	Soil quality post-treatment: The pH increased from 5.2 to 5.8; organic matter doubled (1.25 – 2.50%); available phosphorus increased from 8.3 to 18.7 mg/kg; aluminum saturation decreased from 40% to 25%. Growth: Shortest flowering time (27 days); largest stem diameter (0.86 cm). Yield: Highest pod weight (2850.66 g/plant); longest pod length (96.66 cm); highest number of pods (36.66/plant).	This study
Islam <i>et al.</i>	Tropical legumes (Bangladesh)	Vermicompost (20%) ^b	Soil quality post-treatment: Improved soil structure, water retention, and nutrient availability. Growth: Highest plant height (314.19 cm for bush bean, 259.93 cm for winged bean, 72.87 cm for yard long bean). Yield: Highest pod weight (298.12 g/m ² for bush bean, 728.69 g/m ² for winged bean, 222.45 g/m ² for yard long bean); longest pod length (10.76 cm for bush bean, 22.27 cm for winged bean, 30.00 cm for yard long bean); highest number of pods (58.93 for bush bean, 44.00 for winged bean, 20.86 for yard long bean).	47
Choudhary <i>et al.</i>	Soybean-wheat rotation (India)	Long-term organic manure+NPK ^c	Soil quality post-treatment: Increased organic matter, available N (373 kg/ha), P (10.58 mg/kg), and K (212 kg/ha). Growth: Highest plant height and stem diameter. Yield: Highest grain yield (2.56 Mg/ha for soybean, 4.31 Mg/ha for wheat); longest pod length; highest number of pods.	50
Namakka <i>et al.</i>	Cowpeas (Nigeria)	Single superphosphates (39 kg P/ha) ^d	Soil quality post-treatment: Soil pH 5.6; available phosphorus 3.50 mg/kg; low nutrient status. Growth: Highest plant height (48.79 cm at 9 WAS); highest number of branches (18 at 9 WAS). Yield: Highest grain yield (1830.71 kg/ha in 2015, 1994.62 kg/ha in 2016); longest pod length (3.927 cm at 9 WAS).	45

Notes: ^aData were obtained from the best treatment (P2R2: 3 kg quail manure+25 g natural phosphate);

^bData were obtained from the vermicompost treatment (20%); ^cData were obtained from the combination of manure and NPK fertilizer (MNPK);

^dData were obtained from the 39 kg P/ha treatment.

Abbreviations: NPK: Nitrogen, phosphorus, and potassium; WAS: Weeks after sowing.

(39 kg P/ha) on cowpea growth. Their findings revealed only moderate improvements in available phosphorus and soil pH, indicating the limited effectiveness of chemical phosphate fertilizers when applied in isolation. This aligns with previous research emphasizing the importance of combining organic amendments with phosphate fertilizers to enhance phosphorus solubilization and uptake.

The findings of this study further validate that integrating quail manure and natural phosphate in long bean cultivation significantly enhances soil fertility and plant productivity. The substantial increase in pod weight (2850.66 g/plant), pod length (96.66 cm), and number of pods per plant (36.66) observed in this study underscores the synergistic effect of organic manure and phosphate fertilizers. This integrated approach presents a sustainable alternative to synthetic fertilizers, particularly in nutrient-deficient tropical soils, where maintaining long-term soil health and productivity is essential for sustainable agriculture.

3.4. Implications for sustainable agriculture

The findings of this study highlight the potential of integrating quail manure and natural phosphate fertilizers as a sustainable approach to enhancing soil fertility and crop productivity on marginal podzolic soils. These results align with the global shift toward environmentally friendly agricultural practices that aim to reduce reliance on synthetic inputs while optimizing natural resources. This section explores the implications for sustainable agriculture and evaluates the economic benefits reported in related studies.

3.4.1. Environmental benefits

The integration of organic and natural fertilizers significantly improved soil properties, including increased organic matter, enhanced phosphorus availability, and reduced aluminum toxicity. These changes contribute to a healthier soil ecosystem, which is essential for long-term agricultural sustainability.⁴⁵ The increased organic matter content improves soil structure, water retention, and microbial activity, reducing the risk of soil degradation and erosion.^{37,51} By using natural phosphate as a slow-release source of phosphorus, this approach minimizes nutrient leaching and protects water bodies from eutrophication.⁵²

The adoption of these sustainable practices can also lower the carbon footprint of agriculture. Synthetic fertilizer production is energy-intensive and contributes significantly to greenhouse gas emissions.^{6,7} Replacing synthetic fertilizers with locally sourced quail manure and natural phosphate reduces these emissions, supporting climate-resilient farming systems.^{10,11}

3.4.2. Economic benefits

The economic benefits of this integrated approach extend beyond environmental sustainability. Utilizing quail manure, which is often an underutilized agricultural resource, offers a cost-effective alternative to synthetic fertilizers, reducing dependency on expensive chemical inputs.⁵³ In addition, natural phosphate, sourced from sedimentary rocks, is significantly more affordable than commercial phosphorus fertilizers, making it an accessible option for smallholder farmers.¹⁹ A cost-benefit analysis conducted by Singh and Singh⁵⁴ demonstrated that integrating organic and phosphate fertilizers reduced fertilizer input costs by 25% while increasing crop yields by 30% in legume cultivation. Similarly, a study by Cen *et al.*²¹ reported that the use of organic amendments in temperate farmland quadrupled farmer income, primarily through enhanced soil productivity and reduced reliance on chemical fertilizers.

The results of this study further confirm these economic advantages. Under the P2R2 treatment, the yield per plant reached 2850.66 g, which translates into a 50% increase in marketable produce compared to the control. At current market prices for long beans (approximately \$1.20/kg or IDR 18,000/kg), this yield improvement could result in an estimated \$600 – 750 (IDR 9 – 11 juta) per hectare increase in farmer income. Furthermore, compared to conventional synthetic fertilizers, quail manure and natural phosphate reduce long-term costs by minimizing soil degradation and maintaining sustained fertility. While synthetic fertilizers require repeated applications per growing cycle, organic amendments improve soil structure and nutrient availability over multiple seasons, reducing the frequency of external fertilizer inputs. These benefits provide economic resilience for smallholder farmers, allowing for higher net profits and improved financial stability in low-input farming systems.²¹

3.4.3. Social and policy implications

Adopting these practices on a larger scale could have broader socio-economic benefits. By reducing input costs and improving yields, this approach enhances food security in resource-constrained farming communities.²¹ In addition, promoting the use of locally available organic amendments supports circular economy principles, where agricultural waste is repurposed as a valuable resource. Policymakers can play a crucial role in facilitating the adoption of such sustainable practices. Providing subsidies for natural phosphate, training programs for composting organic waste, and establishing market incentives for sustainably grown produce can accelerate the transition toward environmentally and economically viable farming systems.⁵⁵

3.4.4. Broader relevance for SDGs

The integration of quail manure and natural phosphate fertilizers in this study aligns closely with global efforts to achieve sustainable agricultural practices and addresses multiple United Nations SDGs. The results demonstrate how locally available, low-cost resources can transform marginal soils into productive farmland, contributing to environmental sustainability, economic resilience, and food security in tropical regions.

One of the primary contributions of this research is to SDG 2 (Zero Hunger), which aims to end hunger and promote sustainable agricultural practices. By improving the productivity of long bean cultivation on podzolic soils, this study provides a scalable model for enhancing food production in regions with limited agricultural potential. The significant increases in pod length, number of pods per plant, and pod weight per plant observed under the P2R2 treatment suggest that integrating organic and natural fertilizers can optimize yields without relying on costly synthetic inputs. This is particularly crucial for smallholder farmers, who constitute over 80% of the world's agricultural producers and often lack access to advanced farming technologies.⁵⁶ By enabling these farmers to increase their productivity sustainably, this approach directly supports efforts to achieve food security and improve nutrition.

Furthermore, the environmental benefits of this study align with SDG 12 (Responsible Consumption and Production), which focuses on sustainable management of natural resources and reducing waste. The use of quail manure as an organic amendment exemplifies the principles of a circular economy, where agricultural waste is repurposed as a valuable resource for soil enrichment. This reduces the need for synthetic fertilizers, which are associated with significant environmental costs, including greenhouse gas emissions during production and nutrient runoff during application.⁶⁷ Similarly, natural phosphate provides a slow-release source of phosphorus, minimizing the risk of nutrient leaching into water bodies and reducing the environmental footprint of agriculture.⁶ These practices demonstrate how agricultural systems can be designed to balance productivity with environmental stewardship.

This study also contributes to SDG 13 (Climate Action), which emphasizes the need to mitigate climate change and its impacts. By reducing reliance on synthetic fertilizers, which are energy-intensive to produce, the integrated approach explored in this research lowers the carbon footprint of farming systems. Organic amendments like quail manure not only enhance soil fertility but also sequester carbon, helping to offset greenhouse gas emissions. Improved soil structure and organic matter content reduce erosion and increase water retention,

making agricultural systems more resilient to climate variability and extreme weather events.⁵⁷ These benefits are particularly important in tropical regions, where the impacts of climate change are expected to be severe.

The economic implications of this research further strengthen its relevance to the SDGs. By utilizing locally available resources such as quail manure, farmers can reduce input costs and improve their profitability, contributing to economic resilience and poverty alleviation.^{21,54} The significant increases in yield observed in this study translate directly into higher revenues for farmers, enabling them to invest in education, healthcare, and community development. These outcomes align with the broader objectives of sustainable development, which aim to create inclusive and equitable growth opportunities while preserving natural resources for future generations.²¹

In addition to addressing these specific goals, this study demonstrates the interconnectedness of the SDGs. Sustainable agricultural practices, as explored in this research, create ripple effects that impact multiple aspects of development, from improved livelihoods and food security to environmental protection and climate resilience.²¹ By focusing on the integration of organic and natural fertilizers, this study highlights a pathway for achieving these interrelated goals through innovative yet practical solutions tailored to local contexts.

4. Conclusion

This study demonstrated that integrating quail manure and natural phosphate fertilizers significantly improved soil fertility, crop growth, and yield of long beans on marginal podzolic soils. The P2R2 treatment (3 kg quail manure per plot and 25 g natural phosphate per plant) resulted in the shortest days to flowering (27.00 days), largest stem diameter (0.86 cm), highest number of pods per plant (36.66), and greatest pod weight per plant (2850.66 g). These findings highlight the potential of organic and natural amendments to mitigate soil acidity, enhance phosphorus availability, and sustainably increase crop productivity. The application of this integrated fertilization strategy has practical implications for field-scale implementation, particularly in tropical regions with nutrient-deficient soils. Strategies for large-scale adoption should focus on optimizing application rates, assessing cost-effectiveness, and ensuring long-term soil health benefits. In addition, this approach aligns with global sustainability goals, contributing to SDG 2 (Zero Hunger) by enhancing food production, SDG 12 (Responsible Consumption and Production) by reducing reliance on synthetic fertilizers, and SDG 13 (Climate Action) by promoting organic soil management practices. Future research should focus on long-term field

trials to evaluate the sustainability and scalability of these treatments under real farming conditions. Investigating their effects on soil biodiversity, microbial dynamics, and soil structural stability will provide further insights into their role in maintaining agricultural productivity and ecosystem resilience. Expanding this research across different crop species and agroecological zones will be essential for broadening its applicability and maximizing its impact on sustainable agriculture.

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Conflict of interest

The authors declare that they have no competing interests.

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Ethics approval and consent to participate

The research was conducted in accordance with ethical guidelines, and no human or animal subjects were involved in the study.

Consent for publication

Not applicable.

Availability of data

Data are available from the corresponding author upon reasonable request.

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