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Sustainable Fertilizer Management and Economic Performance of Peanut (*Arachis hypogaea* L.) Farms: Evidence from Guano and KCL Use in Jember, Indonesia

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Abstract: Peanut (Arachis hypogaea L.) is a strategic source of plant-based protein and an industrial raw material in Indonesia; however, national and local production in Jember Regency has declined in recent years, while fertilizer costs continue to rise. This study aims to evaluate the agronomic and economic effects of combining guano and KCL fertilizers on peanut growth, yield components, biomass, and partial farm profitability under smallholder conditions in East Java. A field experiment was conducted from July to October 2025 in Krajan, Slawu, Patrang District, using a 4×2 factorial Randomized Block Design with three replications on peanut variety Katana 2. The treatments consisted of four guano rates (0, 5, 10, and 15 ton/ha) and two KCL rates (75 and 100 kg/ha), applied one week before sowing, followed by standard NPK fertilization and recommended crop management practices. Growth traits (plant height, leaf stalk number, branch number), yield components (sound and empty pods, pod and seed weight, 100-seed weight), and biomass were subjected to two-way ANOVA and DMRT. Guano significantly increased branch number, whereas 100 kg/ha KCL improved sound pods and biomass; however, most yield variables did not differ statistically, making the low-input package without guano and 75 kg/ha KCL the option with the highest partial gross margin. The findings indicate that optimizing guano–KCL combinations can support cost-efficient and more sustainable fertilizer management in peanut agribusiness and agro-industrial supply chains in Indonesia.

Keywords: peanut, guano fertilizer, potassium chloride (KCl), sustainable fertilizer management, smallholder farming, agribusiness, agro-industrial supply chain

1. Introduction

Peanut (*Arachis hypogaea* L.) is one of the most important legume crops in Indonesia, providing a major source of plant-based protein for households and serving as a key raw material for snack, sauce, and peanut butter industries (Bekele et al., 2022; Silitonga et al., 2018). In many regions, including East Java, peanut production is dominated by smallholders who cultivate relatively small plots and are highly sensitive to fluctuations in input prices, especially chemical fertilizers, so that fertilizer management becomes a central factor shaping production costs, farm income, and competitiveness along the peanut value chain (Bekele et al., 2022; Silitonga et al., 2018). Recent empirical work and statistical reports have highlighted stagnating or declining groundnut yields in several production regions, which, combined with growing demand from the processing industry, increase pressure on domestic supply and strengthen the need for more efficient and sustainable input use at the farm level (Bekele et al., 2022; Jahan et al., 2023).

Continuous and unbalanced application of inorganic fertilizers has been widely associated with soil fertility degradation, declining soil organic matter, and reduced nutrient-use efficiency, thereby limiting productivity growth in legume-based systems (Bekele et al., 2022; Silitonga et al., 2018; Tadesse et al., 2013). In contrast, integrated use of organic and inorganic fertilizers has been shown to improve soil physical, chemical, and biological properties while maintaining or enhancing crop yields, including in groundnut production (Bekele et al., 2022; Ghosh & Kaur, 2024; Jahan et al., 2023). Guano, an organic fertilizer derived from bat manure with relatively high contents of nitrogen, phosphorus, potassium, and organic carbon, has the potential to improve soil structure, cation exchange capacity, and biological activity, and can partially substitute mineral fertilizers in smallholder farming systems where organic inputs are locally available (Ghosh & Kaur, 2024; Jahan et al., 2023).

Potassium, commonly supplied as KCL, is a key macronutrient regulating photosynthesis, stomatal function and osmoregulation, enzyme activation, and the formation and filling of pods and seeds, so that appropriate K management is essential for both yield and quality of peanuts under tropical conditions (Ghosh & Kaur, 2024; Silitonga et al., 2018). Experimental studies with compound NPK and K fertilizers in peanut have demonstrated that adequate and balanced K supply increases the number of pods per plant, 100-seed weight, and pod yield per hectare, particularly on suboptimal or acid soils such as Ultisols, which are common in parts of Indonesia and comparable to many upland areas in East Java. (Harahap et al., 2020; Silitonga et al., 2018). At the same time, the combination of organic sources (manure, compost, bio-organic fertilizers) with NPK has been reported to enhance nutrient uptake, root nodulation, and biomass accumulation in peanuts, indicating a synergistic effect between organic amendments and mineral nutrients (El-sherbeny et al., 2022; Ghosh & Kaur, 2024; Sunitha et al., 2023).

Previous research on peanuts and other field crops has consistently reported positive effects of organic fertilizers, including guano-type inputs, together with potassium or NPK fertilization on vegetative growth, nodulation, and yield, yet most investigations have concentrated on agronomic indicators without explicitly linking fertilizer combinations to farm-level cost structures and profitability (Bekele et al., 2022; Jahan et al., 2023; Silitonga et al., 2018). Only a limited number of quantitative studies in groundnut systems explicitly analyze gross margins or cost–benefit indicators for alternative fertilizer packages, even though evidence from Ethiopia and other semi-arid regions shows that combining organic and inorganic fertilizers can enhance both productivity and profitability compared with farmers' customary practices (Bekele et al., 2022; Jahan et al., 2023). Moreover, empirical evidence on how specific combinations of guano and KCL affect growth, yield components, and biomass of peanut variety Katana 2 under smallholder conditions in East Java remains scarce, particularly when framed within agribusiness management and agro-industrial raw material supply perspectives (Silitonga et al., 2018; Sunitha et al., 2023).

Therefore, this study aims to evaluate the effects of different guano and KCL fertilizer combinations on peanut growth, yield components, and biomass under smallholder conditions in Jember, East Java, and to analyze the associated fertilizer costs and partial gross margins as indicators of economic performance (Bekele et al., 2022; Silitonga et al., 2018; Sunitha et al., 2023). By integrating agronomic and economic measurements, the research seeks to generate managerial insights for more cost-efficient and sustainable fertilizer strategies in peanut agribusiness and agro-industrial supply chains in Indonesia, with particular relevance for regions where smallholders face rising fertilizer prices and must balance short-term profitability with long-term soil fertility conservation (Bekele et al., 2022; El-sherbeny et al., 2022; Jahan et al., 2023).

2. Materials and Methods

The field experiment was carried out from July to October 2025 on smallholder peanut fields in Krajan, Slawu Village, Patrang District, Jember Regency, East Java, Indonesia, at an altitude of approximately 146 m above sea level under a humid tropical climate, which is representative of low-elevation peanut-growing environments in the region (Harahap et al., 2020; Silitonga et al., 2018). The experimental design followed a 4 × 2 factorial Randomized Block Design (RBD) with three replications using peanut variety Katana 2, a commonly cultivated variety with an average maturity of around 87 days after sowing, so that the trial captured a full growing cycle under typical smallholder management conditions (El-sherbeny et al., 2022; Sunitha et al., 2023). The first factor consisted of four guano fertilizer rates, namely 0, 5, 10, and 15 ton ha^{-1} (G0, G5, G10, G15), while the second factor comprised two KCL rates, 75 and 100 kg ha^{-1} (K75, K100), resulting in eight treatment combinations arranged in 24 plots, consistent with factorial designs used in peanut fertilizer response studies in Indonesia and other tropical environments (Jahan et al., 2023; Silitonga et al., 2018).

Table 1. Treatment combinations of guano and KCL fertilizer rates

Treatment Combination	Guano Rate	KCL Rate
G0K75	0 ton/ha	75 kg/ha
G5K75	5 ton/ha	75 kg/ha
G10K75	10 ton/ha	75 kg/ha
G15K75	15 ton/ha	75 kg/ha
G0K100	0 ton/ha	100 kg/ha
G5K100	5 ton/ha	100 kg/ha
G10K100	10 ton/ha	100 kg/ha
G15K100	15 ton/ha	100 kg/ha

Guano and KCL were applied once, one week before sowing, by broadcasting at the designated doses and incorporating them into the soil, following common practice for organic amendments and basal K application to ensure nutrient availability during early growth (Ghosh & Kaur, 2024; Silitonga et al., 2018). Subsequent standard inorganic fertilization with NPK was carried out at 14 and 40 days after sowing, in line with split-dose recommendations for peanut, together with recommended agronomic practices including land preparation, planting at 30 cm × 20 cm spacing, irrigation, weeding, hilling, and pest and disease control, thereby aligning the experimental protocol with typical farmer management while allowing controlled variation in guano and KCL inputs (Bekele et al., 2022; Sunitha et al., 2023). Growth variables measured included plant height, number of leaf stalks, and number of branches at 14, 28, and 42 days after sowing, whereas yield components comprised number of sound pods, number of empty pods, pod weight per sample and per plot, dry seed weight, 100-seed weight, and total above-ground and root biomass at harvest, following standard variable sets used in peanut fertilizer and biofertilizer experiments (El-sherbeny et al., 2022; Ghosh & Kaur, 2024).

Data were analyzed using two-way Analysis of Variance (ANOVA) to test the main and interaction effects of guano and KCL on growth, yield components, and biomass, a common approach in factorial fertilizer trials for groundnut and other field crops (Bekele et al., 2022; Harahap et al., 2020). When significant effects were detected, Duncan's Multiple Range Test (DMRT) at 5% and 1% significance levels was employed for mean separation to identify statistically distinct treatment groups, consistent with post-hoc testing procedures applied in related peanut studies (Silitonga et al., 2018; Sunitha et al., 2023). In addition, pod yield per hectare was estimated from plot-level data and combined with local price information and fertilizer cost assumptions to compute partial gross margins for each fertilizer package, thereby explicitly linking agronomic responses to farm-level economic performance in line with recent work on the profitability of integrated organic–inorganic fertilization in groundnut systems (Bekele et al., 2022; Jahan et al., 2023).

3. Results and Discussion

The factorial analysis of variance showed significant effects of guano and KCL on several key traits. Summary results of the ANOVA are presented in Table 2. Statistical significance is denoted as follows: **p<0.01 (highly significant), *p<0.05 (significant), ns = not significant.

Table 2. Summary of two-way ANOVA results for guano and KCL effects on peanut growth and yield

Variable	Guano (K)	KCL (T)	Interaction (K×T)
Plant Height			
14 DAS	ns	ns	ns
28 DAS	ns	ns	*
42 DAS	ns	ns	ns
Leaf Stalk Number			
14 DAS	ns	ns	ns
28 DAS	ns	ns	*
42 DAS	ns	ns	ns
Branch Number			
14 DAS	ns	ns	ns
28 DAS	**	ns	ns
42 DAS	**	ns	ns
Yield Components			
Sound pods (number)	ns	*	ns
Empty pods (number)	ns	ns	ns
Pod weight per sample	ns	ns	ns
Pod weight per plot	ns	ns	ns
Dry seed weight	ns	ns	ns
100-seed weight	ns	ns	*
Biomass			
Above-ground + root biomass	ns	*	ns

The factorial analysis of variance showed that the interaction between guano and KCL significantly affected plant height and number of leaf stalks at 28 days after sowing (DAS), whereas no significant interaction was detected at 14 and 42 DAS for these traits, a pattern that is consistent with reports that early vegetative responses to nutrient supply are often most pronounced around mid-vegetative stages in peanut. The G0K75 combination (no guano with 75 kg ha^{-1} KCL) produced the highest plant height (14.80 cm) and number of leaf stalks at 28 DAS, indicating that under the prevailing soil fertility conditions, moderate KCL without additional guano was sufficient to support early vegetative growth, which aligns with findings that adequate K supply alone can sustain early canopy development on soils with moderate residual fertility. Guano exerted a highly significant main effect on branch number at 28 and 42 DAS, with 15 ton ha^{-1} consistently generating the greatest number of branches (up to 8.39 branches per plant at 42 DAS), whereas lower doses and the control produced fewer branches, corroborating evidence that high organic-matter inputs enhance branching and vegetative vigor even when yield responses are less pronounced.

These vegetative responses, however, did not consistently translate into higher yield, as most yield variables—including pod weight per sample, pod weight per plot, and dry seed weight—did not differ significantly among treatments, a phenomenon frequently observed in peanut fertilizer studies where strong vegetative growth does not always result in proportional increases in pod yield. KCL application significantly increased the number of sound pods and total biomass, with the 100 kg ha^{-1} rate outperforming 75 kg ha^{-1}, confirming the crucial role of potassium in pod formation and dry-matter accumulation that has been documented in other groundnut trials using elevated K or compound NPK rates. The interaction between guano and KCL was significant for 100-seed weight, with G0K75 producing the heaviest seeds (around 80 g per 100 seeds), suggesting that a relatively low-input package with moderate KCL and without guano can still support good seed filling under the tested conditions, similar to findings where moderate fertilizer inputs achieved high seed weight without excessive vegetative growth. In contrast, the number of empty pods and several other yield components remained statistically unaffected by either factor or their interaction, indicating that within the studied dose ranges, seed set and pod filling were relatively stable traits.

Table 3. Fertilizer cost structure by treatment combination (exclusive of NPK and labor)

Treatment	Guano Cost (Rp, million)	KCL Cost (Rp, thousand)	Total Fertilizer Cost (Rp, million)
G0K75	0	974	1.0
G5K75	20.0	974	21.0
G10K75	40.0	974	41.0
G15K75	60.0	974	61.0
G0K100	0	1,300	1.3
G5K100	20.0	1,300	21.3
G10K100	40.0	1,300	41.3
G15K100	60.0	1,300	61.3

To link agronomic performance with farm-level economics, fertilizer costs were estimated using realistic 2025 price assumptions: guano at approximately Rp4.000.000 per ton, KCL at Rp13.000 per kg, and NPK at Rp2.300 per kg under subsidized conditions, values that fall within typical price ranges reported for Indonesian smallholder input markets. For each treatment, per-hectare fertilizer cost was calculated by multiplying these unit prices by the respective guano and KCL rates and the total NPK dose used in the experiment, following standard approaches for partial budget analysis in groundnut fertilizer profitability studies. Pod yield per hectare was derived from plot-level pod weight and then multiplied by a reference farm-gate price of Rp26.000 per kg, which lies within a plausible range of peanut prices in East Java after adjusting for margins between market retail and farm-gate values, as noted in recent analyses of groundnut value chains and price formation. Partial gross margin for each fertilizer package was obtained as the difference between gross revenue and fertilizer costs, and because total yield did not differ statistically across treatments, the G0K75 low-input package generated the highest partial gross margin by combining competitive yield and 100-seed weight with the lowest expenditure on guano and KCL, echoing external evidence that moderately fertilized or integrated packages can outperform high-input options in terms of profitability when yield gains are limited.

The partial gross margin for each fertilizer package was computed as gross revenue minus fertilizer costs. Results show that the G0K75 low-input package generated the highest partial gross margin of Rp 64.78 million per hectare, compared with Rp 44.78 million (G15K75) and Rp 64.48 million (G0K100), echoing external evidence that moderately fertilized or integrated packages can outperform high-input options in terms of profitability when yield gains are limited (Bekele et al., 2022; Jahan et al., 2023). The cost-benefit ratio (gross revenue ÷ fertilizer cost) for G0K75 was 65.78 ÷ 1.0 = 65.78, the highest across all treatments, further confirming the economic efficiency of the low-input package.

Table 4. Partial gross margin analysis by treatment (assuming constant yield across treatments)

Treatment	Guano Revenue (Rp, million)	Fertilizer Cost (Rp, thousand)	Partial Gross Margin (Rp, million)
G0K75	65.78	1.0	64.78
G5K75	65.78	21.0	44.78
G10K75	65.78	41.0	24.78
G15K75	65.78	61.0	4.78
G0K100	65.78	1.3	64.48
G5K100	65.78	21.3	44.48
G10K100	65.78	41.3	24.48
G15K100	65.78	61.3	4.48

The strong response of branch number to high guano rates, without a parallel increase in final yield, suggests that guano primarily stimulated vegetative growth in this single-season experiment rather than efficiently enhancing reproductive output, a pattern also observed where high organic inputs increase canopy size and branching but do not necessarily raise pod yield in the short term (Ghosh & Kaur, 2024; Silitonga et al., 2018). This is consistent with the gradual mineralization of organic nutrients from guano and the possibility that, under the prevailing soil fertility and climate, part of the additional nitrogen and phosphorus was allocated to vegetative structures rather than pod formation, or that other limiting factors constrained the conversion of vegetative vigor into higher pod yield, as reported in multi-season studies of farmyard manure and organic amendments in legume systems (Jahan et al., 2023; Tadesse et al., 2013). Comparable results have been documented in experiments where organic amendments improved growth and soil properties but required repeated applications across several seasons or integrated nutrient management before generating substantial yield gains in groundnut and other crops (Bekele et al., 2022; El-sherbeny et al., 2022).

The significant increase in sound pods and biomass at 100 kg ha^{-1} KCL underscores the physiological importance of potassium in photosynthate transport, enzyme activation, and pod filling in peanuts, in line with observations that higher K or compound NPK doses increase pod number and total dry matter in groundnut on suboptimal soils (Ghosh & Kaur, 2024; Harahap et al., 2020). However, the absence of a clear yield advantage of 100 kg ha^{-1} over 75 kg ha^{-1} KCL points to diminishing marginal returns to potassium under these conditions, which is consistent with response curves reported for groundnut where yield gains flatten once K supply exceeds crop demand or other factors become limiting (Bekele et al., 2022; Silitonga et al., 2018). This suggests that, for soils similar to those in Jember, moderate KCL rates may be sufficient to secure pod formation and biomass accumulation, while higher rates mainly increase fertilizer costs without commensurate yield benefits (Bekele et al., 2022; Harahap et al., 2020).

From a farm-management standpoint, the combination of non-significant differences in total yield among fertilizer treatments and clear differences in fertilizer cost emphasizes the relevance of cost-minimization and partial-budget strategies when output levels are comparable (Jahan et al., 2023). In this context, the G0K75 package emerged as the most economically attractive option, as it avoided the substantial cost of guano (up to approximately Rp60.000.000 ha^{-1} at 15 ton ha^{-1} under the assumed price) and the higher

KCL rate, while still maintaining acceptable agronomic performance in terms of vegetative growth, 100-seed weight, and overall yield, similar to integrated or optimized fertilizer packages that maximize gross margins rather than absolute yield (Bekele et al., 2022; Jahan et al., 2023). This finding aligns with agribusiness and farm-management studies indicating that fertilizer is one of the main variable cost components in peanut production and that optimizing, rather than maximizing, input use is crucial for improving net income in smallholder systems, particularly where price–cost ratios are unfavorable (Arsalan et al., 2023; Jahan et al., 2023; Paramasivan et al., 2023).

At the agribusiness and value-chain level, cost-efficient fertilizer strategies that sustain yield and quality can reduce unit production costs, improve farmers' bargaining power, and enhance the reliability of raw-material supply for peanut-based agro-industries in East Java and Indonesia more broadly, consistent with evidence that profitable fertilizer regimes support more stable groundnut supply chains (Bekele et al., 2022; Gelaye & Luo, 2024; Jahan et al., 2023). The use of guano remains relevant from a long-term soil-health and sustainability perspective, especially when priced closer to subsidized organic fertilizers or when local supply chains reduce transaction costs and improve accessibility for farmers, echoing broader findings on the role of organic inputs in sustaining soil organic matter and resilience (Tadesse et al., 2013; Timilsina et al., 2025). Under current price assumptions, however, high guano rates may be more justified as part of a broader soil-fertility and carbon-building strategy rather than as a short-term yield-maximization tool, which aligns with multi-year analyses showing that the economic payoff of heavy organic applications often materializes over longer horizons or when combined with calibrated mineral fertilization and biofertilizers (Arsalan et al., 2023; Jahan et al., 2023; Paramasivan et al., 2023). Integrating these insights into extension messages and agribusiness decision-making can support fertilizer recommendations that balance agronomic response, cost efficiency, and sustainability, thereby contributing to smallholder livelihood improvement and strengthening the competitiveness of peanut agro-industrial supply chains in Indonesia (Bekele et al., 2022; Gelaye & Luo, 2024; Timilsina et al., 2025).

4. Conclusions

This study shows that different guano and KCL combinations significantly affected vegetative growth and certain yield components of peanut, but did not consistently translate into higher total pod yield under the conditions tested. High guano rates (15 ton ha^{-1}) increased branching, and 100 kg ha^{-1} KCL raised the number of sound pods and total biomass, yet these agronomic gains were insufficient to create a clear yield advantage compared with lower-input treatments, which is in line with previous findings that strong vegetative responses to organic and K fertilization do not always yield proportional increases in pod production. When fertilizer costs were incorporated using realistic 2025 price assumptions, the low-input package without guano and with 75 kg ha^{-1} KCL (G0K75) produced the highest partial gross margin, because it maintained comparable yield and favorable 100-seed weight while minimizing expenditure on guano and KCL, echoing empirical evidence that optimized, rather than maximal, fertilizer use often delivers the best profitability in groundnut systems. These findings indicate that, in smallholder peanut systems similar to those in Jember, optimizing rather than maximizing fertilizer inputs—particularly by carefully calibrating guano and KCL rates—offers a more cost-efficient and practically relevant strategy for farmers, consistent with integrated nutrient-management studies that emphasize economic as well as agronomic performance. At a broader agribusiness scale, such economically efficient and soil-friendly fertilization packages can support more sustainable peanut production and a more reliable, competitively priced raw-material supply for peanut-based agro-industries in Indonesia, reinforcing calls for fertilizer recommendations that jointly account for yield, profitability, and long-term soil health.

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