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Chemical properties analysis of liquid and semi-solid bioconversion products from organic waste and their effects on soil fertility and sweet corn yield

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ABSTRACT

Food security remains a critical global challenge, particularly as land degradation, driven by excessive use of synthetic fertilizers, continues to threaten soil fertility and crop productivity. This study aimed to evaluate the characteristics of liquid and semi-solid fermented organic waste and their effects on several soil chemical properties and sweet corn yield. The experiment was conducted in a corn field in Pagerwangi Village, West Java, Indonesia. The experiment used a Split-Plot Design with three replications. The main plot was the fermented waste product treatment, which consisted of three levels: no product (A_0), liquid product (A_1), and semi-solid product (A_2). The subplot was the N-P-K dose level, which consisted of four levels: 0 N-P-K (a_0), 1/2 N-P-K dose (a_1), 3/4 N-P-K dose (a_2), and standard N-P-K dose (a_3). The research findings indicated that the macro and microelements present in semi-solid products were several times higher compared to liquid ones. Furthermore, the microbial population in semi-solid products exhibited higher density compared to liquid products. Field tests also demonstrated that both liquid product (A_1) and semi-solid product (A_2) significantly increased total nitrogen, organic-C, and soil pH compared to the control (A_0). The highest sweet corn productivity was observed in treatment A_2, with a yield increase of 47.62% compared to the control. The research results suggested that the use of fermented organic waste products could enhance soil fertility and sweet corn production.

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1. INTRODUCTION

Food security has become a global concern. This is due to the increasing human population, which is projected to reach 8.5 billion by 2030 and 9.7 billion by 2050 (Sadigov, 2022). Indonesia is expected to contribute 300 million. At the same time, our capacity to produce sufficient foods keeps being hampered by many problems such as unstoppable land conversion, climate change, biodiversity loss, increased farming costs, decreasing interest in farming, and land degradation (Chew et al., 2019; Kumar et al., 2021). Particularly land degradation, problem must be given special attention as this causes the existing arable land to decrease in productivity, hence increasing production costs, lowering farmer's revenue, and in the long-term, damaging the sustainability of crop production (Eswaran et al., 2001). Land degradation is caused by many but most importantly by irrational and excessive use of synthetic fertilizer as this practice wreaks havoc on soil native microbiome by suppressing nitrogen fixers and amplifying soil decomposer's activity in decomposing organic matter which further leads to decreasing soil organic matter (Widowati et al., 2020) and soil fertility in whole (Bhatt et al., 2019; Jamilah et al., 2024). To answer the problem, an eco-friendlier practice such as organic or semi-organic farming is advocated. In this

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approach, the input of synthetic fertilizer is reduced in part or fully substituted by organic fertilizer (Sharma et al., 2019).

The bioconversion of organic wastes into organic fertilizers happens through a process called fermentation. This process facilitates the breaking down of organic components (e.g. carbohydrates, proteins, lipids, organic acids, etc.) into a more simple and stable organic material assisted by a decomposer microbial consortium in the presence of oxygen, i.e. anaerobic fermentation (Sabater et al., 2020). The final organic product, once applied to the soils, could serve as (Möller, 2018; Pujara et al., 2019) pools for use by plants as either organic fertilizer or soil conditioner. Nevertheless, there are several considerations that must be addressed first that directly affect the characteristics of organic products (Kwanyun et al., 2023; Tsaniya et al., 2021) such as pH, organic-C content, macronutrients (e.g., organic-N, total-N, total P_2O_5, total K_2O), micronutrients (e.g., Fe, Cu, Zn, Mn, etc.), and other compounds such as humic acid, phytohormones (e.g., auxin, cytokinin, gibberellin, etc.) and microbial contents (e.g., total fungi, total N-fixing and P-solubilizing bacteria) to ensure the products meet the standards for organic fertilizers or soil conditioners. Hence it is important to optimize the organic waste fermentation process to generate fermentation products that conform to the criteria as organic fertilizers to apply in soils promoting plant growth and development (Khalisha et al., 2022; Maroušek et al., 2024).

The bioconversion of organic wastes, e.g., vegetable and fruit waste, generates either liquid or semisolid fermentation products depending on the phase harvested. The use of both products, e.g. liquid (LOF) and semisolid organic fertilizer (SOF) has become a trend nowadays due to the multiple benefits aforementioned (Zamri et al., 2021). However, both tend to have low nutrient contents (Roba, 2018) hindering their use in a full cropping system. For instance, typical LOF contains low macronutrient content (Nanda & Berruti, 2021) 0.45 – 1.8, 0.024 – 0.55, and 0.024 – 0.55% for N, P, and K, respectively which do not conform to the standard regulation. The Ministry of Agriculture, Republic of Indonesia mandates for such products to have at least 10% of total macronutrients and 2 – 6% total of every N, P_2O_2, and K_2O content (Kementan, 2019). Therefore, optimization of the fermentation process is critical to generate fermentation products with higher nutritional content to conform with the government's regulations. Among effective strategies to yield high nutrient content of the products can be done physically by grinding the raw organic waste materials first into a finer texture before the fermentation process. Such an approach would obviously increase the surface to area ratio of the materials; rendering better decaying and decomposing processes undertaken by the microbial consortium to generate fermentation products that are higher in nutrient contents (Sharma et al., 2020).

This study aimed to optimize the fermentation process of organic wastes physically by grinding the materials to produce higher nutrient contents. The novelty of this research lies in the innovative development and comparative evaluation of semi-solid organic waste fermentation products (SOF) against conventional liquid organic fertilizers (LOF), demonstrating the superior nutrient concentration and field performance of SOF. The characteristics of the products were assessed physically, chemically, and biologically on several parameters: water solubility, pH, organic C, total bacteria, total fungi, N-fixing bacteria, and P-solubilizing bacteria; to conform to the Indonesian government's regulation. The dynamic of soil properties upon product application was also assessed on parameters such as soil organic C, organic matter (Guo et al., 2020), pH, and cation exchange capacity (CEC) (Mazzon et al., 2018; Pranckietienė et al., 2023; Rathore et al., 2023). Finally, the effect of product application on plant growth and yield was assessed through tissue nutrient content and sweet corn yield (Ngoune Tandzi & Mutengwa, 2020; Solihin et al., 2019) applied in gradual supplementations to reduce inorganic NPK fertilization. Moreover, reducing environmental risks, improving soil fertility, and boosting plant productivity in a more sustainable manner.

2. MATERIAL AND METHODS

2.1. Materials

Organic wastes in the form of vegetables, fruit, and tuber waste were obtained from a local market nearby. Those wastes were subjected to bioconversion into organic fertilizer through an aerobic fermentation process. Bioactivator products created by the vocational school of Universitas Padjadjaran (ASEM-7) were used to assist the fermentation process. ASEM-7 consists of microbial consortia including lactic acid (*Lactobacillus* spp.), actinomycetes (*Streptomyces* spp.), bacteria; yeast, and cellulose degrading fungus (*Pseudomonas* spp, *Bacillus* spp, *Aspergillus* spp, *Saccharomyces* spp., and *Trichoderma* spp.). Sweet corn used for the field experiment was of Paragon variety, obtained from a local vendor.

2.2. Organic waste fermentation process and product analysis

The fermentation process was carried out through two different methods; hence, two fermentation products were obtained. In the first method, the wastes were shredded using a shredding machine and then placed in a 25 L water-resistant plastic bucket. A hole in the bottom of the bucket was made to collect the liquid. Water was then added into the bucket to make the ratio of organic wastes : water = 1 : 3. After that, 50 ml of bio activator (EM4) was added. The digestate was stirred until homogeneous and fermented for 28 days. The final product of the first method was called liquid organic fertilizer (LOF) (Esparza et al., 2020). Meanwhile, in the second method, the wastes were first ground into a finer texture resembling porridges using a grinding machine. After that, the process was identical to the first method, with the distinction that no water was added in the second process. The moisture content solely originated from plant residues and waste materials. The second method required more time (45 days) compared to the first, not only due to the decomposition of solid waste particles that took more time but also to reduce the water content though evaporation. The second method generated products called semisolid organic fertilizer (SOF).

Table 1. Analysis Methods for Various Parameters of Bioconversion Products

No.	Parameters	Method
1.	pH	Electrometry, pH meter (1:5)
2.	Organic-C	Walkley & Black
3.	Organic-N and Total N	Kjeldahl, Titrimetry
4.	P_2O_5	Wet Oxidation, HNO_3 + $HClO_4$, Molybdovanadat, Spectrophotometry
5.	K_2O	Wet Oxidation, HNO_3 + $HClO_4$, AAS – Flamephotometry
6.	Total Fe, Cu, Zn	Wet Oxidation, HNO_3 + $HClO_4$, AAS
7.	Total Mn, Mo	Wet Oxidation, HNO_3 + $HClO_4$, Spectrophotometry
8.	Total B	Wet Oxidation, HNO_3 + $HClO_4$, Azomethine- H, Spectrophotometry
9.	Humic Acid	Gravimetry
10.	Plant Growth Regulator Content (Auxin, Cytokinin, Gibberellin)	High-Performance Liquid Chromatography (HPLC)
11.	N-fixing bacteria,	Quantitative Total Plate Count, JNFB Media
12.	P-solubilizing bacteria	Quantitative Total Plate Count, Pikovskaya Media
13.	Total fungi	Quantitative Total Plate Count
14.	Heavy metals contaminant (As, Hg, Pb, Cd, Cr, Ni)	Wet Oxidation, HNO_3 + $HClO_4$, AAS

Table 2. Extraction and Analysis Method

No.	Parameters	Method	Criteria for Analysis Results*
1.	Organic-C (%)	Walkley & Black	<1 % (poor), 1-2 % (Low), 2-3 % (medium), 3-5 % (high), >5 % Very High
2.	Soil Organic Matter (%)	Calculating organic-C content by a factor of 1.723	
3.	pH	Electrometry, pH meter (1:5)	<4.5 (Strongly acidic), 4.5 - 5.5 (Acidic), 5.5 – 6.5 (Slightly acidic), Neutral (6.6 – 7.5), Slightly alkaline (7.6 – 8.5), >8.5 (Alkaline)
4.	CEC (cmol kg^{-1})	Ammonium acetate (pH=7) extraction, direct distillation	<5 % (poor), 5-16 % (Low), 17-24 % (medium), 25-40 % (high), >40 % Very High
5.	N uptake	Kjeldahl, Titrimetry	
5.	P uptake	Wet Oxidation, HNO_3 + $HClO_4$, Molybdovanadat, Spectrophotometry	
6.	K uptake	Wet Oxidation, HNO_3 + $HClO_4$, AAS – Flamephotometry	

Notes: *Criteria for Analysis Results are based on the Technical Guidelines for Soil, Plant, Water, and Fertilizer Analysisissued by the Indonesian Soil Research Institute.

After that, both products were subjected to analytical tests on several physical, chemical, and biological characteristics including water solubility, pH, organic carbon and nitrogen, nutrients content (total N, P_2O_5, K_2O, Fe, Cu, Zn, Mn, Mo, and B), humic acid, phytohormones content (auxin, cytokinin, gibberellin), and functional microbes (total bacteria, N-fixing bacteria, P-solubilizing bacteria, and total fungi). The quantitative analysis methods used are presented in Table 1.

2.3. Field experiment and experimental condition

A field experiment was conducted to evaluate the application of fermentation products on sweet corn growth and yield. The experiment took place in Pagerwangi Village, Lembang District, West Bandung Regency, West Java Province, Indonesia (latitude: 06°50'13.2360"S and longitude: 107°37'33.2904"E). The experimental site is located in a tropical humid climate (Af), with an altitude of 1300 m, annual mean temperature of 19.5 °C, and annual mean precipitation of 158.18 mm. The experiment was conducted in the rainy season from September 2022 to January 2023. The media used for the experiment was inceptisol. Soil analysis was carried out using the method based on Table 2, to ensure its initial chemical properties.

The field experiment was aimed to investigate the potential of two organic products (LOF and SOF) to supplement inorganic NPK fertilization regimes. To achieve this aim, the field experiment was designed in a split-plot design experiment. The main plot was organic products application which consisted of A0 = without SOF + LOF, A1 = LOF, and A2 = SOF. The subplot was set as gradual NPK fertilization regimes consisted of a1 = 0 NPK (0 kg ha^{-1}), a2= 1/2 NPK (175-40-25 kg ha^{-1}), a3 = 3/4 NPK (263-60-38 kg ha^{-1}), and a4 = 1 standard NPK dosage (350-80-50 kg ha^{-1}). The combination produced 12 treatment combinations, which were replicated three times. The experimental procedure was as such: the media was made in plots sized 1 m × 5 m. Into each plot, the corresponding products were applied, i.e. A0, A1, and A2, at a dose of 1 L per plot. Similarly, NPK dosages were applied as the subplot treatment (A1 to A4). Both products (LOF and SOF) were applied precisely after plot preparation 14 days before transplanting. Meanwhile, NPK fertilizer was applied at 7 and 28 days after transplanting. Subsequent plant maintenance was followed including watering, pest and disease control, etc.

2.4. Assessment of Soil Properties and Plant Tissues Content, and Plant Yield

The dynamic of soil properties after product application was assessed on soil organic carbon (SOC), organic matter (SOM), pH and cation exchange capacity (CEC). Soil samples (depth 0-20 cm) were taken twice on 0 and 14 days after product applications. Quantitative methods employed to assess soil properties are displayed in Table 2. In line with soil, sweet corn plant tissues were also assessed on N-P-K content within the tissues and subjected to tests on soil organic carbon, organic matter, pH, and cation exchange capacity (CEC). Plant tissue samples (N, P, K uptake) were collected at 35 days post-transplantation by uprooting the entire plant, followed by drying and analysis using the methods outlined in Table 2. Maize cobs were harvested at 86 days. The cobs were measured on several parameters namely cobs length (CL in cm), cobs diameter (CD in cm), cobs weight with husks (CWH in g), and cobs weight without husks (CW in g).

2.5. Statistical Analysis

Analysis of the variance procedure was employed to determine the significance of the treatments (fermentation products, NPK dosage, and their interaction). Should there be any significance, Duncan multiple range tests (DMRT) were employed at a confidence level of 95% (α=0.05). The principal Component Analysis (PCA) procedure was also used to gain a deeper understanding on the data. All statistical analyses were performed on SPSS statistical software package version 25.

Table 3. Characteristics of Liquid and Semi-Solid Products Analyzed Based on Several Chemical and Biological Parameters and Compared to the Minimum Technical Requirements Set by the Indonesian Ministry of Agriculture

No.	Parameters	Unit	LOF	SOF	Technical Requirement*	
					Fertilizer	Soil Conditioner
			Chemical parameters			
1.	Organic - Carbon	%	6.34	41.21	min 10	min 10
2.	pH	-	6.21	6.93	4-9	4-9
3.	Organic - Nitrogen	%	0.54	2.05	min 0.5	-
4.	Total - Nitrogen	%	0.68	3.89		-
5.	Total - P_2O_5	%	0.93	3.54	N+P+K 2-6	-
6.	Total - K_2O	%	0.60	2.78		-
7.	Total - Fe	ppm	26.31	226.52	90-900	Total Fe max. 15000 Available Fe max. 500
8.	Total - Mn	ppm	18.41	468.66	25-500	-
9.	Total - Cu	ppm	23.43	103.24	25-500	-
10.	Total - Zn	ppm	11.70	201.53	25-500	Max 5000
11.	Total - B	ppm	5.34	31.14	12-250	-
12.	Total - Mo	ppm	0.86	5.45	2-10	-
			Additional compound			
13.	Humic Acid	%	1.39	12.31	-	-
14.	Auxin	ppm	0.98	9.79	-	-
15.	Cytokinin	ppm	1.36	10.96	-	-
16.	Gibberellin	ppm	0.64	9.64	-	-
			Biological parameters			
17.	Total Number of Functional Bacteria	cfu ml^{-1}	1.30×10^6	2.80×10^{13}	1×10^7 cfu ml^{-1}	-
18.	Total Number of Fungi	cfu ml^{-1}	3.00×10^4	3.00×10^7	1×10^5 cfu ml^{-1}	-
19.	N-Fixing Bacteria	cfu ml^{-1}	3.70×10^7	3.70×10^{10}	Positive	-
20.	P-Solubilizing Bacteria	cfu ml^{-1}	1.20×10^6	1.20×10^{10}	Positive	-
21.	Solubility in water	%	99.61	88.84	-	-
			Heavy metals			
22.	As	ppm	0.01	1.92	max 5.0	max 5.0
23.	Hg	ppm	0.00	0.00	max 0.2	max 0.2
24.	Pb	ppm	0.02	0.71	max 5.0	max 5.0
25.	Cd	ppm	0.03	0.52	max 1.0	max 1.0
26.	Cr	ppm	0.86	4.29	max 40	max 40
27.	Ni	ppm	0.19	1.57	max 10	max 10

Notes: Product A_1 = liquid Organic Product, Product A_2 = Semisolid Organic Product.
*based on Kementan (2019)

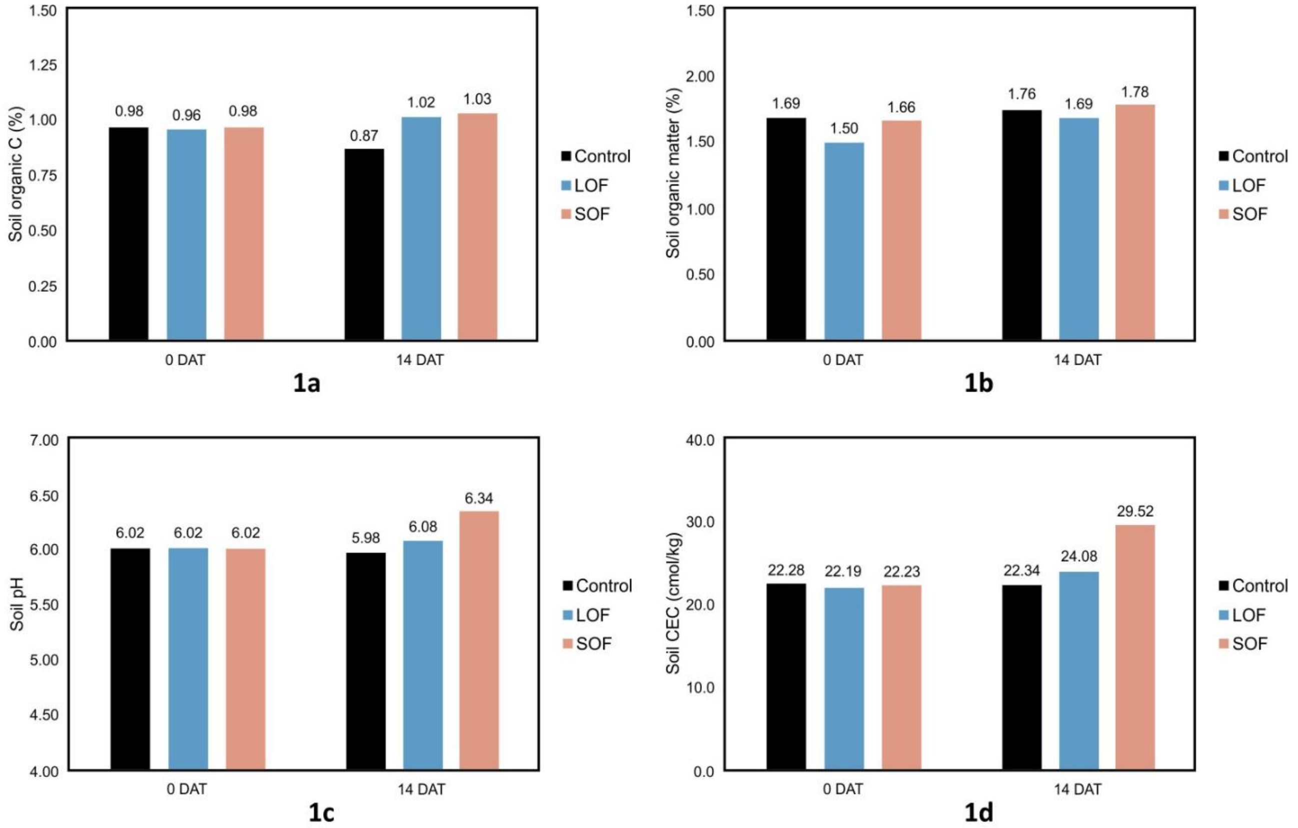

Figure 1. Differences in Soil Organic-C (1a), Soil Organic Matter (1b), pH (1c) and CEC (1d) of various treatments

Notes: The mean values followed by the same letter do not significantly differ based on the DMRT Test at the 5% Level. Lowercase letters are read horizontally, comparing different N-P-K fertilizer doses within the same waste type. Uppercase letters are read vertically, comparing among three different waste types at the same N-P-K dosage.

Table 4. ANOVA Test Results for Soil Parameters under Control, LOF, and SOF Treatments

Parameters	F-statistic	P-value
SOC (%)	2.38	0.24
SOM (%)	6.74	0.072
pH	9.85	0.046*
EC (cmol kg^{-1})	14.12	0.031*

3. RESULTS

3.1. Characteristics of two Fermented Products

The technical evaluation (Table 3) of Liquid Organic Fertilizer (LOF) and Semi-Solid Organic Fertilizer (SOF) highlights notable variations in their chemical and biological properties. SOF contains a higher organic carbon content (41.21%) compared to LOF (6.34%), indicating its greater potential for improving soil organic matter. Both fertilizers maintain a pH within the acceptable range (4-9), making them suitable for most crops. In terms of nutrient composition, SOF provides higher concentrations of organic nitrogen (2.05% vs. 0.54%), total nitrogen (3.89% vs. 0.68%), P_2O_5 (3.54% vs. 0.93%), and K_2O (2.78% vs. 0.60%), all of which comply with the Ministry of Agriculture's technical requirements for organic fertilizers. The assessment of trace elements indicates that SOF contains greater amounts of Fe, Mn, Cu, and Zn, which are essential for plant health. Additionally, SOF offers higher levels of bioactive compounds such as humic acid, auxin, cytokinin, and gibberellin, which contribute to plant growth regulation. The biological properties of SOF reveal a greater presence of functional bacteria (2.80×10^{13} CFU ml^{-1}) and fungi (3.00×10^{7} CFU ml^{-1}), contributing to enhanced soil microbial activity. Furthermore, both fertilizers meet safety criteria for heavy metals, ensuring their suitability for agricultural applications.

3.2. Changes in Soil Carbon, Organic Matter, pH, and Cation Exchange Capacity

The total SOC statistical analysis ($p > 0.05$) indicated that the application of fermented fertilizers did not significantly increase SOC and SOM content (Table 4). However, based on the percentage content classification from the technical guidelines for analysis, the SOF and LOF treatments demonstrated an improvement in classification compared to the control, shifting from "poor" to "low" (Fig. 1a, 1b, and Table 2). On the other hand, SOF significantly increased soil pH (Fig. 1c and Table 4) and CEC (Fig. 1d and Table 4) ($p < 0.05$), although the classification criteria (Table 2) remained within the same range. This study suggests that SOF supplies more organic compounds than LOF, which can contribute to soil fertility. The decomposition of organic matter generates charged organic colloids, leading to an increase in CEC. After 14 days of incubation, soil analysis revealed a significant increase in CEC with the application of semisolid products, indicating that fermented fertilizers effectively enhance soil chemical properties.

Table 5. Statistical Analysis of Nitrogen, Phosphorus, and Potassium Content in Plant Tissues Under Different Treatments

LOF and SOF treatment	N-P-K Treatment			
	a_0	a_1	a_2	a_3
N (%)				
A_0	3.04^{c} B	4.08^{b} B	4.11^{ab} C	4.16^{a} C
A_1	3.36^{c} AB	4.13^{b} AB	4.21^{ab} AB	4.29^{a} B
A_2	3.38^{c} A	4.28^{b} A	4.33^{ab} A	4.40^{a} A
P (%)				
A_0	0.76^{c} C	0.93^{bc} C	1.01^{b} C	1.17^{ab} B
A_1	0.94^{bc} B	1.03^{b} B	1.09^{b} B	1.19^{ab} AB
A_2	1.01^{b} A	1.17^{ab} A	1.21^{a} A	1.20^{a} A
K (%)				
A_0	1.01^{c} C	1.12^{bc} B	1.28^{ab} A	1.30^{ab} A
A_1	1.06^{c} B	1.13^{bc} B	1.31^{a} AB	1.32^{a} AB
A_2	1.11^{bc} A	1.21^{b} A	1.35^{a} A	1.33^{ab} A

Description: The mean values followed by the same letter do not significantly differ based on the DMRT Test at the 5% Level. Lowercase letters are read horizontally, comparing different N-P-K fertilizer doses within the same waste type. Uppercase letters are read vertically, comparing among three different waste types at the same N-P-K dosage.

3.3. Nitrogen, Phosphorus, and Potassium Content on Plant Tissue

The analysis of N, P, and K content in plant tissues (Table 5) revealed significant improvements with the application of SOF compared to LOF and control treatments. SOF consistently resulted in higher nutrient content across all N-P-K treatments. For nitrogen, the highest values were observed in the SOF treatment, ranging from 4.28% to 4.40%, compared to the control group (A0) which exhibited the lowest N content, particularly in the a1 treatment (3.04%). Similarly, phosphorus content was highest in the SOF treatment, peaking at 1.21% in the a3 treatment, while the control group had the lowest values, ranging from 0.76% to 1.17%. Potassium content followed the same trend, with the highest levels found in the SOF treatment (up to 1.35% in the a3 treatment) compared to the control group (A0), which ranged from 1.01% to 1.30%. These results indicate that SOF is more effective in enhancing nutrient uptake by plants due to its higher nutrient concentration (Holland et al., 2020) and improved soil retention properties.

3.4. The Yield Components of Sweet Corn Commodities

The analysis of sweet corn production (Table 6) showed that the application of LOF and SOF significantly improved growth parameters such as cob length, diameter, and weight. Statistical analysis indicated that SOF treatments consistently produced significantly higher values than LOF and the control group. The highest cob length (20.10 cm) was observed in SOF treatment (A_1) with N-P-K level a_3, which was significantly greater than the lowest cob length (17.41 cm) found in the control (A_0, a_0). Similarly, cob diameter was maximized (5.35 cm) under SOF treatment (A_1, a_3), showing a significant improvement over the control (3.78 cm, A_0, a_0). Weight analysis showed a notable increase in cob weight with husk, with the highest weight (728 g) recorded in SOF treatment (A_2, a_3), while the lowest (437 g) was found in the control (A_0, a_0). Likewise, the weight of cob without husk was significantly higher (570 g) in SOF treatment (A_2, a_3), compared to the lowest (309 g) in the control (A_1, a_0). The increase in cob weight, with or without husk, under SOF treatments indicates a more favorable growth environment. These results suggest that the application of SOF is more effective in enhancing growth parameters and sweet corn yield compared to LOF and the control.

3.5. Principal Component Analysis

3.5.1. PCA Biplot

The performance of inorganic and organic fertilizer combination treatment to all parameters by PCA biplot was shown in Figure 4. PCA showed that 75 % N-P-K combined with liquid compost resulted in higher N uptake and maize yield, followed by 100 % N-P-K combined with solid compost with higher K uptake and high maize yield compared with other treatments.

Table 6. Statistical Analysis Data on Sweet Corn Production Differences Across Various Treatments

Liquid & Semisolid Product	N-P-K Treatment			
	a_0	a_1	a_2	a_3
	Cob Length (cm)			
A_0	17.41^{b} C	18.25^{ab} B	17.83^{b} B	18.02^{ab} B
A_1	17.65^{b} C	18.80^{ab} BC	19.96^{ab} A	20.10^{a} A
A_2	17.49^{b} C	18.41^{ab} B	19.80^{ab} A	20.03^{a} A
	Cob Diameter (cm)			
A_0	3.78^{c} C	4.25^{bc} B	4.11^{bc} B	4.34^{bc} B
A_1	4.28^{bc} B	4.41^{bc} AB	4.27^{bc} B	5.35^{a} A
A_2	5.28^{ab} A	4.78^{b} AB	5.25^{ab} A	5.11^{ab} A
	Weight of Cob with Husk (gram)			
A_0	437^{d} D	503^{c} C	671^{b} AB	718^{ab} A
A_1	479^{cd} D	594^{bc} C	707^{ab} AB	721^{a} A
A_2	481^{cd} C	617^{b} B	723^{a} A	728^{a} A
	Weight of Cob without Husk (gram)			
A_0	311^{d}	393^{c}	489^{bc}	493^{bc}
A_1	309^{d}	406^{c}	518^{bc}	530^{bc}
A_2	317^{d}	481^{bc}	563^{b}	570^{a}

Description: The mean values followed by the same letter do not significantly differ based on the DMRT Test at the 5% Level. Lowercase letters are read horizontally, comparing different N-P-K fertilizer doses within the same waste type. Uppercase letters are read vertically, comparing among three different waste types at the same N-P-K dosage.

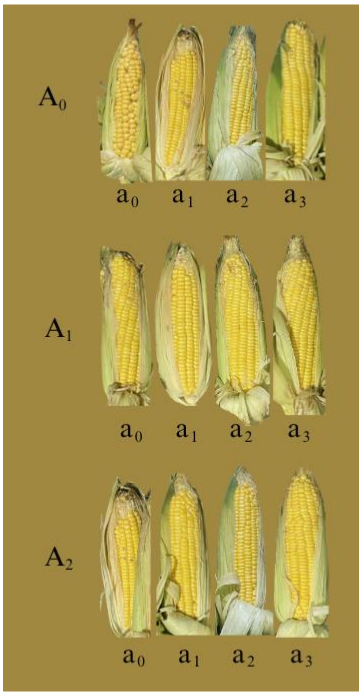

Figure 2. Visual appearance of the yield

The addition of solid compost at 50% and 75% rate of N-P-K increased the uptake of K and P of plant, similar to 100 % N-P-K rate. Treatments without N-P-K fertilizer had the lowest maize yields despite the addition of liquid or solid compost. The best treatment in this study was a combination of liquid compost, solid compost and N-P-K fertilizer. Adding liquid and solid compost can reduce N-P-K fertilizer usage by 25 % while maintaining optimal yields.

3.5.2. Parameter Contribution Based on Variable Effect

The correlation matrix in Figure 4 highlights the relationship between nutrient uptake (N, P, and K) and crop yield. The results indicate a strong positive correlation between nitrogen uptake ($r = 0.90$) and yield, suggesting that increased nitrogen absorption is associated with higher crop productivity. Similarly, potassium uptake ($r = 0.96$) exhibits a very strong correlation with yield, demonstrating its crucial role in plant growth and development. Phosphorus uptake ($r = 0.85$) also shows a significant correlation with yield, albeit slightly lower than nitrogen and potassium. These findings suggest that nutrient uptake, particularly of nitrogen, potassium, and phosphorus, is directly linked to yield performance. The strong interrelationships among these nutrients indicate their collective influence on plant growth and productivity.

4. DISCUSSION

The main findings of this study reveal the advantage of the semi-solid product. This product performed better than the liquid product, as evidenced by its enhanced chemical and biological characteristics as shown in Table 3 and this is in line with the explanation by Zubair et al. (2020), along with its significant impact on several soil properties (Fig. 1a-1d) and sweet corn production parameters (Table 6). The fermentation process of semi-solid organic waste enhances nutrient concentration by breaking down and decomposing organic materials, resulting in higher nutrient levels compared to liquid organic fertilizers (Mashur et al., 2021; Walling et al., 2019). Microorganisms play a crucial role in decomposing organic matter into nutrient-rich substances (Bernal et al., 2017), and this process is more efficient in semi-solid products, where water content is significantly reduced during fermentation (Allaily et al., 2022). As water evaporates or is removed through decomposition (Agegnehu et al., 2021), nutrients in the semi-solid organic fertilizer (SOF) become more concentrated, unlike in liquid organic fertilizer (LOF), which retains higher water content and lower nutrient density. This nutrient concentration allows SOF to contribute more significantly to soil health compared to LOF (Bhuvaneshwari et al., 2019; López-Cano et al., 2018). This is consistent with the research by Chew et al. (2019) and Lin et al. (2019), which states that the macro and micronutrient content in liquid organic fertilizers is lower than in semi-solid products.

The high content of cellulose, hemicellulose, lignin, proteins, and lipids in organic waste, such as plant residues, contributes to the increase in organic matter and soil organic carbon (SOC) when these materials are processed into SOF (Bhuvaneshwari et al., 2019; López-Cano et al., 2018). During decomposition, organic base complexes are formed, which help neutralize soil acidity and increase soil pH. Additionally, the increased microbial activity during decomposition generates alkaline compounds that enhance cation exchange capacity (CEC) by forming complexes with metal cations (Sulok et al., 2021). Improved soil structure and fertility are key factors that make SOF more effective in increasing SOC, organic matter, pH, and CEC compared to LOF (Sayara et al., 2020). The higher nutrient concentration in SOF results in better nutrient availability for plants (Chew et al., 2019; Lin et al., 2019), directly affecting the absorption and accumulation of nutrients in plant tissues. Sweet corn plants treated with SOF showed higher uptake (Table 5) of N, P (Jindo et al., 2020; Sadji-Ait Kaci et al., 2017), and K (Kabdaşlı et al., 2022), as reflected in the nutrient content of plant tissues (Gao et al., 2020; Liu et al., 2019). This improved nutrient availability is the result of greater organic matter content (Ali et al., 2020) and the improved soil properties (Chavez-Rico et al., 2023). The total SOC analysis indicated that fermented fertilizer treatments increased SOC content, with the SOF product showing slightly higher SOC levels than LOF (Fig. 1). Additionally, the fermented fertilizers improved soil pH and

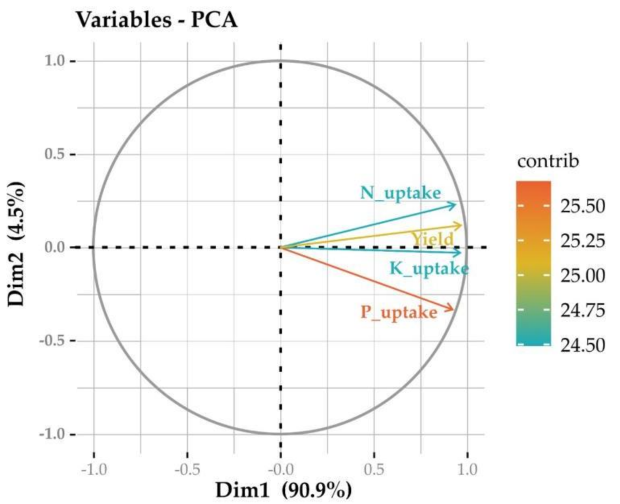

Figure 3. Dependent variable contribution affected by treatment

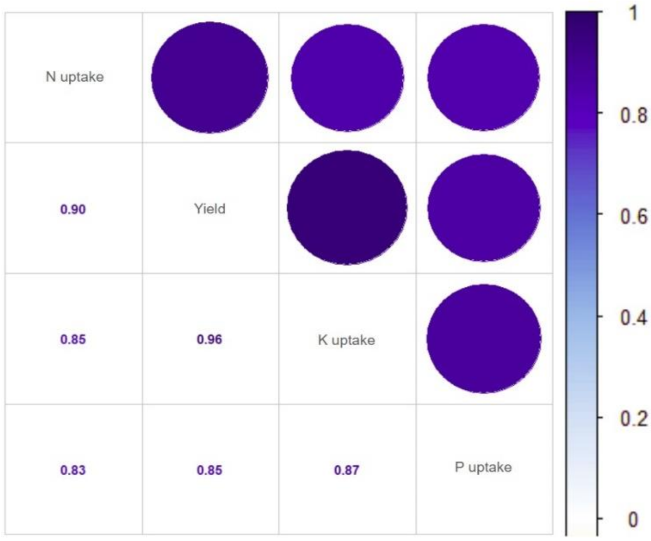

Figure 4. Correlation between observed parameters

cation exchange capacity (CEC). Our study demonstrated that SOF provided more nutrients than LOF. The decomposition of organic matter generates charged organic colloids, enhancing CEC. After a fourteen-day incubation, soil analysis revealed a significant increase in CEC with the application of semisolid products, suggesting that fermented fertilizers effectively enhance soil chemical properties (Mashur et al., 2021; Walling et al., 2019) provided by SOF, particularly the increased CEC, and pH, which support more efficient nutrient cycling and retention in the soil (Brust, 2019; Sayara et al., 2020).

The increased productivity observed in sweet corn treated with SOF can be attributed to the higher nutrient concentration, which improves soil structure and nutrient availability. The nutrient-rich environment created by SOF supports more efficient nutrient uptake (Zandvakili et al., 2019). This is due to the high buffering properties of organic materials and the humus content which is beneficial for improving soil properties Jamilah et al. (2023), leading to enhanced growth parameters such as cob length, diameter, and weight (Table 6) as well as better visual appearance of the corn cobs (Fig. 2). The superior performance of SOF compared to LOF and the control group demonstrates that the semi-solid form of fermented organic fertilizer is more effective in promoting plant growth and productivity (Gao et al., 2020; Liu et al., 2019). Furthermore, SOF aligns with sustainable agricultural practices by reducing the need for inorganic fertilizers and minimizing the environmental impact (Brust, 2019).

Principal component analysis (PCA) of various growth and soil parameters further supports SOF's contribution to sweet corn productivity (Fig. 3). This analysis highlights the key role of nutrient availability, SOC, CEC, and pH in improving yield components, with SOF showing the greatest effect (Fig. 2). The PCA biplot illustrates the clustering of SOF-treated plants based on these enhanced parameters (Fig. 3), reinforcing the effectiveness of SOF as an organic amendment. Additionally, SOF's ability to provide slow-release nutrients and promote beneficial soil microorganisms contributes to its superior performance in improving soil health and crop yield (Gao et al., 2020; Qiao et al., 2019). Overall, the use of fermented organic waste products, particularly in semi-solid form, significantly improves soil chemical properties and sweet corn productivity. SOF not only increases nutrient availability but also supports sustainable agricultural practices, offering an effective alternative to conventional fertilizers (Hua et al., 2018; Muktamar et al., 2018). Through its ability to improve soil health indicators such as SOC, organic matter, pH, and CEC, SOF proves to be a valuable tool in enhancing agricultural productivity while minimizing environmental impact.

5. CONCLUSION

This study demonstrates that the application of semi-solid organic waste fermentation products significantly improves soil chemical properties and sweet corn productivity. Compared to liquid organic fertilizers, the semi-solid product exhibited a higher concentration of organic carbon (41.21% vs. 6.34%), total nitrogen (3.89% vs. 0.68%), phosphorus (3.54% vs. 0.93%), and potassium (2.78% vs. 0.60%). These improved nutrient compositions contributed to increased soil pH, cation exchange capacity (CEC), and microbial activity, thereby enhancing soil fertility. Field trials confirmed that sweet corn treated with the semi-solid product showed a yield increase of 47.62% compared to the control, with the highest cob weight recorded at 570 g without husk and 728 g with husk, significantly outperforming both the control and liquid organic fertilizer treatments. The semi-solid product also improved nitrogen, phosphorus, and potassium uptake in plant tissues, which is crucial for crop growth and productivity. These findings emphasize the valuable role of the semi-solid fermentation product in not only improving soil health but also serving as a natural fertilizer, offering farmers a sustainable and effective alternative to conventional fertilizers. By transforming organic waste into a powerful agricultural resource, this approach supports both higher crop productivity and environmental sustainability. Further research is essential to understand how this organic fertilizer performs over time across different crops and soil conditions, ensuring its broad applicability and long-term benefits for farmers and the ecosystem.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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