CHARACTERISTICS OF LIQUID WASTE-DERIVED ORGANIC FERTILIZER ENRICHED WITH OIL PALM EMPTY FRUIT BUNCHES ASH THROUGH ANAEROBIC FERMENTATION

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Abstract: Palm oil mill effluent (POME) is an organic waste with high levels of BOD, N, P, K, and Mg. Its presence in rivers and soil has led to pollution and negative impacts on the environment. One potential solution to this issue is transforming POME into a valuable liquid organic fertilizer (LOF). This study aims to evaluate the characteristics of LOF derived from POME-derived LOF enriched with oil palm empty fruit bunches (OPEFB) ash through anaerobic fermentation. A 3.5 L of POME and molasses (5% v/v) were introduced into the anaerobic reactor. OPEFB ash was then added at concentrations of 0.35%, 0.46%, and 0.57% w/v. Fermentation was conducted for 5, 8, and 11 days, and Effective Microorganisms (EM4) with concentrations of 1% and 2% v/v were employed to accelerate LOF formation. The evaluation of LOF involved testing its physical characteristics (color, smell, gas, foam, temperature, and EC), fertilizer chemistry (pH, C-organic, Nitrogen, P_2O_5, and K_2O), and biological aspects (contaminant bacteria *E. coli*). The results of the physical observations indicated that all LOF variations had fully fermented after 11 days, characterized by the presence of an alcohol-like odor, brownish color, absence of foam, and gas bubbles. Chemical tests revealed that LOF B2 and LOF A1, fermented for 8 days, exhibited the highest levels of N, P, and K, which were 0.08%, 0.05%, 1.26% for LOF B2, and 0.085%, 0.023%, 1.24% for LOF A1, respectively. Furthermore, the test result for *E. coli* in the LOF B2 and LOF A1 samples after 8 days of fermentation indicated that the *E. coli* level was below 3 MPN per mL. This confirms that the obtained LOF meets the minimum technical requirements specified in the Minister of Agriculture Regulation of the Republic of Indonesia. Therefore, the LOF is suitable for industrial-scale production and application in the agricultural sector.
Keywords: liquid organic fertilizer; anaerobic fermentation; POME; OPEFB ash

Abstrak: Limbah Cair Pabrik Kelapa Sawit (POME) merupakan limbah organik dengan kadar BOD, N, P, K, dan Mg yang tinggi. Kehadirannya di sungai dan tanah telah menyebabkan pencemaran dan memberikan dampak negatif terhadap lingkungan. Untuk mengatasi masalah ini, salah satu solusi potensial adalah mengubah POME menjadi pupuk organik cair (POC) yang bernilai tambah. Penelitian ini bertujuan untuk mengevaluasi karakteristik POC dari POME setelah penambahan abu Tandan Kosong Kelapa Sawit (TKKS) dengan metode fermentasi anaerob. Sebanyak 3,5 L POME dan tetes tebu (5% v/v) dimasukkan ke dalam reaktor anaerobik. Kemudian ditambahkan abu

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TKKS dengan konsentrasi 0,35%; 0,46%; dan 0,57% b/v. Fermentasi dilakukan selama 5, 8, dan 11 hari, dan *Effective Microorganism* (EM4) dengan konsentrasi 1% dan 2% v/v digunakan untuk mempercepat pembentukan POC. Evaluasi POC meliputi pengujian sifat fisik (warna, bau, gas, buih, suhu, dan EC), kimia pupuk (pH, C-organik, Nitrogen, P_2O_5, dan K_2O), dan aspek biologi (bakteri pencemar *E. coli*). Hasil pengamatan fisik menunjukkan bahwa semua variasi POC telah terfermentasi sempurna setelah 11 hari, ditandai dengan adanya bau alkohol, warna kecoklatan, tidak adanya buih dan gelembung gas. Uji kimia menunjukkan bahwa POC B2 dan POC A1 yang difermentasi selama 8 hari menunjukkan kadar N, P, dan K tertinggi berturut-turut, yaitu 0,08%; 0,05%; 1,26% untuk POC B2; dan 0,085%; 0,023%; 1,24% untuk POC A1. Selanjutnya, hasil pengujian *E. coli* pada sampel POC B2 dan POC A1 dengan lama fermentasi 8 hari menunjukkan bahwa kadar *E. coli* di bawah 3 MPN per mL sehingga POC yang diperoleh telah memenuhi persyaratan teknis minimum (PTM) berdasarkan Peraturan Menteri Pertanian No. 261 Tahun 2019.

Kata kunci: Pupuk Organik Cair; Fermentasi Anaerob; POME; Abu TKKS

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Introduction

With a vast land area of 14.59 million hectares in 2020, oil palm cultivation dominates Indonesia's agricultural landscape, propelling the country to its position as the world’s leading producer of crude palm oil (CPO). Statistics Indonesia forecasts Indonesia’s CPO production to reach an impressive 44.76 million tons in 2021 (Badan Pusat Statistik, 2020). The robust growth of the Indonesian palm oil industry also brings about significant quantities of solid waste and biomass, encompassing oil palm empty fruit bunches (OPEFB) (21–23%), palm shells (5–7%), fiber (12–15%), and diverse plant residues such as branches, stems, and leaves (Arfiana et al., 2021). Furthermore, this industry generates notable amounts of palm oil sludge (4%) and palm oil mill effluent (POME), constituting approximately 50% of the waste composition (Cheau Chin et al., 2020; Susanto, Santoso, & Suwedi, 2017; Tabassum, Zhang, & Zhang, 2015).

POME is an organic waste resulting from the processing of fresh fruit bunches (FFB) into crude palm oil (CPO). It comprises a mixture of water (85–95%) (Dominic & Baidurah, 2022; Madaki & Seng, 2013), oil, and solids, and is characterized by its acidic nature and unpleasant odor (Loh, Lai, & Ngatiman, 2019). In the anaerobic pond I, the biological oxygen demand (BOD) levels of POME typically range from 7,333 to 20,147 mg/L (Elfidiah & Roni, 2019; Faisal, Machdar, Gani, & Daimon, 2016; Nursanti, 2013). The processing of FFB into CPO has relied on an open ponding system, primarily due to considerations of cost-effectiveness and operational feasibility.

The unregulated discharge of POME into rivers and land without adequate treatment has led to significant environmental pollution and adverse impacts. These include the disappearance of diverse aquatic organisms, soil acidification, eutrophication, and the emission of unpleasant odors (Yuwono et al., 2015). Previous studies have indicated that POME treated using an anaerobic pond system exhibits BOD levels exceeding 5,000 mg/L. Furthermore, it contains substantial concentrations of organic compounds, as well as essential nutrients such as carbon (C), nitrogen (N), phosphorus (P), and potassium (K) (Abdullah, Md Jahim, Abdul, & Mahmod, 2020; Aznury, Jaksen, Hasan, & Putri Dila, 2018; Dominic & Baidurah, 2022; Maharani, Pamoengkas, & Mansur, 2017; Pujono, Kukuh, Evizal, Afandi, & Rahmat, 2021).

Various solutions have been proposed to mitigate the negative impact of POME. These include converting POME into bio-slurry, harnessing it for biogas production, and transforming it into a value-added product in the form of liquid organic fertilizer (LOF) using the fermentation method. Fermentation methods have demonstrated the ability to eliminate the unpleasant odor associated with POME and impart a desirable *tapai* aroma (Elfidiah, Dedik, Faizal, & Salni, 2012; Tsaniya, Dewi, & Anggo, 2021). However, processing POME into biogas presents challenges due to high production costs and the need for complex equipment. On the other hand, the conversion of POME into LOF offers a more cost-effective solution, aligning with the principles of fermentation. Notably, LOF has the potential to remediate soil damage caused by excessive reliance on chemical fertilizers.

Numerous recent studies have documented various approaches to obtaining LOF from organic-rich materials. For instance, Yerizam et al., 2022 combined *Muntingia Calabura L.* leaves with eggshell waste, Faisal, 2017; Hartini et al., 2018 utilized tofu waste, Wu et al., 2023 explored vegetable waste, Rahmah et al., 2022 focused on coffee waste, while Garritano et al., 2018 investigated solid waste from palm oil mills, namely OPEFB ash, and palm oil mill liquid waste. The utilization of agricultural biomass as fertilizer has gained considerable attention by modifying raw materials, employing both aerobic and anaerobic fermentation methods, and selecting suitable decomposing microorganisms (Fitriyanto et al., 2019) to achieve optimal fertilizer characteristics. Anaerobic fermentation, in particular, offers advantages such as higher nutrient production (Sastro, Bakrie, & Sudolar, 2013) and faster fermentation time (Wignyanto & Hidayat, 2017). Given its organic compound-rich composition, POME exhibits potential (Elfidiah & Roni, 2019; Hau et al., 2020). However, using POME alone without the addition of OPEFB ash as a raw material for liquid organic fertilizer production is deemed ineffective due to insufficient K and P content in the resulting LOF product (0.337% and 0.207%) (Elfidiah et al., 2012; Mulia Raja, Giyanto, & Barus, 2021). Notably, OPEFB ash is recognized for its high P and K content (Arfiana et al., 2019, 2021), offering a viable solution for enhancing P and K levels in fertilizers.

Therefore, it is crucial to find a suitable solution for reducing the volume of POME present in anaerobic ponds with BOD levels exceeding 5,000 mg/L. This reduction is essential to enable the recycling of POME into a valuable product known as LOF, utilizing the anaerobic fermentation method. The objective of this study is to assess the characteristics of LOF derived from POME after incorporating OPEFB ash through anaerobic fermentation, facilitated by the use of Effective Microorganism (EM4).

Material

The materials employed in the production of liquid organic fertilizer consisted of POME, OPEFB ash, molasses, and EM4. POME was sourced from the anaerobic pond treatment waste of continuous system I, and it was estimated to have a BOD value exceeding 5,000 mg/L.

Methods

Fermentation setup

The schematic design of the fermentation setup is presented in Figure 1.

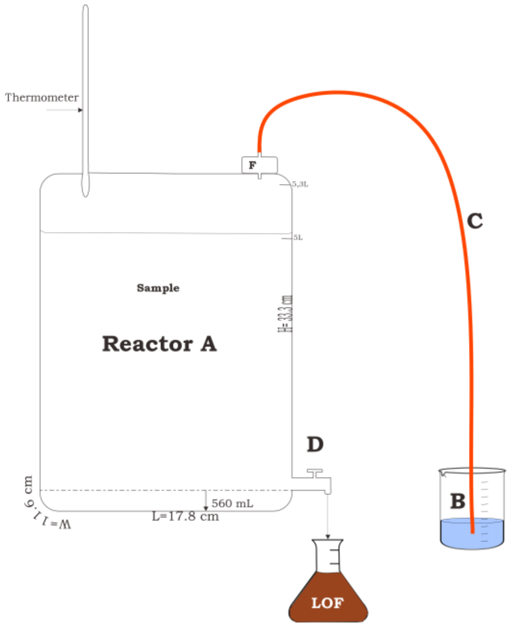

Figure 1. Fermentation setup

Note :

A: 5L-reactor, measuring 33.3cm × 11.6cm × 17.8cm
B: A beaker filled with 500 mL water
C: ½ inch aerator tube
D: LOF sampling tap
E: LOF sample

Preparation of Liquid Organic Fertilizer

Three reactors were used, with each reactor receiving 3.5 L of POME. The composition of each reactor consisted of 175 mL of molasses (5%), which was then varied with OPEFB ash at concentrations of 0.35%, 0.46%, and 0.57% w/v. Additionally, EM4 was added at concentrations of 1% and 2% v/v. The mixture was then left to ferment for 5, 8, and 11 days. The resulting liquid fertilizer was then analyzed in terms of its physical characteristics such as color, gas bubbles, odor, temperature, and EC. Additionally, the biological aspect was examined, specifically the presence of Escherichia coli (*E. coli*) bacteria as a contaminant. This analysis was performed on the sample exhibiting the highest quality, obtained using variations of 1% v/v EM4 and 2% v/v EM4. Furthermore, chemical parameters including pH, C-organic, total nitrogen, P_2O_5, and K_2O in the product were also assessed.

Analysis of POME and OPEFB Ash

The C-organic content was determined using the Walkley-Black method, nitrogen levels were analyzed using the Kjeldahl method, and phosphorus content was measured as P_2O_5 using a UV-Vis spectrophotometer (Shimadzu UV 2700). Potassium (K_2O) levels were measured using an Atomic Absorption Spectrophotometer (Shimadzu AA 7000 with a flame photometer). Additionally, biological testing was conducted to assess the presence of *E. coli* contaminants using the Most Probable Number (MPN) method. The specific references used for testing C-organic, N, P, K, and *E. coli* were FAO point 8.1, AOAC 2.4.03 point 995.04, SNI 2803-2012 point 6.3, SNI 2803-2012 point 6.4.2, and SNI 01-2897-1992 point 3.1, respectively.

Results and Discussion

Characteristics of POME and OPEFB Ash

Preliminary analysis results indicate that POME is abundant in organic matter and exhibits high concentrations of C-organic, N, P, and K, measuring 0.63%, 0.121%, 0.014%, and 0.3%, respectively, with an acidic pH of 5.4. POME is also known for its unpleasant odor (Faisal et al., 2016; Mohammad et al., 2021). On the other hand, OPEFB ash has initial levels of 1.78%, 0.06% N, 1.88% P, and 14.35% K. The ash has a moisture content of 10.83% and an alkaline pH of 11.30. Other studies have reported lower levels of C-organic and K, with 0.55% for the C-organic parameter (Adjei-Nsiah, 2012) and 15.67% for the potassium (Hau et al., 2020).

Characteristics of LOF

Physical characteristics

Physical observations play a crucial role in assessing the maturity level of fertilizer and evaluating the success of the fermentation process. These observations involve assessing various physical characteristics, including color, odor, and the presence or absence of gas bubbles and foam, as well as monitoring fertilizer temperature and EC values.

Table 1. Physical characteristics of the LOF

LOF Variations	Physical Characteristics	Fermentation Time (day)			
		0	5	8	11
A1	Color	-	--	--	---
	Smell	***	**	**	**
	Gas	+	++	++	-
	Foam	●●	●	●	●●
B1	Color	-	---	---	--
	Smell	***	**	**	**
	Gas	-	+	+	-
	Foam	●●	●	●	●●
C1	Color	-	--	--	---
	Smell	***	**	**	**
	Gas	-	+	+	-
	Foam	●●	●	●	●●
A2	Color	-	--	---	---
	Smell	***	**	**	**
	Gas	-	+	+	-
	Foam	●●	●	●	●●
B2	Color	-	--	--	---
	Smell	***	**	**	**
	Gas	-	+	+	-
	Foam	●●	●	●	●●
C2	Color	-	--	---	---
	Smell	***	**	**	**
	Gas	-	+	+	-
	Foam	●●	●	●	●

Note:

LOF A1 : EM4 1% v/v + OPEFB ash 0.35% w/v
LOF B1 : EM4 1% v/v + OPEFB ash 0.46% w/v
LOF C1 : EM4 1% v/v + OPEFB ash 0.57% w/v
LOF A2 : EM4 2% v/v + OPEFB ash 0.35% w/v
LOF B2 : EM4 2% v/v + OPEFB ash 0.46% w/v
LOF C2 : EM4 2% v/v + OPEFB ash 0.57% w/v
Color : - jet black; -- dark brown; --- light brown;
Smell : * smelly (of methane gas); ** fermented aroma; *** POME odor;
Gas : - no bubble; + few bubbles; ++ many bubbles;
Foam : ● foamy; ●● not foamy

Color, smell, gas bubbles, and foam

Table 1 shows the physical characteristics of the fertilizer produced by the 11th day of fermentation for each variation of OPEFB ash and EM4. The observed changes include a transition in color from jet black to light brown, accompanied by a distinct fermentation smell resembling alcohol and the presence of foam. The development of this typical fermentation aroma indicates the maturity of the LOF (Hau et al., 2020; Sundari, Sari, & Rinaldo, 2012; Tsaniya et al., 2021). The formation of foam is attributed to the decomposition of organic compounds into inorganic substances facilitated by the microorganisms present in EM4, which have proven to be effective in the fermentation of organic matter (Jassey et al., 2022; Widowati, Hartatik, & Trisnawati, 2022). As the Minister of Agriculture Regulation No. 261/2019 does not specify parameters for fertilizer maturity regarding color, smell, gas bubbles, and foam, the researchers expanded on these physical aspects by referring to the 2004 SNI standards related to compost maturity (Badan Standardisasi Nasional, 2004). Figure 2 provides a visual representation of the physical characteristics of the LOF.

Figure 2. The final LOF product

LOF Temperature

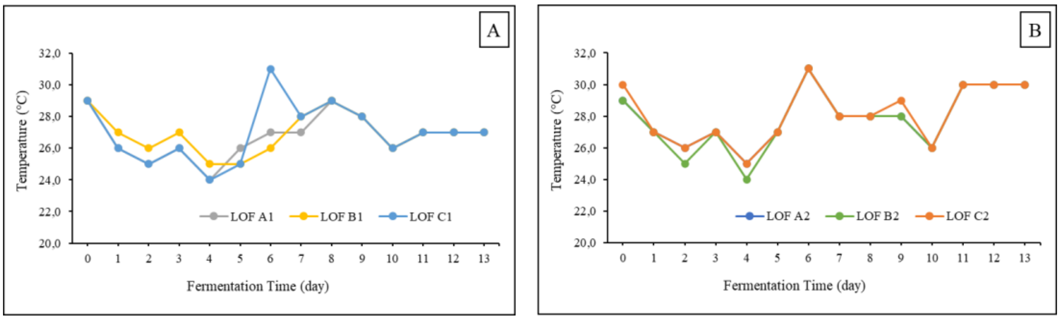

Figure 3. Temperature changes during fermentation (A) 1% EM4; (B) 2% EM4

Figure 3 illustrates the temperature fluctuations of the LOF throughout the fermentation process, ranging from 24–31°C. The observed increase in reactor temperature indicates the activity of decomposer microorganisms present in EM4, which contribute to the decomposition of organic materials. These temperature conditions align with the optimal range for mesophilic bacteria, which thrive and reproduce within temperatures of 15–45°C, with an optimal temperature range of 25–35°C (Dyah & Srikandi, 2017).

Electrical Conductivity (EC)

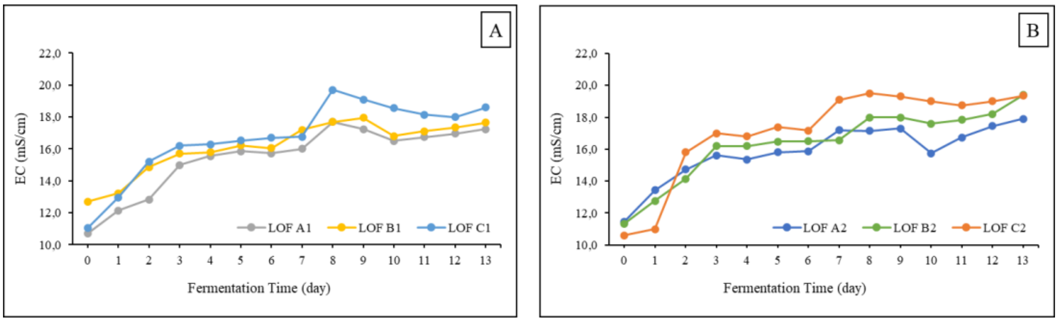

Figure 4. Effects of fermentation time on EC (A) 1% EM4; (B) 2% EM4

Figure 4 illustrates the trend of EC in LOF with varying additions of OPEFB ash over the course of fermentation. It exhibits a substantial increase during the initial phase of fermentation, reaching values ranging from 10.60 to 19.70 mS/cm. The highest EC value was observed in LOF C2 on day 8 (D8) of fermentation. Subsequently, the EC experienced a drastic increase on D3, followed by a more stable phase on D4 to D6 of fermentation. The EC values showed significant fluctuations throughout the rest of the fermentation. It is noteworthy that all LOFs exhibited exceptionally high EC values, whereas good-quality liquid organic fertilizers typically have EC values below 20 dS/m (Phibunwatthanawong & Riddech, 2019).

Chemical characteristics

Overall, the resulting fertilizer exhibited NPK content ranging from 1.088% to 1.377%, indicating higher levels of NPK nutrients compared to various fermented products derived from different raw materials. For instance, fermented products from bananas contained 0.866% NPK (Indrawati et al., 2020), while *Muntingia calabura L.* leaves combined with eggshells yielded 1.2% NPK (Yerizam et al., 2022). Fermentation of sugarcane leaves, molasses, and distillation residues resulted in NPK levels of 1.16%–1.306% (Phibunwatthanawong & Riddech, 2019), and commercial LOF available in the market typically contain 0.46% NPK (Husin, 2012). Moreover, the NPK levels obtained in this study surpassed those of POME-based LOF fermented using Indigenous bacteria (Elfidiah et al., 2012).

pH profile

The LOF obtained from different additions of OPEFB ash with 1% and 2% EM4 concentrations exhibited alkaline pH values ranging from 7.78 to 7.92. Initially, the pH of the LOF experienced a significant decrease during the early stages of fermentation (Nadirah, Awal, Azma, & Sulaiman, 2019). This decline indicates the involvement of microorganisms in the fermentation process, leading to the breakdown of organic matter into organic acids (Kurniawan, Jalaluddin, &

Pulungan, 2022). Subsequently, the pH went through a phase of fluctuation from day 4 to day 9 before stabilizing on the 10th day of fermentation. Figure 5 illustrates the pH range of the LOF, which varied from 7.92 to 4.82. The reported pH values align with the quality standard for LOF, which falls within the range of 4–9.

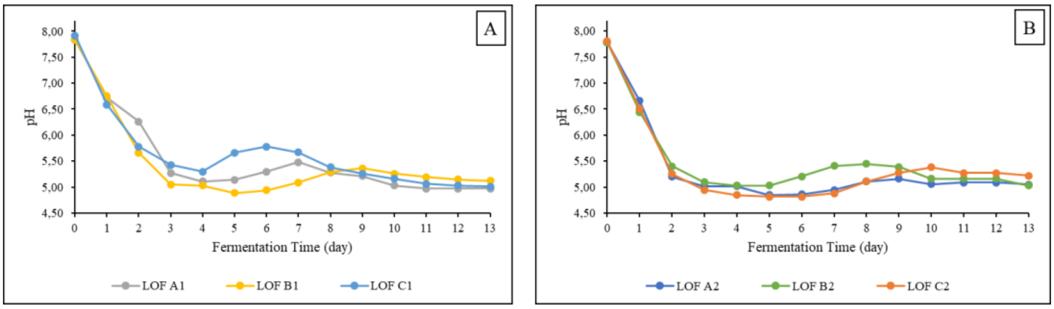

Figure 5. Effects of fermentation time on pH (A) 1% EM4; (B) 2% EM4

C-organic

The C-organic content of the LOF obtained in this study ranged from 1.27% to 1.82% (Figure 6). The highest C-organic content was observed in LOF A2, which reached 1.82% after an 11-day fermentation. In general, the C-organic content showed an increasing trend on D8 of the fermentation process, except for LOF A2 and LOF C1 variations. The fluctuations in C-organic content in LOF A1 and LOF C1 variations suggest that the fermentation process may not have been completed. As microorganisms perform fermentation, they utilize C-organic as a source of energy and nutrition, resulting in its conversion into carbon dioxide (CO_2) and subsequent loss to the air (Phibunwatthanawong & Riddech, 2019).

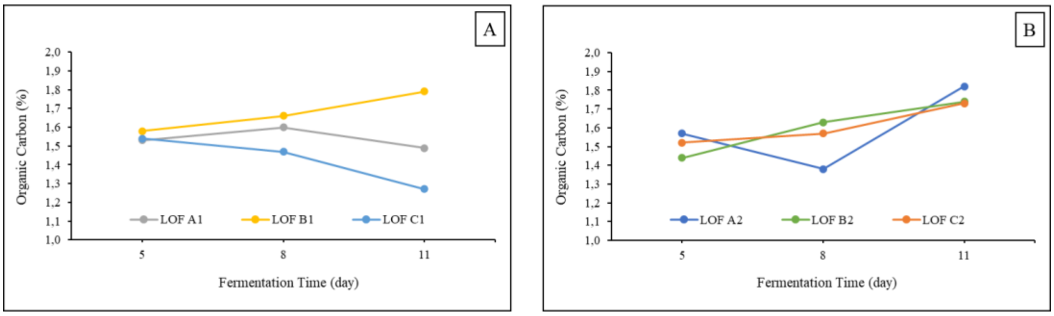

Figure 6. Effects of fermentation time on C-organic levels (A) 1% EM4; (B) 2% EM4

Total Nitrogen (TN)

The analysis results indicated that the highest nitrogen content was observed in LOF A1 and C1 at fermentation times of 8 and 5 days, respectively, with a concentration of 0.09%. Similarly, LOF B1 and LOF A2 exhibited the highest TN on the 11-day fermentation, also at a level of 0.09%. Conversely, in the case of LOF B2 and C2 variations, the TN value remained constant from the 5th, 8th, to 11th day, with 0.08% concentration (Figure 7). Generally, the TN of LOF decreased as the fermentation progressed, except for LOF B1 and A2. This decline is attributed to the microbial decomposition of organic nitrogenous material during the fermentation, leading to a decrease in N content (Phibunwatthanawong & Riddech, 2019).

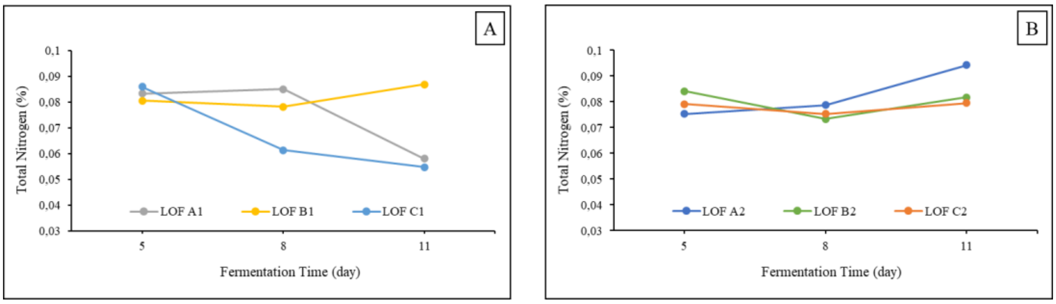

Figure 7. Effects of fermentation time on N-total (A) 1% EM4; (B) 2% EM4

C/N Ratio

The minimum technical requirements (MTR) of fertilizer do not explicitly specify the C/N ratio. However, the C/N ratio plays a crucial role in assessing the maturity level of fermented LOF. For granular organic fertilizer, the recommended C/N ratio is less than 25% (see Figure 8). A mature LOF is characterized by a low C-organic value, indicating that the organic matter degradation process is nearing its final stage and the nutrients are readily available for plants.

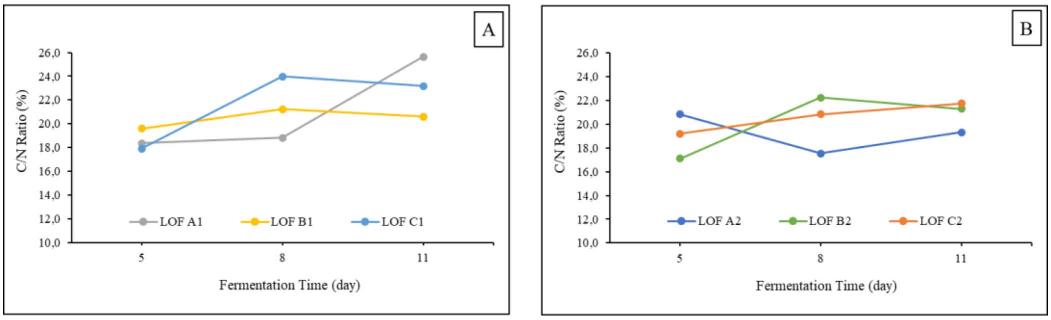

Figure 8. Effects of fermentation time on C/N ratio (A) 1% EM4; (B) 2% EM4

Figure 8 shows that the C/N levels of the LOF samples obtained from the six OPEFB ash variations were determined through calculations, ranging from 17.11% to 25.4%. These values are close to the ideal C/N ratio for soil (Lussy, Walunguru, Kristofel, & Hambamarak, 2017). The varied C/N ratios indicate differences in the LOF fermentation process. A higher C/N ratio (>30%) suggests a longer fermentation process, as it indicates a nitrogen deficiency in the microbial activity, while a low C/N ratio (<20%) can lead to rapid substrate degradation, resulting in the formation of ammonia and the loss of nitrogen content through volatilization (Phibunwatthanawong & Riddech, 2019; Rahmawati, Asriany, & Hasan, 2020).

Phosphorus as P_2O_5

Figure 9 shows that the phosphorus levels in the LOF ranged from 0.01% to 0.05%, with the highest levels observed on day-8 of fermentation. The P content exhibited fluctuations during the fermentation, indicating dynamic changes. This can be attributed to the activity of lactic acid solubilizing bacteria, phosphate solubilizing bacteria, and fungi present in EM4, which contributed to accelerated fermentation. However, on day 11 of fermentation, the P levels in the LOF decreased. This might be attributed to the bacterial utilization of P as an energy source, as reported by previous studies (Hastuti, Astuti, & Hadi, 2022; Tangguda, Valentine, Hariyadi, & Sudiarsa, 2022; Widyabudiningsih et al., 2021).

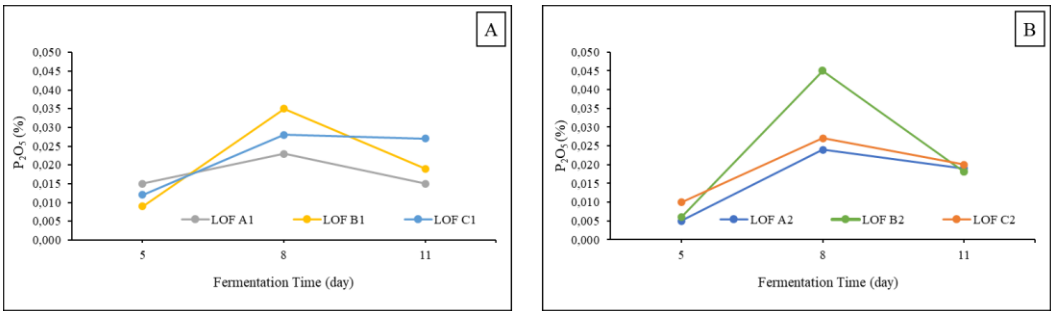

Figure 9. Effects of fermentation time on phosphorus levels (A) 1% EM4; (B) 2% EM4

Potassium as K_2O

The potassium levels in the fertilizer produced in this study ranged from 1.01% to 1.26%. As shown in Figure 10, the potassium compounds, represented as K_2O, initially increased on day 8 of fermentation and continued to increase until day 11, except for samples LOF A1 and LOF B2, which showed a decrease. The addition of OPEFB ash in this study was found to enhance the levels of K_2O, consistent with previous research findings (Arfiana et al., 2019, 2021). The K_2O compound present in the LOF is essential for plant growth and development (Udoetok, 2012).

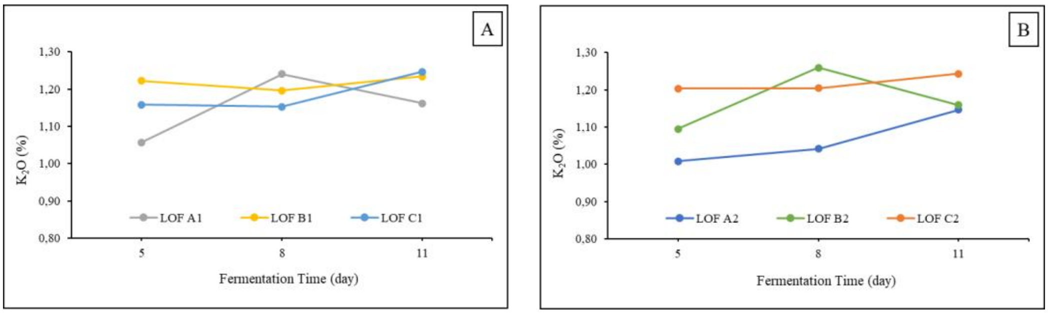

Figure 10. Effects of fermentation time on K_2O levels (A) 1% EM4; (B) 2% EM4

Biological Characteristics

A good LOF is characterized not only by its C-NPK content but also by the absence of contaminant bacteria, such as *E. coli*. According to the MTR regulations, the acceptable limit for *E. coli* in LOF is not exceeding 100 MPN/mL. The biological test conducted in this study revealed that the resulting LOF did not contain any *E. coli* contaminant bacteria. This negative result is likely attributed to the organic matter used and the duration of the fermentation process. Previous literature has reported that a proper fermentation process can effectively eliminate *E. coli* bacteria (Hau et al., 2020; Rahayu, Nurjanah, & Komalasari, 2018). The absence of *E. coli* confirms that the LOF produced in this study has better quality compared to the fermented bio-slurry LOF, which was reported to have an *E. coli* concentration of 8.5×10^3 CFU/mL (Yusnaini, Nur, & Baheri, 2022).

Table 3. Results of biological test on LOF

Sample	MPN/mL	Notes
LOF B2 (H8)	< 3	Negative results were obtained on the presumptive test for *E. coli* in all three tubes
LOF A1 (H8)		

The negative results in the presumptive test using LST media with BPW dilution media at dilutions of 10^{-1}, 10^{-2}, and 10^{-3} in three tubes indicate that the *E. coli* level is below the detection limit of <3 MPN/mL, as shown in Table 3. These results demonstrate that the biological content of the LOF in this study complies with established standards, ensuring its safety for use. LOF available in the market must be free from pathogenic bacteria such as *E. coli*. The government, through the Minister of Agriculture Regulation No. 261/2019 (Kementerian Pertanian Republik Indonesia, 2019), sets a maximum allowed content of <100 MPN/mL for contaminant bacteria in the form of *E. coli* in LOF.

Conclusion

The best LOF characteristics were achieved in LOF B2 and LOF A1, fermented for 8 days, with NPK levels of 1.377% and 1.348% respectively. While the product did not meet the minimum technical requirements for C, N, P, and K levels, it exhibited higher nutrient content compared to other fermented and commercial LOF products. All variations of LOF in this study reached maturity, evidenced by characteristic fermentation indicators such as an alcohol-like aroma, brownish color, and absence of foam and bubbles. Furthermore, the LOF produced in this study was free from *E. coli* contamination, making it safe for agricultural use in accordance with the Minister of Agriculture Regulation No. 261/2019.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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