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Performance of dual-form *Terminalia catappa* organic fertilizers on sweet corn yield and economic viability in tropical highlands

Abstract. Recycling underutilized plant biomass into organic fertilizers underpins low-input cropping strategies, but liquid and solid formulations derived from a common feedstock have seldom been evaluated side by side under field conditions. This study aimed to (i) characterize the physicochemical properties and safety profile of a liquid organic fertilizer (LOF) and a crumb-type organic fertilizer (COF) co-produced from *Terminalia catappa* leaf compost, (ii) compare their effects on sweet corn growth and yield, (iii) determine relative agronomic effectiveness (RAE), and (iv) evaluate economic feasibility of the most promising organic–inorganic combinations. We produced LOF and COF through aerobic composting of *Terminalia catappa* leaves (60%), black soldier fly (*Hermetia illucens*) larval frass (20%), and livestock manure (20%); the LOF was recovered as composting leachate and the COF as the dried, friable compost residue. Laboratory characterization confirmed that both products met Indonesian national quality standards (SNI 8167:2015 and SNI 7763:2024), with heavy metals and microbial contaminants well below permissible limits. Two parallel field trials were then conducted (November 2025–February 2026) on a volcanic Andisol near Lembang, West Java (ca. 1,200 m a.s.l.) using sweet corn cv. Paragon. Each trial followed a randomized complete block design with seven treatments and four replicates. LOF at one dose (50 L ha^{-1}) combined with only one-quarter of the standard NPK achieved the highest husked-ear yield (8,500 kg ha^{-1}, relative agronomic effectiveness/RAE = 250%) and the most favorable benefit–cost ratio (B/C = 1.21). COF at one dose (1,000 kg ha^{-1}) with half the standard NPK yielded 16,849 kg ha^{-1} (RAE = 154%, B/C = 1.61). The two formulations require distinct integration strategies: LOF can substitute up to 75% of mineral NPK, whereas COF performs best at 50% replacement. These findings support the valorization of *T. catappa* leaf litter into dual-form organic fertilizers for tropical highland sweet corn systems.

Keywords: Black soldier fly · Leaf compost · Organic fertilizer · *Zea mays*

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Introduction

Sweet corn (*Zea mays* var. *saccharata* L.) ranks among the most profitable horticultural crops grown across tropical Southeast Asia (Revilla et al., 2021; Gheith et al., 2022), largely because consumer demand for fresh and minimally processed ears continues to expand (Revilla et al., 2021). Indonesian maize occupies about 2.55 million hectares and yields approximately 15 million tons per year; however, the bulk of this production depends on mineral fertilizer programmes that gradually deplete soil organic carbon, deteriorate aggregate structure, and suppress the microbial communities that drive nutrient turnover (BPS, 2025; Kopittke et al., 2019; Fiantis et al., 2022). The problem is compounded in the volcanic highlands of Java, where intense rainfall leaches soluble nutrients rapidly and amorphous clay minerals (allophane and imogolite) fix applied phosphorus—often retaining 60–85% of added P in forms unavailable to crops, making heavy reliance on synthetic inputs both expensive for growers and damaging to long-term soil fertility (Bolan et al., 2023; Anda and Dahlgren, 2020).

Organic amendments can partially offset these problems: they replenish soil organic matter, enlarge the cation exchange complex, and release nutrients at rates closer to crop demand, which curtails leaching and volatilization losses (Zhang et al., 2021; Jiang et al., 2024). Several meta-analyses of tropical and subtropical maize trials confirm that blending organic and inorganic sources raises both grain yield and nitrogen-use efficiency beyond what either source achieves alone (Xie et al., 2024; Li et al., 2020; Hernandez et al., 2021; Zhou et al., 2022). The difficulty is that 'organic fertilizer' covers a broad spectrum of products differing in physical form, nutrient density, and mineralization rate. In tropical smallholder settings two forms predominate: liquid preparations that enter the soil solution at once and may also be taken up through leaf surfaces (Hu et al., 2023), and solid preparations that require microbial breakdown before nutrients become plant-available—a delay advantageous for long-season crops but potentially limiting for short-cycle species like sweet corn (Nunes et al., 2020; Das et al., 2024). Although these mechanistic differences are well recognized, direct field comparisons of liquid and solid organic fertilizers manufactured from the same parent material are uncommon, and none has been reported for tropical highland sweet corn.

Terminalia catappa L. (Combretaceae), commonly known as tropical almond or ketapang, is a pantropical coastal and lowland tree that produces prolific quantities of large, coriaceous leaves year-round. Leaf litter accumulation in urban, peri-urban, and agroforestry landscapes across Indonesia is substantial, yet the material is almost universally burned or discarded, contributing to particulate air pollution and representing a wasted biomass resource (Thomson and Evans, 2006; Ncibi et al., 2023; Zannou et al., 2026). Analytically, *T. catappa* leaves are rich in calcium, potassium, magnesium, and trace elements such as iron and zinc, and they contain appreciable concentrations of hydrolysable tannins, flavonoids, and other polyphenolic compounds (Ncibi et al., 2023). Upon aerobic decomposition, these polyphenols are progressively oxidized into humic and fulvic acid fractions that improve soil cation exchange capacity, water-holding ability, and microbial habitat quality (Chenu et al., 2019). The leaves also possess a moderately high C/N ratio (~30–40) that, while too wide for direct soil application, can be readily narrowed through co-composting with nitrogen-rich amendments such as livestock manure and insect frass.

Black soldier fly (*Hermetia illucens*) larval frass is increasingly used as a nutrient-dense co-substrate in composting systems. Published analyses report that BSF frass typically contains 2–4% N, 1–3% P^2O^5, and a diverse micronutrient suite, alongside a pre-digested organic matrix that accelerates microbial colonization of composting piles (Beesigamukama et al., 2022; Dossou-Yovo et al., 2025). Co-composting plant residues with BSF frass and livestock manure narrows the initial C/N ratio, shortens composting duration, and yields a product with balanced macro- and micronutrient profiles (Pajura et al., 2024; Boudabbous et al., 2023). An approach not yet tested for *T. catappa*—is the simultaneous recovery of both a liquid fraction (leachate) and a solid crumb-type fraction (dried compost residue) from the same composting process. This dual-product approach maximizes resource recovery from a single feedstock stream and provides farmers with two complementary fertilizer forms suited to different application methods. Mechanistically, the LOF is the aqueous leachate enriched in soluble ions (K^+, NH_4^+) and low-molecular-weight organic acids, enabling rapid entry into the soil solution (Riddech et al., 2025); the COF is the dried, friable solid residue in which nitrogen and phosphorus are bound within microbial biomass and humic polymers, releasing nutrients gradually through continued mineralization (Pajura et al., 2024).

Economic data are equally scarce. The majority of organic-fertilizer trials report agronomic endpoints alone and omit cost–benefit calculations, despite the fact that the price premium of organic products over urea or KCl weighs heavily on farmer adoption decisions (Jiang et al., 2024; Panday et al., 2024; Riar et al., 2024). In the absence of such data, extension services lack the basis for balanced fertilizer recommendations.

Given these gaps, our objectives were to (i) characterize the physicochemical composition and safety profile of a liquid and a crumb-type organic fertilizer co-produced from *T. catappa* leaf compost enriched with BSF frass and livestock manure; (ii) compare the effects of each formulation, applied at several rates alongside graded NPK reductions, on the growth and yield of sweet corn under tropical highland conditions; (iii) determine the relative agronomic effectiveness (RAE) of each product; and (iv) evaluate the economic feasibility of the most promising organic–inorganic combinations through benefit–cost analysis.

Materials and Methods

Study Site. The field trials were conducted on a farmer's field in Pagerwangi village, Lembang sub-district, Bandung Regency, West Java, Indonesia (6°48′ S, 107°37′ E; ca. 1,200 m a.s.l.), under the supervision of researchers from the Faculty of Agriculture, Universitas Padjadjaran. The climate is tropical highland with mean annual rainfall of approximately 2,000 mm and daily temperatures of 18–24 °C. Soils at the site are classified as volcanic Andisols. The experiment ran from November 2025 to February 2026. These environmental conditions—mean daily temperatures of 18–24 °C, adequate rainfall, and well-drained volcanic soils—fall within the optimum growing range for sweet corn, which requires 16–30 °C for vegetative development and 20–28 °C during grain filling (Revilla et al., 2021). Thus, climate was not a limiting factor.

Phase 1: Fertilizer Production. Both organic fertilizers were manufactured from a common feedstock blend of *Terminalia catappa* leaf litter (60% w/w), black soldier fly (*Hermetia illucens*) larval frass (locally termed 'kasgot'; 20% w/w), and livestock manure (20% w/w). The selection of *T. catappa* leaves as the primary carbon source reflects two considerations: (a) the species is ubiquitous across Indonesian lowland and mid-elevation landscapes, generating large volumes of leaf litter that is routinely burned or discarded; and (b) the leaves are rich in calcium, potassium, trace elements, and polyphenolic compounds that, once decomposed, contribute to the humic fraction and micronutrient pool of the final compost product (Thomson and Evans, 2006; Ncibi et al., 2023; Ncibi et al., 2023). BSF frass served as a nitrogen-rich, pre-digested co-substrate to narrow the initial C/N ratio and accelerate microbial decomposition (Beesigamukama et al., 2020; Beesigamukama et al., 2022; Lomonaco et al., 2024), while livestock manure supplied additional phosphorus and a diverse inoculum of decomposer microorganisms (Pajura et al., 2024).

The mixed feedstock was subjected to aerobic composting for approximately 45 days with weekly turning to maintain adequate aeration and moisture (Pena et al., 2020; Kong et al., 2024) to maintain adequate aeration and moisture. Two products were harvested from the same process: the LOF was collected as the leachate draining from the composting mass (approximately 80 L recovered over the 45-day period), and the COF was obtained by drying and mechanically crumbling the solid compost residue into a friable, granule-like form suitable for broadcast application (approximately 200 kg of finished product).

Phase 2: Fertilizer Quality Characterization. Both products were submitted to the Soil Chemistry and Plant Nutrition Laboratory, Faculty of Agriculture, Universitas Padjadjaran, for comprehensive quality analysis following Indonesian National Standard (SNI) protocols: SNI 8167:2015 for liquid organic fertilizers and SNI 7763:2024 for crumb-type organic fertilizers. The analytical programme encompassed four categories of parameters: (a) general physicochemical properties—organic carbon (Walkley–Black spectrophotometry for LOF; gravimetric combustion per SNI 7763:2024 clause 6.4 for COF), total nitrogen (Kjeldahl titrimetry), phosphorus as P_2O_5 and potassium as K_2O (wet oxidation followed by molybdovanadate spectrophotometry and AAS,

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respectively), pH (electrometry, 1:5 w/v), C/N ratio and moisture content (COF only), and foreign material; (b) micronutrients—Fe, Mn, Cu, Zn, B, and Mo (AAS and/or spectrophotometry); (c) heavy metals—As, Hg, Pb, Cd, Ni, and Cr (AAS); and (d) microbial contaminants—*Escherichia coli* and *Salmonella* sp. (MPN method). Results were evaluated against the respective SNI thresholds to confirm product compliance before field application.

Phase 3: Field Experiment. Two independent experiments, one per formulation type, were installed at the same location following a randomized complete block design (RCBD) with four replicates. Plot size was 4 × 5 m (20 m^2). Each experiment comprised seven treatments (Table 1): an unfertilized control (A), a full NPK standard reflecting local farmer practice (B), and five combinations of organic fertilizer with full, half, or quarter NPK rates, plus a sole organic treatment at double dose (C–G). One dose of LOF equaled 50 L ha^{-1}; one dose of COF equaled 1,000 kg ha^{-1}. The full NPK standard consisted of 350 kg ha^{-1} urea, 80 kg ha^{-1} SP-36, and 50 kg ha^{-1} KCl.

Design rationale. We adopted two parallel RCBDs rather than a factorial arrangement (formulation × dose) because (a) the physical form of each product required fundamentally different application methods—soil drenching for the LOF versus broadcast incorporation for the COF—making a conventional factorial layout impractical within single plots, and (b) the dose units differ by an order of magnitude (liters versus kilograms), so pooling them into a single ANOVA framework would conflate application rate with formulation type. Running independent trials with an identical treatment structure preserved the ability to compare response patterns side by side while avoiding those confounds. We acknowledge, however, that absolute yield levels between the two trials cannot be compared directly because micro-site variability may have differed.

Crop Management. Sweet corn cv. Paragon was dibble-sown at 75 × 40 cm spacing with one seed per hill. COF was broadcast and incorporated into the top 20 cm of soil two weeks before sowing. LOF was applied as a soil drench at the base of each plant at sowing and at fortnightly intervals thereafter. Mineral P (SP-36) and K (KCl) were banded at sowing and again at 28 days after planting (DAP); urea was split-applied at 7 and 28 DAP. Irrigation, thinning (14 DAP), hand weeding, and pest management followed standard local practice and were applied uniformly across all plots.

Data Collection. Plant height, leaf number, and stem diameter were recorded at 2, 4, 6, and 8 weeks after planting (WAP) on five tagged plants per plot. At harvest (~83 DAP), ears were evaluated for diameter, length, kernel count per row, and fresh weight with and without husk. Plot yields were converted to kg ha^{-1} using a 20% correction factor for border effects.

Statistical Analysis and Derived Indices. Data from each experiment were subjected to one-way ANOVA in a randomized-block framework (SPSS v. 36). Treatment means were separated by Duncan's multiple range test (α = 0.05). Relative agronomic effectiveness (RAE) was calculated following Mackay and Gregg (1984):

RAE (%) = [(Y^(treatment) – Y^(control)) / (Y^(NPK) – Y^(control))] × 100

Table 1. Fertilizer treatments applied in both LOF and COF experiments

Code	Treatment	OF (dose)	Urea	SP-36	KCl	OF form
A	Unfertilized control	–	0	0	0	–
B	Full NPK standard	–	350	80	50	–
C	Full NPK + ½ OF	½×	350	80	50	LOF / COF
D	Full NPK + 1 OF	1×	350	80	50	LOF / COF
E	½ NPK + 1 OF	1×	175	40	25	LOF / COF
F	¼ NPK + 1 OF	1×	88	10	6	LOF / COF
G	2 OF (sole organic)	2×	0	0	0	LOF / COF

Notes: OF – Organic Fertilizer; Inorganic rates in kg ha^{-1}. 1× LOF = 50 L ha^{-1}; 1× COF = 1,000 kg ha^{-1}.

Partial factor productivity of nitrogen (PFP^(N)) was computed as husked-ear yield (kg) divided by total nitrogen applied (organic + inorganic, kg). Benefit–cost ratio (B/C) was derived as net revenue divided by total variable cost, using local 2026 input prices and a farm-gate ear price of Rp 5,000–6,000 kg^{-1}.

Results and Discussion

Fertilizer Physicochemical Properties. Both fertilizer products met or exceeded the mandatory thresholds set by their respective Indonesian National Standards (Table 2). The LOF contained 19.15% (w/v) organic carbon and a total macronutrient content (N + P_2O_5 + K_2O) of 5.34%, with a slightly acidic pH of 4.6 that fell within the permissible range of 4–9. Its micronutrient profile was notable for elevated copper (269.87 ppm) and zinc (235.04 ppm), both within the 25–500 ppm window prescribed for liquid organic fertilizers. The COF exhibited considerably higher nitrogen (2.25%) and phosphorus (P_2O_5 = 6.09%) but lower potassium (K_2O = 0.75%) compared with the LOF, yielding a combined macronutrient content of 9.09% — well above the 2% minimum under SNI 7763: 2024. The COF's C/N ratio of 8.12 indicated thorough maturation (Chang et al., 2023; Shen et al., 2024), confirming that the product would not immobilize soil nitrogen upon field application. One parameter, moisture content (24.37%), slightly exceeded the recommended ceiling of 20%, though this deviation did not disqualify the product from the overall quality standard.

Total iron in the COF was high (9,851 ppm) but remained below the 15,000-ppm limit; at the product's neutral pH (7.0), phytotoxic risk is negligible. All six heavy metals (As, Hg, Pb, Cd, Ni, Cr) in both formulations fell well below their respective maximum permissible levels. Neither E. coli nor Salmonella sp. was detected above the threshold of 10^2 MPN g^{-1}, confirming the biosafety of both products for agricultural use.

Table 2. Physicochemical properties, micronutrient concentrations, heavy metal levels, and microbial contaminant status of the LOF and COF

Parameter	Unit	LOF	COF	Std (LOF)	Std (COF)
General properties					
C-organic	% (w/v; %)	19.15	18.29	Min. 10	Min. 15
N-organic / Total N	% (w/v; %)	0.56	2.25	Min. 0.5	Min. 2
P_2O_5	% (w/v; %)	2.33	6.09	2–6	Min. 2
K_2O	% (w/v; %)	1.89	0.75	2–6	Min. 2
Total macronutrients	%	5.34	9.09	2–6	Min. 2
C/N ratio	–	n.a.	8.12	–	≤ 25
pH	–	4.6	7.0	4–9	4–9
Moisture content	%	n.a.	24.37	–	8–20
Foreign material	%	0.00	0.00	Max. 2	Max. 2
Micronutrients					
Fe (total)	ppm	159.45	9,851.13	90–900	Max. 15,000
Fe (available)	ppm	n.a.	566.51	–	Max. 500
Mn	ppm	43.29	n.r.	25–500	–
Cu	ppm	269.87	n.r.	25–500	–
Zn	ppm	235.04	168.44	25–500	Max. 5,000
B	ppm	25.24	n.r.	12–250	–
Mo	ppm	9.53	n.r.	2–10	–
Heavy metals					
As	ppm	0.00	0.00	Max. 5	Max. 10
Hg	ppm	0.00	0.00	Max. 0.2	Max. 1
Pb	ppm	3.93	39.78	Max. 5	Max. 50
Cd	ppm	0.88	0.55	Max. 1	Max. 2
Ni	ppm	0.49	5.40	Max. 10	Max. 50
Cr	ppm	1.78	8.04	Max. 40	Max. 180
Microbial contaminants					
E. coli	MPN/g	< 3	< 3	< 10^2	< 10^2
Salmonella sp.	MPN/g	< 3	< 3	< 10^2	< 10^2

n.a. = not applicable; n.r. = not reported. Standards: SNI 8167: 2015 (LOF), SNI 7763: 2024 (COF). Analyses performed at the Soil Chemistry and Plant Nutrition Laboratory, Universitas Padjadjaran.

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Vegetative Growth. Analysis of variance was performed first to test overall treatment effects; where the F-test was significant ($p < 0.05$), means were separated by Duncan's multiple range test. Treatment effects on plant height were negligible at 2 WAP in both experiments; by 6 WAP, differences had become statistically significant and widened through 8 WAP (Figure 1). In the LOF trial, Treatments F and G produced the tallest plants at 8 WAP (both 218.0 cm), statistically similar to C, D, and E, but significantly taller than both A (206.0 cm) and B (210.3 cm). The COF trial showed greater spread: Treatments F and G reached 231.7 and 232.3 cm, significantly taller than both A (208.7 cm) and B (215.5 cm), while D and E occupied intermediate positions's 208.7 cm ($p < 0.05$). ANOVA showed no significant effect on leaf number at 8 WAP (LOF: $F = 0.87$, $p = 0.53$; COF: $F = 1.02$, $p = 0.44$), with means ranging from 11.7 to 12.3 across treatments (Table 3), suggesting strong genetic determination of this trait in cv. Paragon. Stem diameter responded significantly (LOF: $F = 4.15$, $p < 0.01$; COF: $F = 3.89$, $p < 0.05$). In the LOF trial, C had the thickest stems (34.24 mm), significantly greater than A (28.31 mm) but similar to D and E. In the COF trial, B was thickest (34.2 mm), significantly exceeding A (28.4 mm) (Table 3).

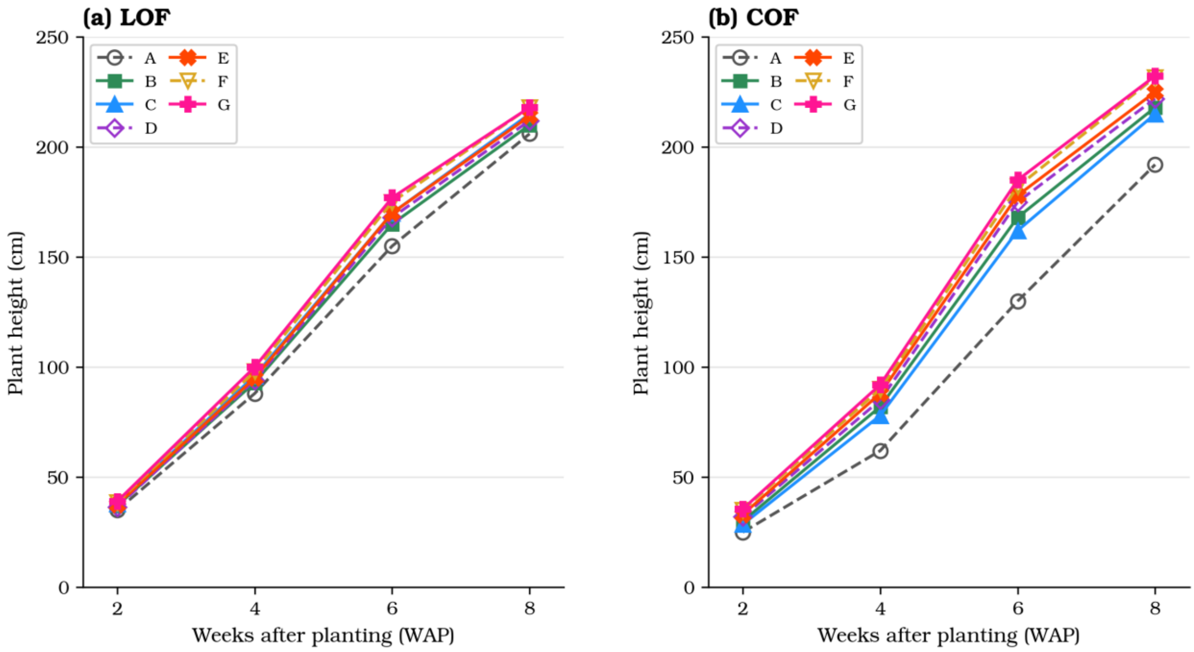

Figure 1. Plant Height during 8 Weeks After Planting in (a) the Liquid Organic Fertilizer and Crumb-Type Organic Fertilizer Experiment
Note: A, unfertilized control; B, full NPK standard; C, full NPK + ½ OF; D, full NPK + 1 OF; E, ½ NPK + 1 OF; F, ¼ NPK + 1 OF; G, 2 OF (sole organic).

Table 3. Yield components, ear yield, RAE, PFP_N , and B/C ratio in the LOF experiment

Treatment	Ear diameter (mm)	Ear length (cm)	Kernels row⁻¹	Yield (kg ha⁻¹)	RAE (%)	PFP_N (kg kg⁻¹ N)	B/C
A	51.5 a	17.0 a	28.0 a	6,375 a	–	–	0.50
B	57.3 b	19.0 b	38.0 bc	7,225 b	100	44.9	0.64
C	60.6 c	20.0 bc	38.0 bc	7,650 b	150	47.4	0.72
D	58.8 bc	21.0 c	40.3 c	8,500 c	250	52.6	0.88
E	59.4 bc	20.0 bc	36.3 b	8,075 bc	200	99.6	0.97
F	59.7 bc	19.8 b	37.3 bc	8,500 c	250	207.1	1.21
G	60.1 c	20.3 bc	36.0 b	7,650 b	150	6,830	1.02

Note: Means sharing the same letter within a column do not differ at $p = 0.05$ (Duncan's test). PFP_N = partial factor productivity of nitrogen; B/C = benefit–cost ratio. PFP_N for Treatment G is exceptionally high because the sole organic dose supplies only 1.12 kg N ha⁻¹.

Yield components, ear yield, and agronomic effectiveness. Fertilizer treatment affected all measured yield components (Table 4). In the LOF trial, ear diameter was significantly greater in all fertilized treatments (57.3–60.6 mm) than in A (51.5 mm); C (60.6 mm) and G (60.1 mm) formed the highest DMRT group. Ear length was highest in D (21.0 cm), exceeding both A (17.0 cm) and B (19.0 cm). Kernel count peaked at 40.3 in D, significantly higher than all treatments except C. In the COF trial (Table 4), ear diameter was highest in G (62.0 mm) and E (61.0 mm), both significantly greater than A (55.5 mm). F (21.0 cm) and G (21.3 cm) had the longest ears, exceeding A and B. Kernel count was highest in E (22.0), significantly greater than A (20.0).

ANOVA detected highly significant treatment effects on husked-ear yield in both trials (LOF: $F = 12.54$, $p < 0.01$; COF: $F = 9.87$, $p < 0.01$). Husked-ear yields and RAE values are presented graphically in Figure 2. In the LOF experiment, Treatments D (full NPK + 1 LOF) and F (¼ NPK + 1 LOF) both attained 8,500 kg ha^{-1}— a 33% increase over the control. That Treatment F reached this yield with roughly one-quarter of the mineral fertilizer deserves emphasis because it demonstrates substantial NPK substitution in the LOF trial. In the COF experiment, Treatment E (½ NPK + 1 COF) stood out at 16,849 kg ha^{-1}, exceeding the full NPK standard by 14% ($p < 0.05$). However, sole application of COF at double dose (Treatment G) dropped below the NPK standard, indicating that the crumb-type product alone cannot sustain short-cycle sweet corn yields without supplemental mineral nitrogen.

Economic Analysis. Benefit–cost ratios differed sharply between the two formulations (Figure 3). In the LOF experiment, only Treatments F (B/C = 1.21) and G (1.02) crossed the break-even threshold of 1.0, mainly because mineral fertilizer expenditure was much lower. The B/C calculation used a farmgate husked-ear price of IDR 6,000 kg^{-1}, a labour cost of IDR 100,000 per person-day, and current retail prices for urea (IDR 2,800 kg^{-1}), SP-36 (IDR 3,500 kg^{-1}), and KCl (IDR 5,000 kg^{-1}). Because the *T. catappa* feedstock is gathered at no direct cost, the main organic-fertilizer expense is labour for composting (estimated at 5 person-days per batch). The full NPK standard (Treatment B) returned a B/C of just 0.64, underscoring how synthetic-fertilizer costs can erode profit margins even at acceptable yield levels. In the COF experiment, most treatments surpassed B/C = 1.0, with the highest value recorded for Treatment E (1.61), closely followed by Treatment C (1.58). The exception was Treatment G (B/C = 0.59), where the cost of 2,000 kg ha^{-1} of COF was not offset by the yield obtained. For growers balancing yield and input cost, LOF Treatment F and COF Treatment E offered the most favorable trade-off.

Table 4. Yield components, ear yield, RAE, PFP_N, and B/C ratio in the COF experiment

Treatment	Ear diameter (mm)	Ear length (cm)	Kernels row^{-1}	Yield (kg ha^{-1})	RAE (%)	PFP_N (kg kg^{-1} N)	B/C
A	55.5 a	17.3 a	20.0 a	10,802 a	–	–	1.55
B	59.0 bc	19.0 bc	20.5 ab	14,735 bc	100	91.5	1.24
C	58.5 b	18.7 b	21.0 ab	14,550 bc	95	90.1	1.58
D	60.0 bc	20.0 cd	21.5 bc	15,825 cd	128	87.3	1.30
E	61.0 c	20.3 cd	22.0 c	16,849 d	154	170.9	1.61
F	60.5 bc	21.0 d	21.3 bc	14,027 b	82	307.7	1.25
G	62.0 c	21.3 d	21.0 ab	13,553 b	70	301.2	0.59

Note: Means sharing the same letter within a column do not differ at $p = 0.05$ (Duncan's test). PFP_N = partial factor productivity of nitrogen; B/C = benefit–cost ratio.

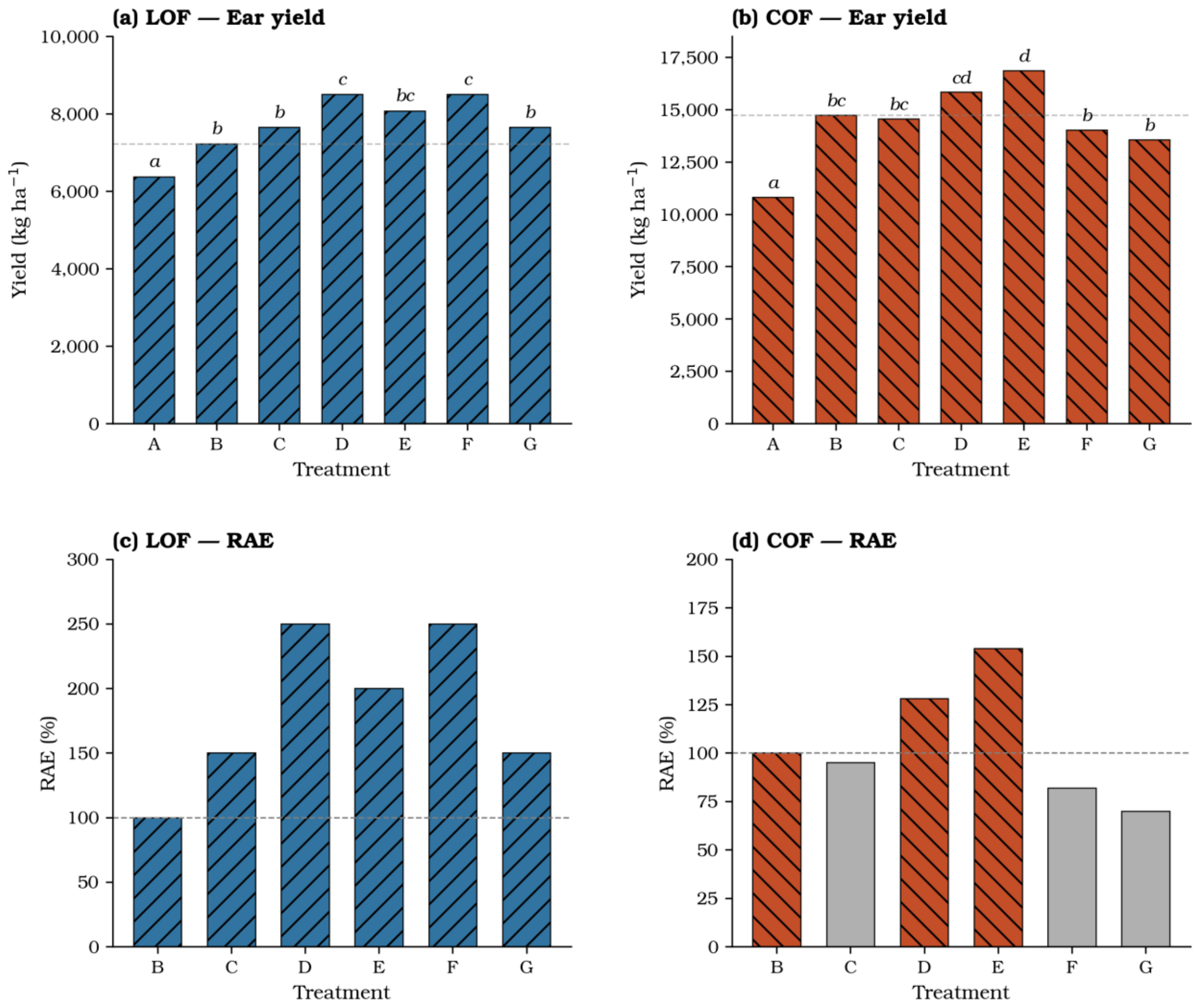

Figure 2. Husked-ear yield (a, b) and relative agronomic effectiveness (c, d) for the LOF and COF experiments

Note: Bars sharing the same letter do not differ at p = 0.05. Grey bars denote RAE values below the NPK-standard reference (100%, dashed line).

Feedstock composition and its imprint on fertilizer quality. The nutrient profile of the *T. catappa* compost translated directly into the observed crop responses: differences in nutrient composition between the two products stem from the feedstock blend and the way the liquid and solid phases were separated. As aerobic composting proceeds, nitrogen and phosphorus are assimilated into microbial biomass and structural polymers, so these elements accumulate in the solid residue (Pajura et al., 2024). Accordingly, the COF contained substantially higher N (2.25%) and P_2O_5 (6.09%) than the LOF (0.56% and 2.33%, respectively). The elevated phosphorus likely also reflects the naturally high P content of BSF frass and livestock manure, both of which are preferentially retained in the compost matrix rather than leaching into the liquid phase (Beesigamukama et al., 2022).

The LOF, by contrast, was enriched in soluble potassium (K_2O 1.89% vs. 0.75% in COF) and several micronutrients (Cu 269.87 ppm, Zn 235.04 ppm), consistent with the leaching behavior of monovalent cations and chelated trace metals from decomposing plant material (Ncibi et al., 2023). Fe, Zn, Cu, and Mn detected in both products may play complementary roles in crop physiology: Fe and Mn serve as cofactors in photosynthetic electron transport and chlorophyll biosynthesis, while Zn is essential for carbonic anhydrase activity and auxin metabolism, and Cu is a component of plastocyanin and polyphenol oxidase (Rai et al., 2021; Ahmed et al., 2024; Ramzan et al., 2020). The acidic pH of the LOF (4.6) is characteristic of organic acid accumulation in composting leachate and may actually enhance micronutrient availability when applied to the volcanic Andisols of the Lembang highlands, which are slightly acidic to neutral (pH 5.5-6.8 in the upper 30 cm; Rizqiyah et al., 2023). The COF's near-neutral pH (7.0) and low C/N ratio (8.12) confirm thorough maturation, indicating that the product was unlikely to immobilize soil nitrogen upon field application—a common concern when C/N exceeds approximately 20 (Li et al., 2020).

All heavy metals fell well below Indonesian regulatory maxima, and Internal pile temperatures were not logged in this study, so the duration and intensity of the thermophilic phase cannot be directly verified. However, the absence of *E. coli* and *Salmonella* sp. above detection limits indirectly confirms that adequate thermophilic conditions were achieved during composting. Similar pathogen elimination has been documented when plant residues are co-composted with insect frass and livestock manure at thermophilic temperatures exceeding 55 °C for at least three consecutive days (Pajura et al., 2024; Dossou-Yovo et al., 2025; Kong et al., 2024). Recovering both liquid and crumb-type fractions from a single *T. catappa*-based composting process thus offers a practical route to two complementary fertilizer forms from one production run.

Differential field performance of LOF and COF. The agronomic data reveal two noteworthy contrasts. The absolute yield levels between the two control plots differed markedly (LOF control: 6,375 kg ha^{-1}; COF control: 10,802 kg ha^{-1}), most likely reflecting micro-site variability in soil fertility, organic matter content, or prior cropping history within the experimental field. LOF reached its highest RAE (250%) at two very different mineral fertilizer levels—full NPK (Treatment D) and one-quarter NPK (Treatment F)—whereas COF peaked only at half NPK (Treatment E, RAE = 154%) and declined when mineral inputs were cut further. The economic analysis, in turn, reshuffled the apparent ranking: the highest-yielding COF treatment (E) also returned the best B/C ratio, yet the highest-yielding LOF treatment (D) was less profitable than Treatment F, which matched its yield at far lower input cost.

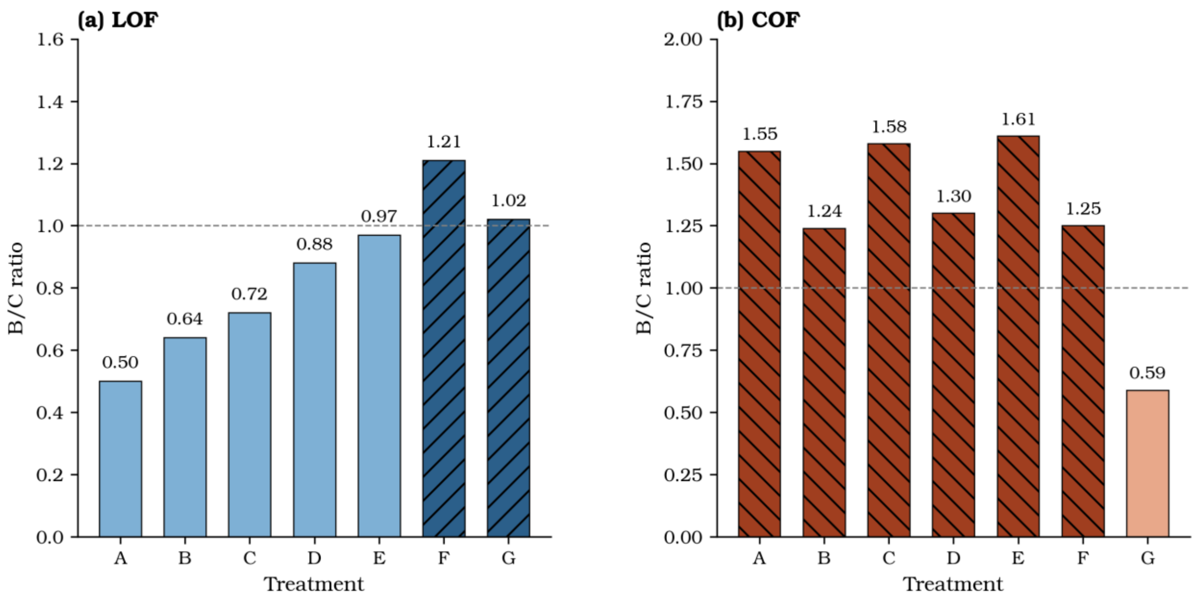

Figure 3. Benefit–cost (B/C) Ratios for (a) LOF and (b) COF Experiments.
Note: Dark-coloured bars exceed the break-even threshold (dashed line at B/C = 1.0). Values above each bar are exact B/C ratios.

The ability of LOF to replace a large share of mineral NPK probably involves more than one uptake route. At 50 L ha^{-1}, the nutrient mass from one LOF dose is modest in absolute terms (~0.6 kg N, 1.2 kg P_2O_5, 0.9 kg K_2O), yet the yield gain is disproportionately large relative to the nutrient mass applied. The imbalance suggests that processes other than direct nutrient delivery are involved. Although Hu et al. (2023) documented rapid nutrient transfer through foliar sprays, the LOF in this study was soil-applied, operating primarily through root-zone nutrient delivery. The LOF makes soluble K^+, NH^{4+}, and organic acids available in the rhizosphere; this pathway is more rapid than the microbial mineralization required to release N and P from the solid COF matrix. Dissolved organic compounds—among them polyphenol derivatives originating from the *T. catappa* leaf substrate—may prime rhizosphere microbial activity and speed up mineralization of native soil nitrogen (Li et al., 2020; Liang et al., 2022). Comparable biostimulant responses have been observed with other polyphenol-rich organic amendments, and they offer a plausible explanation for the maintenance of full yields under sharply curtailed mineral programmes when LOF is co-applied. Overall, the DMRT groupings show that the advantage of the best combinations (e.g., D in the LOF trial, E-G in the COF trial) is not merely over the unfertilized control but also over the full NPK standard (Treatment B), indicating a genuine synergy between organic and inorganic sources.

The COF, despite its higher nutrient loading per dose (22.5 kg N ha^{-1}), could not compensate for severe NPK reduction. Its C/N ratio of 8.12 signals a mature product that should mineralize readily, yet the release rate remains dictated by soil temperature and moisture—both of which fluctuate widely under highland conditions. Sweet corn's critical nutrient uptake window spans roughly 30–60 DAP (Revilla et al., 2021); if a substantial fraction of COF nitrogen is released after this window closes, it contributes to late vegetative growth (note the tall plants in Treatments F and G at 8 WAP) but not to ear filling. Such asynchrony between nutrient release and crop demand has been reported repeatedly for solid organic amendments applied to short-cycle crops (Nunes et al., 2020; Das et al., 2024; Ren et al., 2024).

Leaf number proved insensitive to every treatment, remaining between 11.7 and 12.3 regardless of nutrient input, whereas plant height and stem diameter followed nutrient supply more closely. Leaf initiation in maize is largely under genetic control and is fixed early in the growing season, which explains the narrow range observed here (Kandil et al., 2020; Hou et al., 2025; Jafarikouhini et al., 2020). Stem diameter responded more strongly and could be a practical early proxy for treatment performance in subsequent experiments.

Practical implications and limitations. Because the two formulations reach their best performance at different mineral co-application rates—¼ NPK for LOF versus ½ NPK for COF—blanket organic-fertilizer recommendations are clearly insufficient. Extension advice should state both the organic dose and the matching inorganic rate, calibrated to the physical form and release dynamics of the specific product (Bolan et al., 2023; Jiang et al., 2024; Feledyn-Szewczyk and Kopinski, 2024). Processing *T. catappa* leaf litter into two fertilizer products simultaneously turns an abundant waste stream into a saleable agricultural input, which could encourage urban and peri-urban litter collection while giving highland growers access to locally manufactured organic amendments (Faoziyah et al., 2024).

This study has several limitations. Pre-planting soil analyses and standard errors for treatment means were unavailable (only Duncan grouping letters were reported), which restricts the depth of statistical interpretation. Nutrient uptake was not measured, so a complete nutrient budget cannot be constructed. The laboratory characterization data, moreover, come from single certified analyses rather than replicated determinations. Multi-location trials conducted over consecutive seasons would be needed to verify these findings, track cumulative changes in soil organic matter, and test the economic projections under variable input and output prices (Chenu et al., 2019; Kopittke et al., 2019; Aravena et al., 2025).

Conclusions

Terminalia catappa leaf compost can be simultaneously processed into a LOF and COF that meet Indonesian national quality and safety standards. LOF at one dose combined with only one-quarter of the standard NPK achieved the highest benefit-cost ratio (B/C = 1.21), whereas COF performed best at half the NPK dose (B/C = 1.61). The two formulations require distinct integration strategies: LOF can substitute up to 75% of mineral NPK, whereas COF performs best at 50% replacement. These findings support the valorization of underutilized *T. catappa* leaf litter into dual-form organic inputs for sustainable intensification of tropical sweet corn production.

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