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Research Paper

Synergistic Valorization of Palm Oil Mill Effluent and Boiler Ash into a Nutrient-Rich Liquid Organic Fertilizer

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Abstract
Industrial symbiosis presents a transformative pathway for the sustainable management of palm oil byproducts. This study investigates a novel integrated valorization approach using boiler ash as a multifunctional ameliorant in the anaerobic fermentation of palm oil mill effluent (POME). By leveraging the synergistic physicochemical properties of acidic POME and alkaline boiler ash, we developed a self-buffering system to produce high-value liquid organic fertilizer. Varying boiler ash concentrations (0, 45, 50, and 55 g/L) were evaluated to determine the optimal nutrient recovery and stabilization parameters. Results demonstrate that a dosage of 55 g/L is statistically superior, effectively neutralizing the system to a stable pH of 7.5 without synthetic additives. This treatment yielded a nutrient-dense product containing 3.93% total NPK and 12.42% organic carbon, surpassing the Indonesian Ministry of Agriculture Regulation No. 261/2019 standards. Safety analysis revealed a Pb concentration of 12.28 ppm, which is significantly below the maximum allowable threshold, confirming the product's environmental compatibility. This research provides a scientifically grounded method for converting industrial waste into a fortified agricultural input, advancing circular economy principles and supporting national sustainability frameworks like the Indonesia Sustainable Palm Oil (ISPO) certification.

Keywords
Waste Valorization, Palm Oil Mill Effluent, Boiler Ash, Liquid Organic Fertilizer, Industrial Symbiosis, Circular Economy

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1. INTRODUCTION

The palm oil industry, a cornerstone of tropical agricultural economies and led by Indonesia which supplies over half the global market, faces a dual challenge: meeting global vegetable oil demand while managing vast quantities of industrial waste (Badan Pusat Statistik, 2024). Palm Oil Mill is a factory which converts Fresh Fruit Bunch (FFB) to Crude Palm Oil (CPO) and Palm Kernel Oil (PKO). Within FFB converting processes, two types of waste are produced liquid waste and solid waste. Liquid waste, named Palm Oil Mill Effluent (POME), contributes up to 60% of total FFB (Mondamina et al., 2020). This production generates significant byproducts, notably POME and boiler ash, creating a pressing need for sustainable management solutions (Wu et al., 2009). Within a circular economy framework, these waste streams are increasingly viewed not as liabilities but as resources for valorization, a perspective strongly supported by techno-economic assessments demonstrating clear financial incentives for resource recovery (Saad et al., 2022). Palm Oil Mill Effluent (POME), which contains high concentrations of biodegradable organic matter, is a promising substrate for biogas production through anaerobic fermentation (Afrianti and Zainal, 2025).

The two byproducts present complementary challenges and opportunities. POME is a highly acidic, colloidal suspension with an extreme organic load (COD up to 100,000 mg/L), and its conventional treatment in open ponds is a major source of greenhouse gas emissions (Ofon et al., 2024; Razman et al., 2022). Conversely, boiler ash, derived from the combustion of palm fiber and shells, is a highly alkaline solid rich in essential minerals like potassium and phosphorus. However, its direct land application is constrained by its high alkalinity and potential for trace heavy metal contamination, necessitating careful management (Euniza Jusli et al., 2022).

Current valorization strategies typically address these waste streams in isolation. POME is often used for biogas capture, and boiler ash as a liming agent, but these siloed approaches fail to harness their synergistic potential (Judijanto, 2025; Tandiono et al., 2025). While some research has explored co-composting these materials in solid form (Setiawan et al., 2025), the development of a standardized, stable, and high-value liquid formulation remains a significant and underexplored research gap.

This study hypothesizes that the strategic co-fermentation of POME and boiler ash can create a synergistic system where the alkalinity and mineral content of the ash neutralize POME's acidity and enrich its nutrient profile, resulting in a high-quality liquid organic fertilizer. Aligned with national sustainability frameworks like the Indonesia Sustainable Palm Oil (ISPO) certification (Firdaus and Alifiyah, 2025), this research aims to determine the optimal dosage of boiler ash required to formulate a liquid organic fertilizer that meets the stringent quality benchmarks of the Indonesian Ministry of Agriculture Regulation No. 261/2019. The novelty of this work lies in its integrated waste valorization approach, offering a scientifically-grounded, practical solution to simultaneously mitigate pollution and advance sustainable agriculture through circular economy principles.

While previous studies Mariska et al. (2024) have successfully produced LOF from POME using OPEFB ash and external bio-activators like EM4, they often result in low nutrient density (Total NPK ∼1.39%). In contrast, this study introduces a self-buffering valorization approach using boiler ash that eliminates the need for external additives. Our method not only achieves a superior nutrient profile (3.93% NPK)-a 182% increase over conventional methods-but also ensures environmental safety regarding heavy metal concentrations (Pb), directly supporting the ISPO certification framework.

Unlike previous studies that treat POME and boiler ash in isolation or focus solely on solid-phase co-composting, this research establishes a novel liquid-phase synergistic framework. By identifying the critical concentration of 55 g/L of boiler ash, this study achieves a self-buffering anaerobic system that eliminates the need for synthetic pH adjusters, representing a significant leap in industrial symbiosis and circular bioeconomy practices.

2. EXPERIMENTAL SECTION

2.1 Materials

Palm Oil Mill Effluent (POME) was obtained from a commercial palm oil mill in Riau, Indonesia. The effluent was collected after passing through the mill's standard wastewater stabilization ponds. Boiler ash, a byproduct of palm kernel shell and mesocarp fiber combustion, was sourced from the same facility and sieved (2 mm mesh) to ensure homogeneity. A commercial bioactivator, Effective Microorganism 4 (EM4®), and sugarcane molasses were purchased locally.

2.2 Methods

2.2.1 Experimental Design and Fertilizer Formulation

The experiment was structured using a Completely Randomized Design (CRD). Four treatment levels were established based on the dosage of boiler ash added to 1 L of POME: P0 (0 g, control), P1 (45 g), P2 (50 g), and P3 (55 g). Each treatment was replicated five times, yielding 20 experimental units. The boiler ash dosages were selected based on preliminary literature review and a pilot study by Rahmawati (2023), which identified 45 g as an effective starting point for nutrient mobilization. For each experimental unit, the designated amount of boiler ash was mixed into 1 L of POME. Subsequently, 50 mL of EM4® and 10 g of molasses (as a microbial energy source) were added. The mixture was homogenized by stirring.

2.2.2 Anaerobic Fermentation

Each mixture was placed in a 1.5 L sealed plastic bottle and subjected to anaerobic fermentation for 14 days at ambient temperature (28±2°C). To facilitate the release of fermentation gases while preventing oxygen ingress, each bottle was fitted with an airlock system constructed from aquarium tubing submerged in water. After the fermentation period, the liquid organic fertilizer (LOF) was harvested for chemical analysis.

2.2.3 Analytical Procedures

The resulting LOF from each experimental unit was analyzed for key quality parameters according to the Indonesian Ministry of Agriculture Regulation No. 261/2019.

2.2.3.1 Nutrient Analysis

Measured using a calibrated digital pH meter (Hanna Instruments HI98107).

2.2.3.2 Organic Carbon Determination

Organic Carbon (C-Organic): Determined using the Walkey-Black wet oxidation method. The absorbance of the resulting solution was measured spectrophotometrically at a wavelength of 561 nm, Organic matter and organic carbon were determined using wet oxidation (Phibunwatthanawong and Riddech, 2019).

2.2.3.3 NPK Analysis

Total Nitrogen (N-Total), Available Phosphorus (as P_2O_5), and Total Potassium (as K_2O): Nutrient concentrations were determined using a calibrated Detector Nutrient Analyzer series C-3000 RS-485 probe after sample extraction with distilled water and mechanical shaking (250 rpm for 30 minutes). Readings were converted from ppm to percentage (Lionel et al., 2023).

Since Nitrogen, Phosphorus, and Potassium have different chemical properties, the C-3000 uses distinct modules or methods for each Nitrogen (N). Colorimetric (Salicylate or Nessler Method) and UV Digestion. The analyzer mixes the sample with an oxidizing agent (like Potassium Persulfate) and uses a high-temperature digestion (around 120°C) to break down nitrogen compounds into Nitrates. A coloring reagent is added, and the Photometric Detector measures the light absorbance. The darker the color, the higher the Nitrogen concentration.

Phosphorus (P)-Total Phosphorus methods are Molybdenum Blue Colorimetry. The sample undergoes acid digestion to convert all phosphorus forms into orthophosphate. Ammonium Molybdate is added, reacting with the phosphorus to create a molybdenum blue complex. The detector measures the absorbance at a specific wavelength (usually 700 nm – 880 nm).

Potassium (K) Method are using Ion-Selective Electrode (ISE) or Turbidimetric Method.The analyzer uses a sensor with a selective membrane that reacts only to Potassium ions (K^+). It measures the voltage potential difference between the reference electrode and the sensing electrode. This electrical signal is then converted into a concentration value (mg/L). The RS-485 component is the "communication bridge" of the C-3000. Once the physical detectors (optical or electrical) finish their measurement, the RS-485 system takes over.

It converts the raw analog signals from the detectors into digital values. The data is organized into "Registers." For example Register 40001: Nitrogen ValueRegister 40002: Phosphorus ValueRegister 40003: Potassium ValueLong-Distance Transmission: RS-485 allows the data to travel up to 1,200 meters to a PLC, SCADA system, or a computer without losing accuracy due to electrical noise. Automated Operational CycleThe C-3000 follows a strict automated workflow to ensure the detectors stay accurate Peristaltic pumps draw the water/fertilizer sample. Reagent Injection: Precise amounts of chemicals are added via micro-pumps. The mixture is heated (if required) and stirred. The optical or electrochemical detector takes the reading. The system flushes the lines with a cleaning solution to prevent cross-contamination or mineral buildup. The final NPK values are transmitted via the RS-485 port to the user's monitor.

2.2.3.4 Heavy Metal Analysis

Heavy metal (Pb) measured using an Atomic Absorption Spectrophotometer (AAS). The analysis conducted in this study employed an Atomic Absorption Spectrophotometer, specifically the AAS-7800 Shimadzu, which is a very reliable and commonly used technique for measuring heavy metals concentration in wastewater (POME) (Jijingi et al., 2025).

Preparation of Samples for Atomic Absorption Spectrophotometer to exclude any solid particles that might hinder the measurement, the extracts from each sample were passed through a 0.45-micron membrane filter. This was followed by the addition of nitric acid (HNO_3) to the filtrate to immobilize the metals in the solution.

Standard calibration solutions for each of the identified heavy metals Lead (Pb) were prepared by diluting certified metal stock solutions in deionized water. To ensure quantification accuracy, a calibration curve was plotted by graphing the absorbance against concentration for each element.

The absorbance of each sample was measured at the wavelength corresponding to the target heavy metal. The quantities of the metals in the samples were determined using the calibration curve.

2.2.4 Statistical Analysis

Data were subjected to Analysis of Variance (ANOVA) to determine the effect of boiler ash dosage on the measured parameters. Where the ANOVA indicated a significant effect ($p < 0.05$), a post-hoc Duncan's Multiple Range Test (DMRT) was performed to compare treatment means. All statistical analyses were conducted using SAS 9.0 software.

3. RESULT AND DISCUSSION

3.1 Effect on pH and Compliance with Standards

The addition of boiler ash exerted a highly significant effect ($p < 0.01$) on the final pH of the liquid organic fertilizer. As shown in Table 1, pH values systematically increased with higher boiler ash dosages, ranging from 7.3 in the control (P0) to 7.5 in the P3 treatment. Critically, all formulations, including the control, produced a final pH within the 4-9 range stipulated by the national standard. Post-hoc analysis revealed that the 55 g dosage (P3) resulted in a significantly higher pH compared to the control. The most significant challenge in anaerobic fermentation of POME is the rapid accumulation of Volatile Fatty Acids (VFAs), which typically drops the pH and inhibits microbial activity. The addition of boiler ash acts as a natural alkaline reservoir. The alkaline oxides (K_2O, CaO, and MgO) and carbonates present in the ash react with the organic acids in POME. At the 55 g/L threshold, the system achieves a stoichiometric balance that buffers the pH to 7.5. This near-neutral state is optimal for methanogens and hydrolytic bacteria, ensuring a more complete decomposition of organic matter compared to the highly acidic control group.

This study successfully demonstrates that the synergistic combination of Palm Oil Mill Effluent (POME) and boiler ash through controlled fermentation can produce a high-quality liquid organic fertilizer (LOF). The results consistently show that increasing the dosage of boiler ash progressively and significantly improves all key chemical properties of the final product-pH, NPK macronutrient content, and C-Organic content. This approach represents a significant advancement in the valorization of byproducts from the palm oil industry, transforming two waste streams into a single, value-added agricultural input, a core tenet of the circular economy model for agro-industry (Siagian et al., 2024).

Table 1. Effect of Boiler Ash Dosage on the pH of Liquid Organic Fertilizer

Treatment	pH	Ministry of Agriculture Regulation No. 261/2019 Standard 4-9
P0 = 0 g boiler ash	7.3[c]	Compliant
P1 = 45 g boiler ash	7.4[bc]	Compliant
P2 = 50 g boiler ash	7.4[ab]	Compliant
P3 = 55 g boiler ash	7.5[a]	Compliant

The positive outcomes observed across all measured parameters are not independent phenomena but are intricately linked, with the boiler ash acting as the primary catalyst. The initial and most critical effect of the ash addition was the modulation of the fertilizer's pH (Table 1). By buffering the typically acidic POME and maintaining a stable, near-neutral pH (7.3-7.5), the ash created a more favorable environment for the microbial consortium introduced via the EM4 bioactivator. The initial and most critical effect of the ash addition was the modulation of the fertilizer's pH. By buffering the typically acidic POME, the ash created a more favorable environment for the microbial consortium. This finding is consistent with a large body of literature identifying pH regulation as a master variable governing the entire composting process (Yang et al., 2021).

Specifically, maintaining a suitable pH is paramount for mitigating carbon and nitrogen losses while enhancing the conservation of key nutrients (Li et al., 2023). The use of alkaline amendments, such as the boiler ash in this study, is a well-documented strategy to achieve this stabilization, thereby optimizing the final product quality (Xiao et al., 2017).

3.2 Macronutrient Enrichment

Boiler ash dosage had a highly significant positive effect ($p < 0.01$) on the content of all measured macronutrients (Total N, P_2O_5, and K_2O), as detailed in Table 2. The highest dosage (P3: 55 g) yielded the richest nutrient profile, with values of 0.51% N, 1.75% P_2O_5, and 1.67% K_2O. The total macronutrient content ($N+P_2O_5+K_2O$) increased from 3.06% in the control to 3.93% in the P3 treatment. All formulations successfully met the regulatory requirement of 2%-6% total macronutrients. The increase in total NPK to 3.93% indicates a highly efficient mineral leaching process. Boiler ash, a byproduct of burning shells and fibers, is naturally rich in silica-bound minerals. The acidic nature of raw POME facilitates the leaching of these minerals into the liquid phase.

Crucially, boiler ash functions not merely as a simple additive but as a multifunctional process ameliorant. First, it is a direct source of inorganic nutrients, significantly enriching the fertilizer with plant-available potassium (K_2O) and phosphorus (P_2O_5) (Table 2), a finding well-supported by the elemental characterization of various biomass ashes (Sun et al., 2023). Second, the improved pH and mineral balance fostered a more robust microbial metabolism. This enhanced activity likely stimulated more efficient nitrogen mineralization and fixation, explaining the significant increase in Total Nitrogen (Table 2), an element not present in the ash itself. Enhanced microbial N-cycling in pH-neutralized organic substrates has been extensively documented (Tiquia, 2002).

3.3 Enhancement of Organic Carbon Content

The C-Organic content was significantly influenced ($p < 0.05$) by the addition of boiler ash (Table 3). A clear positive trend was observed, with the P3 treatment achieving the highest C-Organic content at 12.42%. This was significantly greater than the control group (P0) at 10.26%. All treatments surpassed the minimum requirement of 10% C-Organic set by the national standard.

The high Organic Carbon (12.42%) content suggests that the minerals are not merely suspended but likely form stable organo-mineral complexes. These complexes are beneficial for soil application as they prevent rapid nutrient leaching and improve slow-release characteristics. The stable conditions promoted a fermentation pathway that conserved organic carbon, resulting in a higher final C-Organic percentage (Table 3) by minimizing carbon loss through methanogenesis, a common issue in untreated POME decomposition (Afrianti and Zainal, 2025). These findings have profound implications for sustainable agriculture and waste management. The method provides a practical blueprint for a circular economy within the palm oil sector, a priority highlighted in recent global sustainability assessments (UNEP, 2024). The resulting LOF, with its balanced NPK ratio, regulation-compliant pH, and high organic carbon content (>12% in the optimal treatment), is ideally suited for improving the health of tropical agricultural soils, which are often acidic and depleted of organic matter. As emphasized in a landmark (Lal, 2021), increasing soil organic carbon is paramount for enhancing nutrient retention, water-holding capacity, and long-term agricultural resilience.

While this study provides a strong proof-of-concept, future research should focus on scaling up production and conducting comprehensive agronomic trials to evaluate the fertilizer's long-term effects on crop yield and soil health. A thorough analysis of the boiler ash for potential heavy metals is also an essential next step to ensure environmental safety before widespread application, as the accumulation of trace metals from biomass ash is a recognized environmental concern (Putro, 2022). In conclusion, the strategic use of boiler ash to enrich and stabilize POME fermentation is a highly effective and sustainable method for producing a

Table 2. NPK Macronutrient Content of the Liquid Organic Fertilizer

Treatment	N (%)	P_2O_5 (%)	K_2O (%)	Total $N+P_2O_5+K_2O$ (%)	Ministry of Agriculture Regulation No. 261/2019 Standard
P0 = 0 g boiler ash	0.35^c	1.40^c	1.31^c	3.06	Compliant
P1 = 45 g boiler ash	0.39^{bc}	1.48^{bc}	1.36^{bc}	3.23	Compliant
P2 = 50 g boiler ash	0.40^b	1.51^b	1.42^b	3.33	Compliant
P3 = 55 g boiler ash	0.51^a	1.75^a	1.67^a	3.93	Compliant

Table 3. Average C-Organic Content of the Liquid Organic Fertilizer

Treatment	C-Organic (%)	Ministry of Agriculture Regulation No. 261/2019 Standard Minimum 10%
P0 = 0 g boiler ash	10.26^b	Compliant
P1 = 45 g boiler ash	10.96^{ab}	Compliant
P2 = 50 g boiler ash	11.42^{ab}	Compliant
P3 = 55 g boiler ash	12.42^a	Compliant

superior organic fertilizer. This research provides a clear, actionable pathway for the palm oil industry to transform its environmental liabilities into valuable assets, contributing significantly to both agricultural productivity and a more sustainable industrial ecosystem.

3.4 Heavy Metal Analysis (Pb Concentration)

The Pb concentration was significantly influenced ($p < 0.05$) by the addition of boiler ash (Table 4). To evaluate the environmental safety of the final product, lead (Pb) concentrations were analyzed for the optimal formulation. The product derived from the 55 g/L dosage contained a Pb concentration of 12.28 ppm. As detailed in Table 4, this concentration is significantly lower than the maximum allowable limit of 50 ppm defined by national safety standards. These results confirm that the integration of boiler ash at the specified dosage does not compromise the toxicological safety of the fertilizer for agricultural applications.

A critical concern in valorizing industrial byproducts is the presence of potentially toxic trace elements, which can accumulate in the soil-plant system (Judijanto, 2025). In this study, the Pb concentration in the optimal formulation (55 g/L) was detected at 12.28 ppm, which is significantly below the maximum threshold of 500 ppm stipulated by the Indonesian Ministry of Agriculture Regulation No. 261/2019.

The low bioavailability of Pb in the final product is governed by two synergistic mechanisms. First, the high Organic Carbon (12.42%) provides functional groups, such as carboxyl and hydroxyl, that act as natural chelating agents. These groups facilitate the formation of stable, non-toxic organo-mineral complexes with Pb^{2+} ions, effectively sequestering the metal within the organic matrix (Setiawan et al., 2025; Rezwan et al., 2024). Second, the neutralization of the system to pH 7.5 drastically reduces the solubility of Lead compared to its highly mobile and ionic state in acidic raw POME (Wu et al., 2009). In this near-neutral range, Pb tends to undergo surface precipitation or strong adsorption onto the porous silicate surfaces of the boiler ash (Hamzah et al., 2019; Euniza Jusli et al., 2022). These findings confirm that the synergistic use of POME and boiler ash not only optimizes nutrient recovery but also provides an inherent chemical safety barrier, ensuring the fertilizer is suitable for sustainable agricultural application without compromising environmental health (Euniza Jusli et al., 2022).

Table 4. Heavy metal (Pb) Concentration

Treatment	Pb (ppm)	Ministry of Agriculture Regulation No. 261/2019 Standard Minimum 10%
P0 = 0 g boiler ash	12.78^a	Compliant
P1 = 45 g boiler ash	13.35^b	Compliant
P2 = 50 g boiler ash	15.77^{bc}	Compliant
P3 = 55 g boiler ash	12.28^c	Compliant

4. CONCLUSIONS

This research concludes that the synergistic co-fermentation of Palm Oil Mill Effluent and boiler ash is a highly effective waste valorization strategy. An optimal dosage of 55 g of boiler ash per 1 L of POME produced a superior liquid organic fertilizer that significantly enhanced pH, macronutrient content, organic carbon levels, and safe Pb level. This formulation fully complied with national quality standards, demonstrating a viable, scientifically-grounded pathway for the palm oil industry to convert environmental liabilities into valuable assets for sustainable agriculture, thereby closing a critical loop in the circular economy.

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