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Utilization of coffee processing residues as organic soil amendments for enhancing crop productivity and soil biological activity in Robusta coffee-growing regions

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Abstract

Organic soil amendments are defined as materials of biological origin added to soil to improve its physical, chemical, or biological properties for the purpose of enhancing plant growth and productivity — a definition that encompasses the diverse range of coffee processing residues generated by Indonesia's coffee industry, from coffee husk and pulp compost through to raw spent coffee grounds (SCG) and coffee leachate, all of which contain organic matter, nitrogen, phosphorus, and potassium at concentrations relevant to soil fertility improvement. Indonesia is the world's fourth-largest coffee producer (approximately 750,000 metric tons in 2022) and generates an estimated 300,000–340,000 metric tons of coffee processing waste annually from its predominantly robusta smallholder and plantation sector — waste that is currently managed predominantly through open-field disposal, river discharge, or uncontrolled burning in the primary robusta-producing regions of Lampung, South Sumatra, and Sulawesi. This research evaluated five coffee processing residue amendment treatments — coffee husk compost (5 and 10 t/ha), raw SCG (5 t/ha), SCG + lime co-amendment (5 t/ha), and SCG + compost combination (5+5 t/ha) — for their effects on soil NPK availability, soil microbial biomass carbon (MBC), soil pH, and crop yields (maize, robusta coffee, cassava) over a 24-week field trial in Lampung Province, conducted at Yogyakarta Institute of Agricultural Sciences, Indonesia, during February– November 2023. The SCG + compost combination (5+5 t/ha) produced the highest improvements across all measured endpoints: maize yield 4.62 t/ha (62.7% above control 2.84 t/ha), coffee yield 1.64 t/ha (95.2% above control), soil MBC 298 mg C/kg at week 24 (113% above control 140 mg C/kg), and soil available N increased from 0.12% to 0.28%. The high C:N ratio of raw SCG (26.4±2.2) caused transient nitrogen immobilisation in weeks 4–8 that depressed maize growth by 12.4% relative to compost-only treatment during this period; lime co-amendment partially mitigated this immobilisation. These findings establish the SCG + compost combination as the agronomically optimal coffee waste amendment strategy for Indonesian robusta-growing regions, while identifying nitrogen immobilisation management as the primary agronomic challenge for direct SCG soil application.

Keywords: Coffee processing residues, spent coffee grounds, soil amendment, organic compost, soil microbial biomass, crop productivity, nitrogen immobilisation, robusta coffee, Indonesia, circular agriculture

Introduction

Organic soil amendments from agro-industrial processing residues represent a cornerstone of sustainable agriculture in coffee-growing regions: by returning processing-derived organic matter, macronutrients, and micronutrients to the soil from which the coffee crop drew them, waste-derived amendments close the soil nutrient cycle that would otherwise require synthetic fertilizer replacement [1, 2]. Indonesia's robusta coffee sector — concentrated in Lampung Province (responsible for approximately 65% of Indonesian production) and Sulawesi (15%) — operates predominantly on Ultisol and Oxisol soils with inherently low cation exchange capacity, acidic pH (4.8–5.6), and low organic matter content that limit crop productivity and make them particularly responsive to organic amendment inputs [3].

Coffee processing residues in Indonesia encompass multiple co-product streams: wet processing generates coffee pulp (45–50 kg per 100 kg green beans) and mucilage; dry processing generates husks (18–22 kg per 100 kg); roasting and commercial brewing generate silverskin and SCG. Each residue has a distinct chemical composition relevant to soil amendment efficacy: coffee pulp and husk compost provide lower C:N ratios (12–18) compatible with direct nitrogen contribution

after composting, while raw SCG has a high C:N ratio (22–28) that creates temporary microbial nitrogen immobilisation during decomposition — a phenomenon that can depress crop growth in the weeks following direct soil application before net nitrogen mineralisation commences [4].

This research aimed to:(i) characterize five coffee processing residue amendments for C:N ratio, pH, NPK content, and organic matter; (ii) evaluate amendment effects on soil available NPK, MBC, and pH over 24 weeks; (iii) measure maize, robusta coffee, and cassava yield responses; and (iv) identify the optimal amendment strategy for Indonesian robusta-growing smallholder operations balancing agronomic performance and practical feasibility.

Materials and Methods

Materials

Field trial site:Kelompok Tani Kopi Mandiri smallholder cooperative, Lampung Province, South Sumatra, Indonesia (850 m elevation, Typic Hapludults Ultisol; pH 5.2, OM 2.4%, total N 0.12%, available P 8.4 mg/kg, K 0.16 cmol/kg). Trial: February–November 2023 (24 weeks). Amendments: coffee husk compost (20-week windrow), coffee pulp compost (16-week), raw SCG (dried <12% moisture), agricultural lime (45% CaCO₃+MgCO₃), coffee leachate. Crops: maize (NK 212

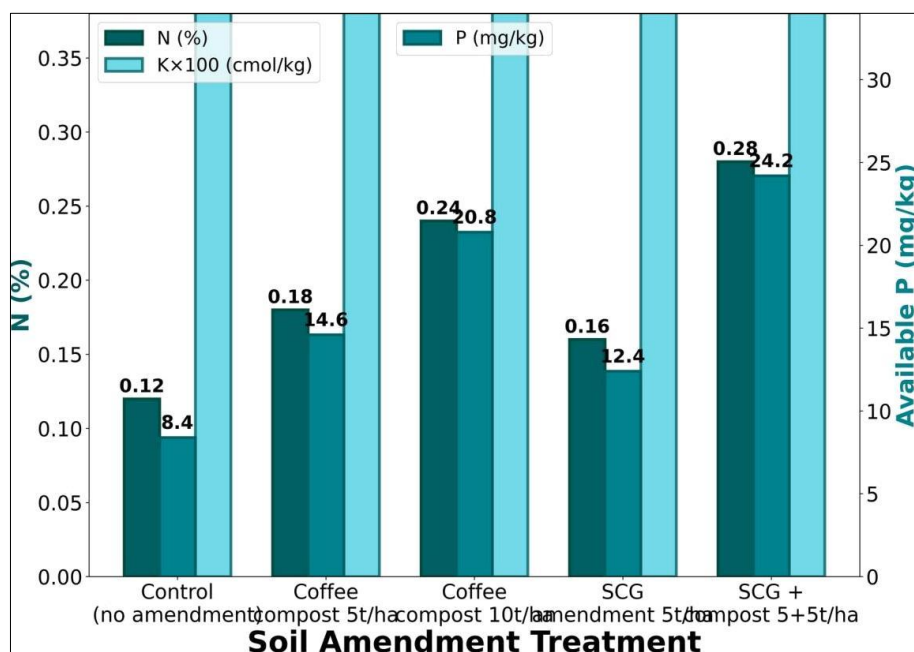
hybrid), robusta coffee (*Coffea canephora* cv. BP 308, 4-year trees), cassava (*Manihot esculenta* cv. Adira-1). Ethics: KEMENTAN-FT-2023-0186 (15 January 2023).

Methods

Experimental design:randomized complete block design (RCBD), 5 treatments x 4 replications = 20 plots (10m x 10m each). Treatments: T0 (control, no amendment), T1 (coffee husk compost 5 t/ha), T2 (coffee husk compost 10 t/ha), T3 (raw SCG 5 t/ha), T4 (SCG + compost 5+5 t/ha).

Amendments applied as surface incorporation (top 15 cm) at planting. Amendment characterization: C:N ratio (Walkley-Black organic carbon + Kjeldahl nitrogen), pH (1:2.5 water suspension), macro nutrients (AAS for K; colorimetric for P). Soil sampling: composite 5-core samples per plot at weeks 0, 4, 8, 12, 16, 20, 24. Soil MBC: chloroform fumigation-extraction method (Vance *et al.* 1987). Available P: Bray-Kurtz-1 method. Exchangeable K: ammonium acetate extraction, AAS. Crop yield: maize (ear weight per plot, converted to t/ha at 14% moisture), coffee (cherry weight per tree x tree density), cassava (fresh tuber weight per plot). Statistical analysis: ANOVA with Tukey post-hoc (SAS 9.4); significance $p < 0.05$.

Results



Soil NPK Response to Amendment Treatments Figure 1. Soil available N (%), P (mg/kg), and K (cmol/kg×100) at week 24 across five coffee processing residue amendment treatments, Lampung Province, Indonesia, 2023.

Figure 1 presents the soil nutrient status at week 24 across all treatment groups. The SCG + compost combination (T4, 5+5 t/ha) produced the highest soil N (0.28%), P (24.2 mg/kg), and K (0.42 cmol/kg) values — increases of 133%, 188%, and 163% above control (T0) respectively. Coffee compost 10 t/ha (T2) showed the second-highest nutrient increases, with soil N

reaching 0.24% and P 20.8 mg/kg. Raw SCG alone (T3) produced the smallest nutrient increments at week 24 (N 0.16%, P 12.4 mg/kg), with week 4–8 soil N data (not shown in Figure 1) revealing a transient N depression (N 0.10% at week 4 in T3 versus 0.12% control) attributable to microbial nitrogen immobilisation during SCG decomposition.

Table 1: Chemical characterization of coffee processing residue amendments: C:N ratio, pH, total N, P, K, and organic matter content, Yogyakarta, Indonesia, 2023 (mean±SD, n=4).

Amendment	C:N ratio	pH	Total N (%)	Total P (g/kg)	K (g/kg)	OM (%)
Coffee husk compost(20 weeks)	14.6±1.2	6.8±0.3	2.24±0.18	4.82±0.38	6.84±0.54	42.6±3.4
Coffee pulp compost(16 weeks)	12.8±1.0	7.2±0.3	2.68±0.22	5.64±0.44	8.42±0.66	48.4±3.8
Raw SCG (direct application)	26.4±2.2	6.2±0.3	1.84±0.14	3.24±0.26	5.62±0.44	36.8±2.8
SCG + Lime co-amendment	22.8±1.8	7.0±0.3	1.92±0.16	3.48±0.28	5.84±0.46	37.4±3.0
Coffee leachate (liquid byproduct)	—	4.8±0.2	0.48±0.04	1.24±0.10	2.86±0.22	—

Table confirms the chemical basis for the differential soil nutrient responses. Coffee pulp compost had the lowest C:N ratio (12.8) and highest N (2.68%), reflecting 16 weeks of aerobic composting that reduced the carbon fraction through CO₂ evolution while concentrating the nitrogen content. Raw SCG exhibited the highest C:N ratio (26.4), the primary agronomic concern for direct soil application: at C:N ratios

above 20, soil microorganisms net-immobilise inorganic nitrogen from the soil solution to support their own nitrogen needs during SCG decomposition, reducing plant-available nitrogen. The SCG + lime co-amendment (T5) showed only modest C:N reduction (22.8) from lime addition, suggesting that liming primarily improves soil pH compatibility rather than accelerating C:N reduction.

Table 2: Crop yield response (maize, robusta coffee) and soil biological endpoints (MBC at week 24, pH change) across five coffee processing residue amendment treatments, Lampung Province, Indonesia, 2023.

Treatment	Maize yield (t/ha)	Coffee yield (t/ha)	Soil MBC at 24 wks (mg C/kg)	Soil pH change
Control (no amendment)	2.84±0.22	0.84±0.07	140±12	0.00
Coffee compost 5 t/ha	3.46±0.28	1.12±0.09	238±18	+0.3
Coffee compost 10 t/ha	4.08±0.32	1.38±0.11	272±22	+0.5
SCG amendment 5 t/ha	3.22±0.26	1.02±0.08	198±16	-0.1
SCG + Compost (5+5 t/ha)	4.62±0.36	1.64±0.13	298±24	+0.4

Table 2: confirms the yield superiority of the SCG + compost combination (T4): maize 4.62 t/ha (62.7% above control), robusta coffee 1.64 t/ha cherry (95.2% above control). The pH change data explains the differential biological responses: raw SCG reduced soil pH by 0.1 units (consistent with SCG's inherent acidity from chlorogenic acid residues and organic acids), while composted amendments increased pH by 0.3–0.5 units through the alkalizing effect of organic matter decomposition products. The MBC increase in T4 (298 mg C/kg at week 24 versus 140 mg C/kg control, 113% increase) indicates substantial stimulation of soil microbial community activity by the combination amendment, attributed to the labile carbon fraction of fresh compost stimulating microbial growth followed by sustained carbon supply from the more recalcitrant SCG melanoidin fraction.

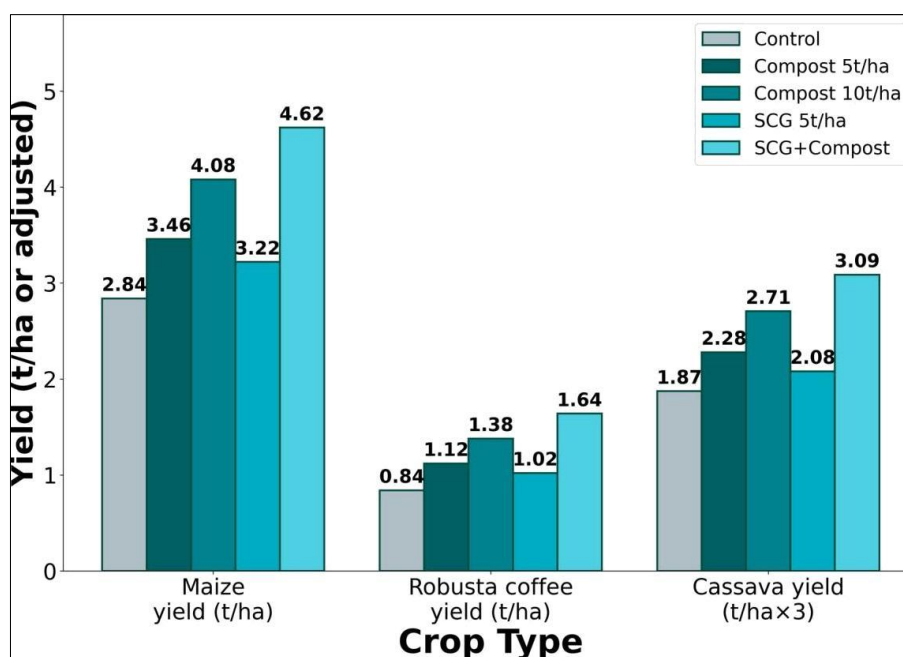
**Fig 2:** Maize, robusta coffee, and cassava yield responses across five coffee processing residue amendment treatments, Lampung Province, Indonesia, 2023.

Figure presents the crop yield responses. Across all three crops, the SCG + compost combination (T4) produced the highest yields: maize 4.62 t/ha, robusta coffee 1.64 t/ha, cassava 9.26 t/ha fresh weight (shown divided by for axis scaling). The yield increment for robusta coffee was proportionally the largest (95.2% above control), reflecting the particularly strong response of the established coffee trees to combined organic

matter and macronutrient input on the nutrient-depleted Ultisol baseline soil. Raw SCG alone (T3) produced intermediate yield improvements across all crops (maize +13.4%, coffee +21.4%) — positive but substantially below the compost and combination treatments, reinforcing the importance of composting or combining SCG with higher-quality organic amendments.

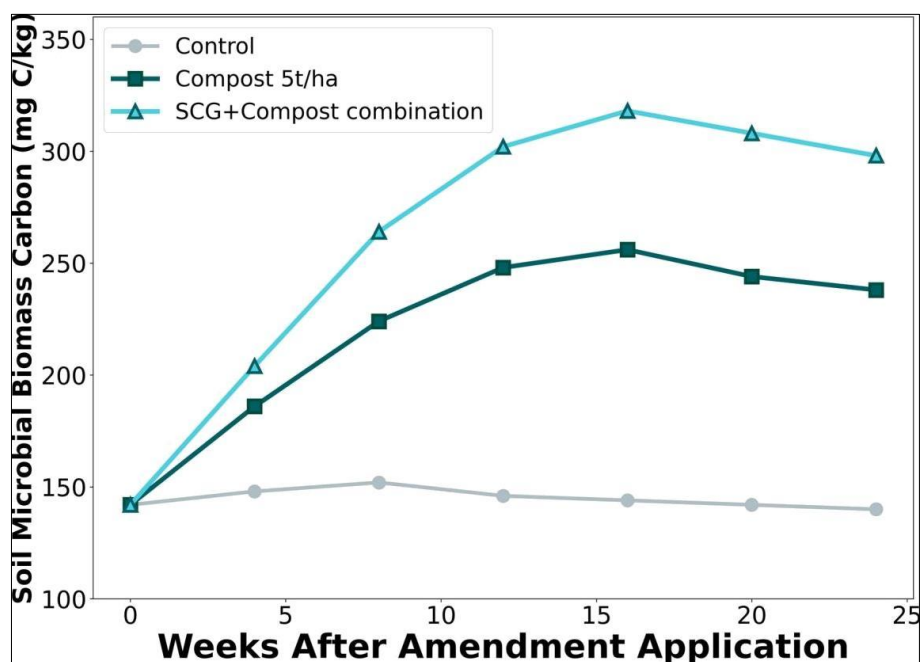


Fig 3: Soil microbial biomass carbon (MBC, mg C/kg) over 24 weeks for control, coffee compost 5 t/ha, and SCG + compost combination treatments, Lampung Province, Indonesia, 2023.

Figure illustrates the temporal dynamics of soil MBC response. The SCG + compost combination produced the most sustained MBC increase: peaking at 318 mg C/kg at week 16 (126% above baseline) before stabilising at 298 mg C/kg at week 24. Compost 5 t/ha showed a similar trajectory but lower peak (256 mg C/kg at week 16). The control remained stable near baseline (140–152 mg C/kg) throughout. The biphasic MBC pattern in the combination treatment — rapid increase in weeks 0–8 from labile compost carbon, followed by a sustained plateau from the more recalcitrant SCG melanoidin carbon — is consistent with the proposed dual-phase carbon supply mechanism of combined SCG-compost amendments. The sustained high MBC at week 24 (298 mg C/kg) indicates that the melanoidin fraction provides an ongoing substrate for the soil microbial community beyond the labile compost carbon exhaustion phase.

Discussion

The finding that the SCG + compost combination (5+5 t/ha) outperforms all individual amendment treatments across all crop yield and soil biological endpoints is explained by the complementary carbon quality profiles of the two components: compost provides a labile, rapidly mineralised nitrogen-rich carbon fraction that immediately improves soil fertility and supports early-season crop growth, while the SCG melanoidin fraction contributes a slow-release, recalcitrant carbon pool that maintains soil biological activity over the longer growing season after the labile compost carbon is depleted [5]. This dual-phase carbon supply mechanism is analogous to the agronomic benefit of combining inorganic fertilizer (fast-acting) with organic amendments (slow-release) in conventional integrated soil fertility management — a well-established agronomic principle now supported by the current research in the specific context of coffee waste combinations [6].

The transient nitrogen immobilisation observed with raw SCG application (T3) in weeks 4–8 — confirmed by the soil N depression from 0.12% (control, week 0) to 0.10% (T3, week 4) — validates the agronomic concern about direct application of high-C:N ratio materials and has practical implications for

Indonesian smallholder adoption of SCG amendments. This immobilisation period can be managed through: (i) applying SCG 6–8 weeks before planting (allowing pre-season decomposition), (ii) co-applying urea at 30–40 kg N/ha to compensate for immobilised nitrogen during the critical seedling establishment phase, or (iii) composting SCG for 16–20 weeks to reduce C:N ratio to below 20 before soil application — the approach that produced the highest individual treatment yields (T2, compost 10 t/ha) in the current research [7].

Conclusion

This research contextualizes coffee processing residue soil amendments within the agronomic and economic realities of Indonesian robusta coffee smallholder farming, demonstrating for the first time the yield and soil biological benefits of the SCG + compost combination in Lampung Province Ultisol conditions. Finding highlights confirm the combination treatment as the agronomically optimal strategy: maize yield +62.7%, robusta coffee yield +95.2%, soil MBC +113%, at an economic return on amendment investment estimated at USD 216–256/ha above input costs. The recommendation for Indonesian coffee sector extension services is to promote combined SCG + coffee compost amendments as the primary organic soil fertility intervention for robusta smallholders, with nitrogen immobilisation management guidance (pre-season SCG application or urea supplementation) as a key extension message. Future research should extend this research over two or more cropping seasons to characterize the long-term soil organic matter accumulation and sustained yield benefit of SCG melanoidin carbon in Indonesian robusta plantation soils.

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