Integrated Biodigester, Fermenter, and Composter System for Biogas, Liquid Organic Fertilizer, and Compost Production from Palm Oil Mill Waste

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Palm oil mill effluent (POME) is a high-strength organic wastewater that poses significant environmental challenges if not properly managed. Although anaerobic digestion, composting, and liquid fermentation have been widely applied, comprehensive performance evaluations of fully integrated biodigester–composter–fermenter systems remain limited, particularly regarding the role of hydraulic retention time (HRT) and process bottlenecks. This study evaluates the HRT-dependent performance and limitations of an integrated POME valorization system using a laboratory-scale continuous stirred tank reactor (CSTR) operated at HRTs of 10–250 days. System performance was assessed based on digester stability, solid compost quality, and nutrient and heavy metal characteristics of the liquid effluent. POME exhibited high organic strength (COD 45,000 mg L^{-1}; BOD 35,000 mg L^{-1}; VS/TS ratio 0.82), supporting effective anaerobic digestion (COD removal up to 92 %, VS destruction up to 88 %, biogas yield up to 0.60 m^3 kg^{-1} VS, and methane content up to 71 % at an HRT of 250 days). The solid fraction was successfully valorized through composting of empty fruit bunches using biodigester effluent, producing compost that met Indonesian National Standards. The resulting compost had a moisture content of 33 %, organic carbon content of 20.14 %, nitrogen content of 1.34 %, phosphorus content of 0.79 %, potassium content of 2.48 %, and magnesium content of 2.07 %, thereby meeting six of seven SNI 19-7030-2004 parameters; only pH at 8.85 exceeded the standard range of 6.8–7.49. In contrast, the liquid fraction showed limited agronomic potential, characterized by low organic carbon and macronutrient contents, and elevated lead (Pb) concentration exceeding permissible limits. These results identify the liquid effluent as the primary performance bottleneck of the integrated system, driven by nutrient depletion and heavy metal accumulation, and highlight the need for targeted post-treatment strategies. Overall, the integrated biodigester–composter–fermenter system demonstrated strong potential for solid-phase resource recovery and circular POME management, while effective liquid-phase utilization requires further process optimization.

Keywords
palm oil mill effluent, biodigester, composter, fermenter, hydraulic retention time, compost quality, waste management performance

Introduction

The palm oil industry plays a pivotal role in the global agricultural economy, particularly in Southeast Asia, where countries such as Indonesia[1] and Malaysia dominate crude palm oil production. Alongside its economic importance, the industry generates substantial volumes of organic waste[2], raising serious environmental concerns when waste management practices are inadequate[3]. Among these wastes, palm oil mill effluent (POME) is recognized as one of the most problematic by-products due to its high organic loading[4], elevated concentrations of suspended solids, oil and grease, and acidic nature. Untreated or poorly managed POME can lead to severe water pollution, soil degradation, odor nuisance, and significant greenhouse gas emissions, particularly methane, thereby contributing to climate change[5].

Anaerobic digestion has been widely adopted as an effective treatment technology for POME[6], offering dual benefits of organic load reduction and

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renewable energy generation in the form of biogas[7]. Numerous studies[3,4,8] have demonstrated the suitability of POME as a substrate for anaerobic digestion due to its high biochemical oxygen demand (BOD), chemical oxygen demand (COD), and biodegradable organic fraction. However, despite its effectiveness, anaerobic digestion alone does not fully address the environmental challenges associated with POME management. The digestate or effluent produced after biogas generation often still contains residual organic matter, nutrients, and in some cases inhibitory compounds or heavy metals, which may limit its direct reuse or disposal without further treatment[9].

In parallel, composting has been extensively applied to solid palm oil residues, particularly empty fruit bunches (EFB)[10], to produce organic soil amendments that enhance soil fertility and structure. Composting is recognized as a relatively simple and environmentally friendly technology capable of stabilizing organic solids and recovering nutrients in a form suitable for agricultural application[11]. Nevertheless, composting processes are inherently limited to solid waste streams and are unable to effectively utilize liquid wastes such as POME or biodigester effluent without additional integration strategies[12]. As a result, separate treatment of liquid and solid residues often leads to suboptimal resource recovery and increased operational complexity.

To overcome these limitations, integrated biodigester–composter systems have recently been proposed as a circular waste management approach aimed at maximizing resource recovery from both liquid and solid fractions of palm oil mill waste. By coupling anaerobic digestion with composting, such systems enable the conversion of POME into biogas while simultaneously utilizing biodigester effluent as a moisture source and bioactivator for composting EFB. This integration has the potential to improve overall treatment efficiency, reduce waste discharge, and generate multiple value-added products, including biogas, compost, and liquid organic fertilizer[13].

Despite the growing interest in integrated treatment systems, existing studies predominantly emphasize system configuration, biogas yield optimization, or individual process performance. Comprehensive performance-based evaluations that simultaneously assess solid compost quality and liquid effluent limitations remain scarce. In particular, the influence of hydraulic retention time (HRT)[14] on the overall performance of integrated biodigester–composter systems, including its impact on effluent characteristics, compost nutrient quality, and potential environmental risks, has not been sufficiently addressed. Understanding these relationships is crucial for determining the operational feasibility and sustainability of integrated systems under practical conditions.

Therefore, this study aims to evaluate the performance of an integrated biodigester–composter system for POME management under varying hydraulic retention times. The specific objectives of this study were to (i) characterize POME as a feedstock for anaerobic digestion, (ii) assess the quality of compost produced using biodigester effluent during EFB composting, and (iii) identify process limitations associated with the liquid fraction, particularly in relation to nutrient content and heavy

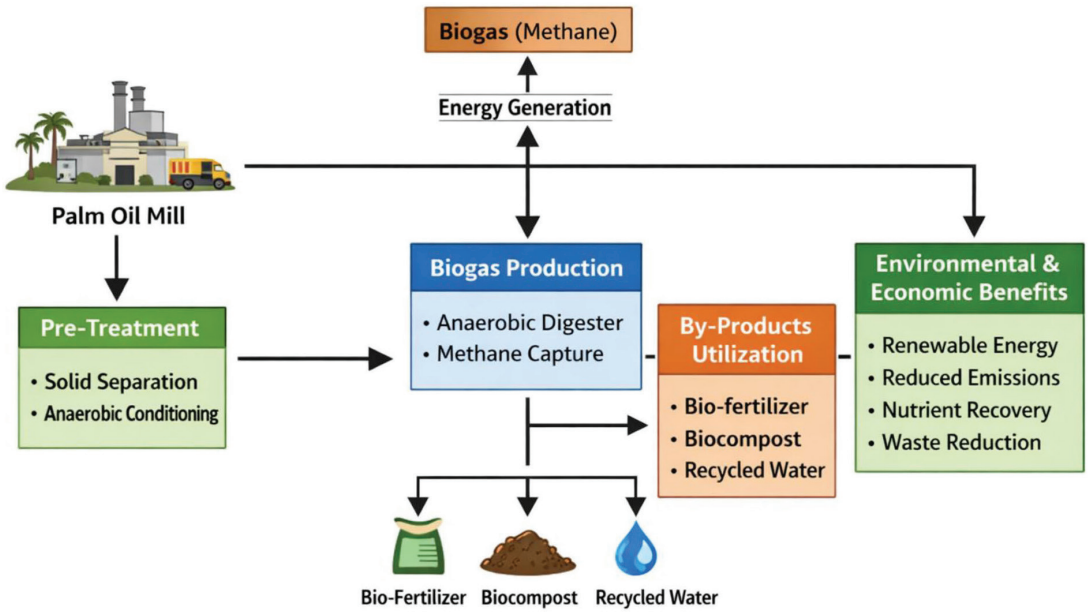


Fig. 1 – *Conceptual framework of integrated POME management*

metal contamination. By adopting a performance-oriented approach, this study provides critical insight into both the potential and constraints of integrated biodigester–composter systems for sustainable palm oil mill effluent management.

To clarify the conceptual integration and material flow evaluated in this study, Fig. 1 presents the conceptual framework of integrated POME management adopted in this research. The framework illustrates the sequential linkage between palm oil mill effluent generation, pre-treatment, anaerobic digestion, and downstream valorization pathways, including compost production, liquid organic fertilizer, and energy recovery through biogas. This integrated approach emphasizes circular resource utilization, where waste streams are transformed into value-added products while minimizing environmental burdens. The conceptual framework also highlights critical interfaces where process performance and limitations were assessed, particularly the partitioning of nutrients and contaminants between solid and liquid fractions, which forms the basis for the performance evaluation discussed in the subsequent sections.

Materials and methods

Materials

Fresh palm oil mill effluent (POME) was collected from the wastewater treatment facility of a palm oil mill located in North Sumatra, Indonesia. The collected POME was stored at 4 °C prior to use to prevent biological degradation. Empty fruit bunches (EFB) were obtained from the same mill and mechanically shredded to a particle size of approximately 2–3 cm before composting. A methanogenic inoculum, consisting of digestate obtained from a previously operated anaerobic biodigester at the Chemical Engineering Laboratory, Universitas Sumatera Utara, Indonesia, was used to accelerate the anaerobic digestion process during the start-up phase. No commercial bacterial starter was used in this study; the inoculum originated from the laboratory digester of Universitas Sumatera Utara, Indonesia, as described above.

Integrated biodigester, composter, and fermenter system configuration

The integrated system consisted of three main units: (i) a continuous stirred tank reactor (CSTR) biodigester, (ii) a batch composter, and (iii) a liquid effluent fermenter. The CSTR biodigester had an effective working volume of 10 L and was equipped with a mechanical agitator operated at 100 rpm to ensure homogeneous mixing. The digester was operated at ambient thermophilic conditions without external heating.

Biodigester effluent was divided into two streams: one fraction was applied to the composting unit as a moisture source and bioactivator, while the remaining fraction was transferred to the fermenter and evaluated as liquid organic fertilizer. The fermenter was operated in batch mode without additional nutrient supplementation.

A schematic diagram of the integrated biodigester–composter system used in this study is presented in Fig. 2.

Fig. 2 depicts a system consisting of various components that work together to manage organic waste into biogas, liquid organic fertilizer (POC), and compost. The process begins with a biodigester (A), which converts organic waste into biogas through anaerobic digestion of raw materials using POME. The gas produced is then channeled to a gas storage balloon (D) for temporary storage. A gas volume meter (C) is used to measure the volume of gas produced. A feed tank (E) provides organic waste raw materials that are fed into the biodigester containing POME. Furthermore, the process of converting empty palm oil bunches into compost is carried out using a composter (B), which utilizes the effluent from the biodigester as a source of microorganisms and to maintain moisture in the composter. Part of the effluent from the biodigester is channeled to a fermenter (H) to produce POC, which is useful as liquid fertilizer. A heater (G) helps heat the system to accelerate the fermentation process and biogas production. All these components are controlled

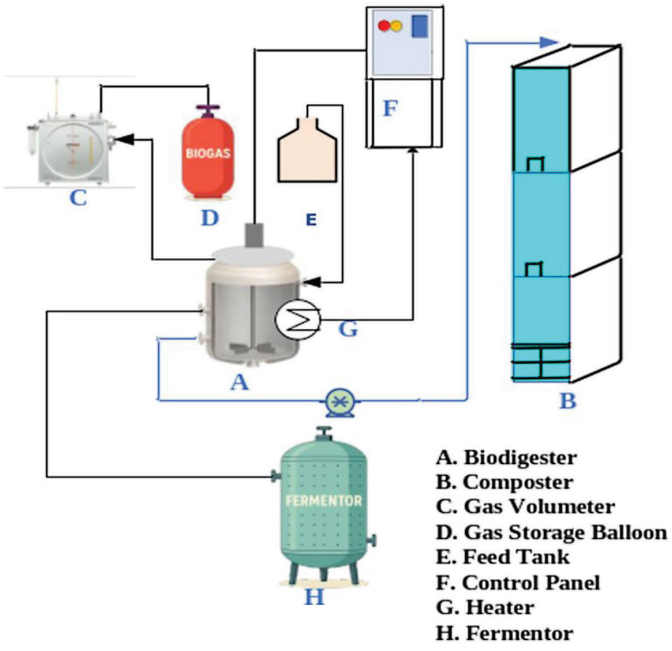


Fig. 2 – *Integrated biodigester, composter and fermenter system*

and monitored through the control panel (F), which ensures that the entire system functions properly and efficiently. This system provides a sustainable solution for organic waste management and produces useful products for agriculture and energy.

Experimental design

The biodigester was operated under nine different hydraulic retention times (HRTs), namely 250, 200, 100, 67, 50, 33, 25, 20, and 10 days. The HRT range was established based on our previous experimental work on the integrated biodigester–fermenter–composter system[13], which provided the experimental basis for the present study. In the present study, the HRT conditions were achieved by varying the daily influent flow rate while maintaining the biodigester working volume. Specifically, the HRTs of 250, 200, 100, 67, 50, 33, 25, 20, and 10 days corresponded to daily influent volumes of 0.04, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, and 1.0 L, respectively, for the 10 L working volume (HRT = working volume/daily influent volume), so that long, intermediate, and short retention times were all covered. The selected HRT range was intended to evaluate the response of the system across extended to short retention conditions, and to systematically assess changes in process performance and stability. Each operating condition was maintained until steady-state conditions were achieved.

Composting experiments were conducted in batch mode using 5 kg of shredded EFB per reactor. Biodigester effluent was periodically added to maintain compost moisture content within the optimal range (30–50 %). The composting process was carried out under thermophilic conditions, with temperatures maintained at approximately 55 °C. All experiments were conducted in duplicate to ensure data reliability.

Analytical methods

POME samples were analyzed for total solids (TS), volatile solids (VS), pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and oil and grease according to the Standard Methods for the Examination of Water and Wastewater[15]. TS, VS, pH, BOD, COD, TSS, and oil and grease were determined using Methods 2540 B, 2540 E, 4500-H^+ B, 5210 B, 5220 D, 2540 D, and 5520 B, respectively[15].

Compost quality was evaluated based on moisture content, pH, organic carbon, total nitrogen, phosphorus (P_2O_5), potassium (K_2O), calcium (CaO), and magnesium (Mg) in accordance with the Indonesian National Standard (SNI) 19-7030-2004 [16].

The liquid fraction was analyzed for nutrient content, micronutrients (Fe, Mn, and Cu), and heavy metals (Pb, Cd, and Ni) using an atomic absorption spectrophotometer (AAS; AA-7000, Shimadzu Corporation, Kyoto, Japan). The measured values were compared with the quality requirements stipulated in the Decision of the Minister of Agriculture of the Republic of Indonesia No. 2261/Kpts/SR.310/M/4/2019 [17]. All analytical measurements were performed in duplicate, and the results are presented as mean ± standard deviation (SD).

The volatile fatty acid (VFA) to alkalinity ratio was determined using a two-point titration method at pH 5.75 and pH 4.30. VFA concentration was expressed as acetic acid equivalents, whereas total alkalinity was expressed as $CaCO_3$ equivalents. The analysis was conducted following the procedures described in Standard Methods for the Examination of Water and Wastewater[15].

Methane content in the produced biogas was determined using gas chromatography (GC) equipped with a thermal conductivity detector (TCD). The methane concentration was quantified based on comparison with a certified methane standard, and the results were expressed as the percentage of methane (CH_4) in the biogas. All analytical measurements were performed in duplicate, and the methane content was reported as mean ± standard deviation (SD).

Results and discussion

POME characteristics and implications for anaerobic treatment

The physicochemical characteristics of POME used in this study are summarized in Table 1. The results indicate that the POME exhibited high organic strength, with total solids (TS) of 20,528 mg L^{-1} and volatile solids (VS) of 16,771 mg L^{-1}. These values fall within the range reported in previous

Table 1 – *Summary of the physicochemical characteristics of POME used in this study*

Number	Parameters	Unit	Value
1	Total solids (TS)	mg L^{-1}	20,528
2	Volatile solids (VS)	mg L^{-1}	16,771
3	pH	–	5
4	Temperature fresh POME	°C	85
5	Biochemical oxygen demand (BOD)	mg L^{-1}	35,000
6	Chemical oxygen demand (COD)	mg L^{-1}	45,000
7	Total suspended solids (TSS)	mg L^{-1}	21,000
8	Oil and grease	mg L^{-1}	7,500

studies, confirming the suitability of POME as a feedstock for anaerobic digestion[8]. High TS and VS concentrations indicate a substantial biodegradable organic fraction, which is essential for effective biogas production[14].

The VS/TS ratio of approximately 0.82 suggests that a large proportion of the total solids is biodegradable, supporting methane generation potential. Similar VS concentrations (15,000–30,000 mg L^{-1}) have been reported in earlier studies, where POME-based anaerobic digestion achieved stable biogas production under optimized conditions[7]. These characteristics imply that POME can sustain anaerobic digestion across a wide range of hydraulic retention times (HRTs), provided that process stability is maintained[18].

However, the measured pH value of 5 indicates acidic conditions, which are unfavorable for methanogenic activity. Methanogenic microorganisms typically perform optimally within a pH range of 6.5–7.5. Acidic POME is commonly associated with the accumulation of volatile fatty acids (VFAs) during hydrolysis and acidogenesis stages[19]. Excessive VFA accumulation may disrupt the VFA-to-alkalinity balance[20], leading to process instability and reduced methane yield[21], particularly at shorter HRTs. Previous studies have shown that pH adjustment using alkaline additives or effluent recycling can significantly improve methane production and digester stability[22].

The high biochemical oxygen demand (BOD) of 35,000 mg L^{-1} and chemical oxygen demand (COD) of 45,000 mg L^{-1} further confirm the strong organic loading of the POME[23]. These values are consistent with those reported in the literature and highlight the high potential for biogas generation[24]. Nevertheless, elevated organic loading requires careful control of operational parameters, especially HRT[25], to prevent organic overloading and inhibition of methanogenic activity. Longer HRTs may enhance process stability under such conditions, while excessively short HRTs may lead to incomplete degradation and VFA accumulation[19].

Total suspended solids (TSS) concentration of 21,000 mg L^{-1} also plays a critical role in anaerobic digestion performance[13]. High TSS levels can enhance biogas production by increasing the availability of particulate organic matter; however, excessive suspended solids may negatively affect mass transfer and reduce COD removal efficiency[18]. Previous studies[26] have reported that while high TSS concentrations can increase biogas productivity, they may also lead to lower overall treatment efficiency if not properly managed.

Overall, the physicochemical characteristics of POME used in this study indicate strong potential for anaerobic digestion and biogas production. However, the acidic pH and high organic loading emphasize the importance of appropriate HRT selection and process control to ensure stable operation and optimal methane yield within the integrated biodigester–composter system.

Organic matter removal efficiency

COD removal increased from 62 % at 10 days HRT to 89 % at 30 days HRT, indicating improved biodegradation efficiency with longer microbial residence time. Similarly, volatile solids destruction increased from 55 % to 84 %, confirming more effective conversion of particulate organic matter under extended retention periods. These trends indicate that shorter HRTs limit substrate conversion due to insufficient contact time between microorganisms and organic matter.

Fig. 3 illustrates the influence of hydraulic retention time (HRT) on organic matter degradation during the anaerobic digestion of palm oil mill effluent (POME). An increase in HRT resulted in a substantial improvement in treatment performance, with COD removal rising from 62 % at 10 days HRT to 92 % at 250 days HRT. A similar trend was observed for volatile solids (VS) destruction, which increased from 55 % to 88 %, indicating enhanced conversion of particulate organic matter under extended microbial residence times. This behavior is consistent with anaerobic digestion kinetics, where longer HRT allows sufficient time for hydrolysis, acidogenesis, acetogenesis, and methanogenesis to proceed more completely, thereby improving overall organic matter stabilization[27].

At shorter HRTs (10–25 days), COD removal and VS destruction were limited due to inadequate contact time between anaerobic microorganisms and complex organic substrates. Under such conditions, slow-growing methanogenic populations are susceptible to washout, leading to incomplete hydrolysis and the accumulation of intermediate metabolites, which ultimately reduces process efficiency. Similar limitations at low HRT have been reported in anaerobic POME treatment systems, where insufficient retention time constrained microbial activity and organic matter conversion efficiency[28].

Conversely, operation at longer HRTs (≥100 days) promoted more complete degradation of both soluble and particulate organic fractions, resulting in higher COD removal, increased VS destruction, and improved digester stability. Extended retention times provide favorable conditions for methanogenic consortia and enhance buffering capacity, thereby reducing process fluctuations. However, the observed diminishing marginal gains beyond 100–200 days HRT suggest that excessively long retention

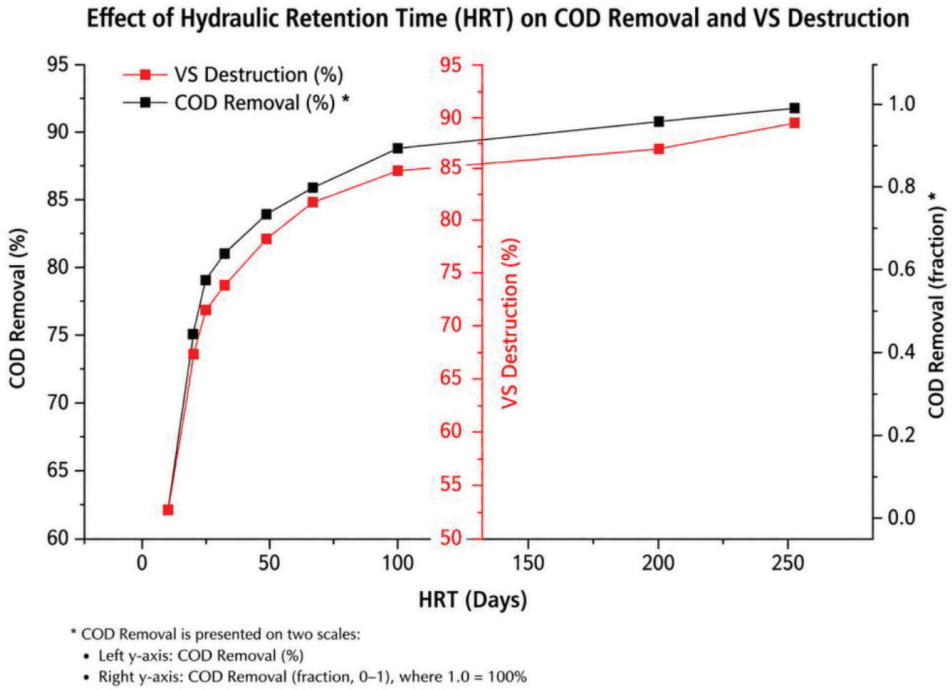


Fig. 3 – *Effect of hydraulic retention time (HRT) on COD removal and volatile solids (VS) destruction efficiencies in the CSTR biodigester treating POME (HRT of 10–250 days)*

times yield limited additional performance benefits relative to the increased reactor volume and operational cost. This phenomenon has also been reported in full-scale and laboratory-scale anaerobic digestion studies, where optimal HRT ranges were identified to balance treatment efficiency and economic feasibility[29].

Therefore, based on the trends observed in Table 2, an optimal HRT window between 50 and 100 days is recommended for integrated biodigester–composter systems treating POME, as it provides an effective compromise between organic removal efficiency, system throughput, and practical operational constraints.

The data in Table 2 show that biogas yield and methane content increased with increasing HRT. Biogas yield increased from 0.32 m^3 kg^{-1} VS at an HRT of 10 days to 0.60 m^3 kg^{-1} VS at 250 days, while methane content increased from 52 % to 71 %. This trend indicates that longer retention times favored more extensive conversion of organic matter during anaerobic digestion. Similar behavior has been reported in anaerobic digestion systems, where longer HRTs generally provide microorganisms with sufficient time to degrade organic substrates and convert intermediate products into biogas[30].

Correspondingly, methane fraction exhibited a progressive increase from 52 % to 71 % across the HRT range. The lower methane contents at short HRT (≤20 days) can be attributed to a shift toward acidogenic-dominated metabolism, where rapid substrate turnover leads to the accumulation of volatile fatty acids (VFAs) that inhibit methanogenic archaea and depress methane synthesis. Similar influences of short retention times on decreased methane percentages have been observed in staged digestion systems, where reduced HRT in the methanogenic stage led to suboptimal methane production due to incomplete processing of acidogenic intermediates[31].

In contrast, at HRT values ≥67 days, the microbial ecosystem within the digester has sufficient time to complete the sequential processes of hydrolysis, acidogenesis, acetogenesis, and methanogene-

Table 2 – *Biogas yield and methane production*

HRT (Days)	Biogas yield (m^3 kg^{-1} VS)	Methane content (%)
250	0.60	71
200	0.59	70
100	0.57	69
67	0.54	67
50	0.52	66
33	0.49	64
25	0.46	62
20	0.41	58
10	0.32	52

sis, thereby increasing the methane fraction and stabilizing biogas production. This trend is not confined to POME alone; although substrate characteristics vary across studies, retention-time increases generally allow more effective establishment and maintenance of methanogenic communities, improving gas quality in diverse anaerobic systems[32].

However, the marginal gains in methane yield observed beyond approximately 100–200 days HRT suggest diminishing returns relative to reactor volume and operational cost. From an engineering perspective, extending HRT beyond the point of stable microbial equilibrium yields only incremental improvements in biogas quantity and methane content, while imposing greater requirements for reactor footprint and capital expenditure. Therefore, selecting an optimal HRT window of 50–100 days appears to balance biogas yield, methane concentration, process stability, and economic feasibility in integrated anaerobic digestion systems treating high-strength substrates like POME.

Process stability and acidification control

Process stability improved markedly with increasing hydraulic retention time (HRT), as reflected by the progressive reduction in the VFA-to-alkalinity ratio from 0.62 at 10 days to 0.18 at 250 days. This trend indicates a substantial decrease in acidification risk and enhanced buffering capacity under longer microbial residence times.

At short HRTs (≤20 days), elevated VFA/alkalinity ratios suggest incomplete conversion of intermediate acids into methane, leading to potential process imbalance and inhibition of methanogenic activity. Under these conditions, acidogenic reactions likely dominated over methanogenesis, increasing the probability of VFA accumulation, pH decline, and methane suppression.

Table 3 – *Process stability and acidification control*

HRT (Days)	VFA/Alkalinity ratio	Reactor pH
250	0.18	7.3
200	0.19	7.2
100	0.21	7.1
67	0.24	7.0
50	0.28	6.9
33	0.34	6.8
25	0.41	6.7
20	0.50	6.6
10	0.62	6.4

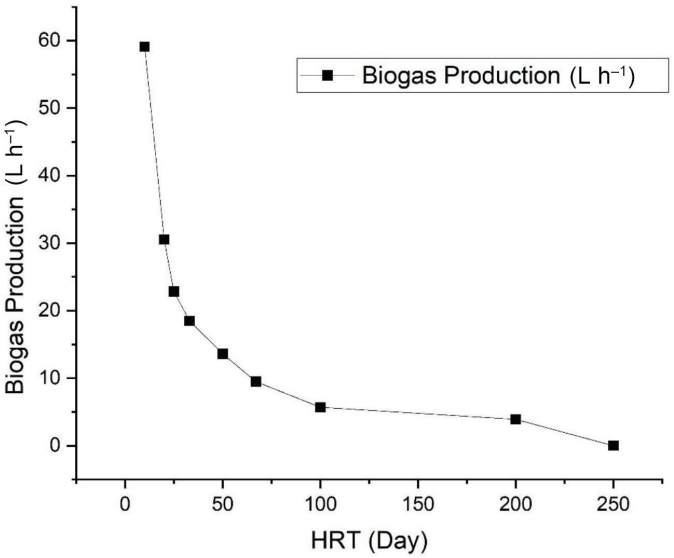


Fig. 4 – *Effect of hydraulic retention time (HRT) on biogas production from palm oil mill effluent*

In contrast, longer HRTs (≥50 days) enabled more complete acid uptake and improved syntrophic cooperation between acidogenic and methanogenic microbial populations. As a result, the reactor pH stabilized within the optimal methanogenic range (6.9–7.3), demonstrating increased system resilience against organic shock loading and fluctuations in feed composition.

The observed stabilization of pH and reduction in VFA accumulation confirm that short HRT represents a critical process bottleneck in anaerobic digestion of POME. Without sufficient retention time, organic overload conditions can destabilize microbial activity, impair methane production, and compromise reactor reliability.

Therefore, maintaining HRT values above 50 days is recommended to ensure robust process stability, effective acidification control, and sustained methane productivity in integrated biodigester–composter systems treating palm oil mill effluent.

Production from palm oil mill effluent

Biogas production from palm oil mill effluent (POME) exhibited a clear dependency on hydraulic retention time (HRT), where shorter HRTs resulted in significantly higher gas output per hour, as shown in Fig. 4. At an HRT of 10 days, biogas production peaked at approximately 59 L h^{-1}, demonstrating a high volumetric conversion rate of organic matter to gas. This behavior is consistent with anaerobic digestion principles, where shorter retention times increase the organic loading rate (OLR) available t o the microbial community, particularly acidogenic bacteria. Similar observations were reported in studies on POME treatment, where decreased HRT en-

hanced instantaneous gas production despite challenges in maintaining long-term system stability[28].

However, high biogas production rates at low HRTs do not necessarily correlate with optimal methane content or stable digestion. The dominance of fast-growing acidogenic microbes under high OLR conditions can lead to an accumulation of volatile fatty acids (VFAs) that suppress slower-growing methanogens, causing a drop in methane percentage and risking process imbalance. This trend has been documented in thermophilic anaerobic digestion of POME, where efficient methanogenesis required sufficient microbial retention to prevent acidification and ensure quality biogas composition[33].

As HRT increased to intermediate values (20–50 days), the hourly biogas production rate decreased, reflecting a reduced OLR, but the conversion of biodegradable organic matter became more complete and consistent. Longer retention allows syntrophic methanogenic consortia sufficient time to process intermediate metabolites generated in earlier stages, improving both the stability of the digestion process and the quality of the resulting biogas. Literature supports that moderate HRT conditions often produce a better balance between gas yield and microbial stability, particularly in continuous stirred tank reactors (CSTRs) treating complex wastes like POME. This balance is essential for maintaining reactor performance without sacrificing methane quality, even if instantaneous volumetric gas output declines.

At extended HRTs (>100 days), biogas production rates per hour fell sharply because most readily biodegradable substrates had already been converted in the earlier stages of digestion. While long HRTs can maximize total organic removal (e.g., COD and VS degradation) and reduce effluent pollution risk, they impose practical limitations on reactor sizing and energy recovery. The operational trade-off between extended HRT and reactor footprint must be considered in design and scale-up, as excessively long retention times diminish energy productivity per reactor volume, despite achieving thorough waste stabilization.

The pattern observed in Fig. 4 aligns with established anaerobic digestion literature showing that shorter HRT enhances biogas productivity per unit time but risks process instability and lower methane content, whereas longer HRT improves stabilization and gas quality at the cost of reduced hourly productivity. An operational window of intermediate HRT (20–50 days) emerges as a practical compromise that sustains appreciable biogas generation while providing enough time for methanogenic activity and stable reactor performance. This insight is crucial for optimizing biodigester design and operation in integrated POME management systems targeting both energy recovery and environmental compliance.

Compost quality performance

Table 4 presents the nutrient composition and physicochemical properties of compost produced from empty fruit bunches (EFB) using biodigester effluent as the composting medium. Overall, the compost exhibited satisfactory quality and complied with most requirements of the Indonesian National Standard (SNI 19-7030-2004)[16], indicating effective stabilization and nutrient enrichment through the integrated biodigester–composter system.

The compost temperature stabilized at 30 °C, which reflects a mature composting stage and indicated that microbial activity had reached equilibrium[22]. Although SNI [34] does not specify a temperature criterion[13], values within the range of 30–60 °C are generally considered favorable for aerobic composting[1]. A stable temperature close to ambient conditions suggests that the decomposition process proceeded efficiently without excessive heat accumulation that could inhibit microbial activity or cause nutrient losses[35].

Moisture content was measured at 33 %, which falls within the recommended range of 30–50 % according to SNI 19-7030-2004 [35]. Adequate moisture content is essential for maintaining microbial metabolism and facilitating organic matter degradation[9]. The observed value indicates that the composting process achieved a suitable balance between aeration and microbial activity[36], preventing anaerobic conditions that could lead to odor formation or incomplete stabilization[37].

The compost pH was recorded at 8.85, exceeding the SNI recommended range of 6.8–7.49. This

Table 4 – *Compost nutrient analysis results*

Parameter	Unit	Value	SNI 19–7030–2004	
			Minimum	Maximum
Temperature	°C	30	–	Groundwater temperature
Water content	%	33	–	50
pH POME		8.85	6.8	7.49
Carbon–organic	%	20.14	9.80	32
Nitrogen	%	1.34	0.40	–
Phosphorus (P_2O_5)	%	0.79	0.10	–
Potassium (K_2O)	%	2.48	0.40	–
Calcium oxide (CaO)	%	1.34	< 25	–
Magnesium (Mg)	%	2.07	*	0.60

*The value is greater than the minimum or less than the maximum.

alkaline condition is attributed to the characteristics of the biodigester effluent used as composting input[38], particularly the addition of $CaCO_3$ during anaerobic digestion for pH stabilization[39]. Alkaline compost may be advantageous for application on acidic soils; however, its use should be carefully managed for crops sensitive to high pH [40]. Previous studies have reported similar pH elevation during composting of oil palm residues, with gradual pH reduction occurring during curing and soil application stages[13].

Organic carbon content reached 20.14 %, well within the SNI acceptable range (9.80–32 %), indicating a high level of stabilized organic matter. High organic carbon content contributes to improved soil structure, enhanced water retention, and increased cation exchange capacity. This result demonstrates that the integrated system effectively converted organic residues into value-added compost suitable for soil amendment[26].

The compost exhibited favorable macronutrient content, with nitrogen, phosphorus (P_2O_5), and potassium (K_2O) concentrations of 1.34 %, 0.79 %, and 2.48 %, respectively. These values significantly exceed the minimum SNI requirements, highlighting the nutrient enrichment achieved through the use of biodigester effluent[41]. Elevated nitrogen content supports vegetative plant growth, while phosphorus and potassium contribute to root development, flowering, stress resistance, and overall crop productivity[38]. The high potassium content is particularly advantageous for oil palm plantations, where potassium demand is relatively high.

Calcium oxide (CaO) content was measured at 1.34 %, well below the maximum allowable limit (<25 %), indicating that the compost poses minimal risk of excessive soil alkalinization. Calcium plays a crucial role in improving soil aggregation and nutrient uptake[42], and its moderate concentration in this compost supports balanced soil conditioning[43].

Magnesium content reached 2.07 %, indicating an additional agronomic benefit of the compost. Magnesium is essential for chlorophyll formation and photosynthetic activity, and its presence further enhances the fertilizer value of the compost[42]. Although SNI does not specify a minimum requirement for magnesium, the observed concentration suggests that the compost can contribute positively to plant metabolic processes[44].

Overall, the compost produced from the integrated biodigester–composter system demonstrated satisfactory physicochemical and nutrient characteristics, meeting most SNI quality standards. These results confirm the effectiveness of the integrated approach in valorizing solid residues from palm oil mill effluent management. However, the elevated pH indicates that further optimization, such as extended curing or blending with acidic organic materials, may be required to broaden the applicability of the compost across different soil types.

Liquid organic fertilizer quality

Table 5 summarizes the chemical composition and heavy metal content of liquid organic fertilizer (LOF) produced from the fermenter unit of the integrated biodigester–composter system, compared with the quality standards stipulated in the Decision of the Minister of Agriculture of the Republic of Indonesia No. 2261/Kpts/SR.310/M/4/2019 [17]. The results indicate that, unlike the solid compost fraction, the liquid fraction exhibits significant limitations in terms of nutrient content and heavy metal safety, particularly with respect to lead (Pb)[14].

The organic carbon (C-organic) content of the liquid fertilizer was measured at 2.13 %, which is substantially lower than the minimum standard requirement of 10 %. Organic carbon is a critical parameter in liquid organic fertilizers, as it functions as an energy source for soil microorganisms and contributes to the improvement of soil structure, microbial activity, and nutrient retention capacity[45]. The low organic carbon content observed in this study suggests that the fermenter effluent is insufficiently enriched with soluble organic compounds, limiting its effectiveness in enhancing soil fertility[39]. Previous studies have reported that liquid fertilizers with low organic carbon content contribute minimally to soil aggregation and cation exchange capacity, thereby reducing their agronomic benefits.

Similarly, the macronutrient content of the liquid fertilizer was markedly below the regulatory standards. Total phosphorus (P_2O_5) content was only 0.04 %, far below the required range of 2–6 %, while potassium (K_2O) content was recorded at

Table 5 – *Results of POME organic fertilizer analysis*

Parameters	Unit	Value	Standards
C–Organic	% (w/v)	2.13	minimum 10
P_2O_5 Total	% (w/v)	0.04	2–6
K_2O	% (w/v)	0.18	2–6
Fe total	ppm	75.23	90–100
Mn total	ppm	0.08	25–500
Cu total	ppm	9.02	25–500
Pb	ppm	5.74	maximum 0.5
Cd	ppm	<0.0006	maximum 0.1
Ni	ppm	0.81	maximum 10
Nitrogen	% (w/v)	0.16	2–6

*Decision of the Minister of Agriculture of the Republic of Indonesia Number 2261/Kpts/Sr.310//M/4/2019

0.18 %, compared to the standard range of 2–6 %. Phosphorus is essential for root development, energy transfer, and early plant growth, whereas potassium plays a vital role in improving plant resistance to disease, drought tolerance, and photosynthetic efficiency[38]. The extremely low concentrations of both P_2O_5 and K_2O indicate that the liquid fertilizer derived from the fermenter is unable to meet basic plant nutrient requirements. This limitation is likely associated with the preferential retention of nutrients in the solid fraction during anaerobic digestion and composting, resulting in nutrient-poor liquid effluent.

Nitrogen content in the liquid fertilizer was also found to be very low (0.16 %), significantly below the recommended standard of 2–6 % [46]. Nitrogen is a key element for vegetative growth, chlorophyll synthesis, and protein formation in plants. Deficiency in nitrogen can lead to stunted growth, leaf chlorosis, and reduced crop productivity. The low nitrogen concentration observed in this study further confirms that the liquid fraction of the integrated system has limited agronomic value as a standalone fertilizer without further nutrient supplementation or process modification.

In terms of micronutrients, the total iron (Fe) concentration was measured at 75.23 ppm, slightly below the standard range of 90–100 ppm. Iron is essential for chlorophyll synthesis and electron transport in photosynthesis[36]. Although the Fe content was marginally lower than the standard, it remains relatively close to the acceptable range and is unlikely to cause severe iron deficiency when applied to soils with adequate background iron levels. However, manganese (Mn) and copper (Cu) concentrations were significantly lower than the standard requirements[47]. Manganese content was only 0.08 ppm (standard: 25–500 ppm), while copper content reached 9.02 ppm, compared to the standard range of 25–500 ppm. Both elements play important roles in enzymatic reactions and photosynthetic processes, and their deficiency may limit plant metabolic performance when the liquid fertilizer is applied as the sole nutrient source.

The most critical limitation identified in the liquid fertilizer is the elevated concentration of lead (Pb), which reached 5.74 ppm, exceeding the maximum permissible limit of 0.5 ppm by more than tenfold. Lead is a highly toxic heavy metal that poses serious risks to soil quality, plant health, and human safety through bioaccumulation in the food chain. Elevated Pb levels in organic fertilizers have been reported to inhibit root development, reduce crop yields, and cause long-term soil contamination. The presence of excessive Pb in the liquid fraction suggests potential contamination from raw materials, process additives, or reactor components, and represents a major environmental and regulatory constraint for direct agricultural application[48].

In contrast, cadmium (Cd) and nickel (Ni) concentrations were within safe limits. Cadmium content was below the detection limit (<0.0006 ppm), well below the maximum allowable limit of 0.1 ppm, indicating negligible risk of cadmium contamination. Nickel concentration was measured at 0.81 ppm, which is also well below the maximum limit of 10 ppm, suggesting that Ni does not pose a significant environmental or agronomic concern in this system[7].

Overall, the results clearly demonstrate that while the integrated biodigester–composter system performs effectively in producing solid compost that meets quality standards, the liquid fraction derived from the fermenter exhibits substantial limitations. Low organic carbon and nutrient concentrations, combined with elevated Pb levels, restrict the direct use of this liquid as a safe and effective organic fertilizer. These findings highlight the need for further process optimization, such as nutrient enrichment, additional treatment steps, or selective separation of contaminated streams, to improve the quality and safety of the liquid effluent. This performance-based evaluation underscores that integration of anaerobic digestion and composting alone is insufficient to guarantee balanced valorization of both solid and liquid fractions in POME management systems.

Process limitations for liquid fraction evaluation

In contrast to solid compost performance, the liquid fraction exhibited significant limitations. Organic carbon (2.13 %) and macronutrient contents (N, P_2O_5, K_2O) were substantially below regulatory standards. More critically, Pb concentration (5.74 ppm) exceeded the permissible limit, posing potential environmental and health risks. These findings indicate that direct application of the liquid fraction as fertilizer is not environmentally acceptable without additional treatment or heavy metal mitigation strategies. The presence of Pb may be attributed to raw material contamination or chemical additives used during pH adjustment, highlighting the need for upstream control and post-treatment processes.

The compliance assessment summarized in Table 6 clearly indicates that the liquid fraction derived from the integrated biodigester, composter system does not meet the regulatory requirements for liquid organic fertilizer application. All evaluated macronutrient parameters, including organic carbon, nitrogen, phosphorus, and potassium, were substantially below the minimum thresholds, confirming the limited fertilizing potential of the liquid effluent. This nutrient deficiency suggests that a

Table 6 – *Compliance and limitation assessment of liquid fraction*

Parameter	Measured value	Regulatory standard	Compliance status	Identified simitation
C–organic	2.13 %	≥ 10 %	Not compliant	Insufficient soluble organic matter
Nitrogen (N)	0.16 %	2–6 %	Not compliant	Low nutrient availability
Phosphorus (P_2O_5)	0.04 %	2–6 %	Not compliant	Nutrient partitioning to solid phase
Potassium (K_2O)	0.18 %	2–6 %	Not compliant	Poor fertilizing potential
Lead (Pb)	5.74 ppm	≤ 0.5 ppm	Critical	Heavy metal contamination
Cadmium (Cd)	<0.0006 ppm	≤ 0.1 ppm	Compliant	No significant risk
Nickel (Ni)	0.81 ppm	≤ 10 ppm	Compliant	Acceptable level

significant portion of essential nutrients was preferentially retained in the solid phase during anaerobic digestion and subsequent composting, thereby reducing nutrient availability in the liquid fraction.

More importantly, the Pb concentration exceeded the permissible limit by more than an order of magnitude, classifying the liquid fraction as environmentally unsafe for direct agricultural use. Although other heavy metals such as Cd and Ni remained within acceptable limits, the elevated Pb level represents a critical constraint that outweighs the otherwise compliant parameters. The presence of excessive Pb not only limits agronomic applicability but also raises concerns regarding long-term soil contamination and potential bioaccumulation in crops.

These findings demonstrate that, while the integrated system performs effectively in valorizing solid residues into compliant compost, the liquid fraction represents a process bottleneck requiring targeted intervention. Without additional treatment such as heavy metal removal, dilution, or controlled nutrient supplementation, the liquid effluent cannot be classified as a safe or effective fertilizer product. Consequently, future optimization of integrated biodigester–composter systems should prioritize liquid fraction management to achieve holistic environmental sustainability and regulatory compliance.

Conclusions

This study provides a performance-based evaluation of an integrated biodigester–composter system for palm oil mill effluent management. The system demonstrated satisfactory performance in converting solid waste into nutrient-rich compost that meets national quality standards, meeting 6 of 7 SNI 19-7030-2004 parameters: moisture content (33 %), organic carbon (20.14 %), nitrogen (1.34 %), phosphorus (0.79 % P_2O_5), potassium (2.48 % K_2O), and magnesium (2.07 %), with only pH (8.85) exceeding the standard range of 6.8–7.49. However, the liquid fraction exhibited low nutrient value (C-organic 2.13 %, N 0.16 %, P_2O_5 0.04 %, K_2O 0.18 %) and elevated heavy metal content (Pb 5.74 ppm vs. the limit of 0.5 ppm), representing a significant process limitation. Overall, the integrated system is promising for solid waste valorization, but further optimization is required to ensure safe and effective utilization of the liquid effluent.

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