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Potential of Boiler Ash from 30 and 60 Ton/Hour Palm Oil Mills as a Nutrient Source in Palm Plantation

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Abstract: The palm oil industry generates large amounts of biomass waste, one of which is boiler ash produced from the combustion of fiber and shell in palm oil mill boilers. Boiler ash is generally underutilized and is commonly stockpiled around factory areas, potentially causing environmental pollution. This study aimed to evaluate the potential of boiler ash from palm oil mills (POM) with capacities of 30 ton/hour and 60 ton/hour as a nutrient source for oil palm plantations. The research employed a quantitative descriptive method using mass balance analysis, laboratory analysis, and Independent Samples T-Test. The results showed that the 60 ton/hour POM produced a higher amount of boiler ash, reaching 16,712.75 tons, compared to 8,624.40 tons from the 30 ton/hour POM. Boiler ash from the 30 ton/hour POM had a higher Nitrogen content of 0.36%, while boiler ash from the 60 ton/hour POM contained higher levels of Potassium (4.79%), Phosphorus (2.17%), Magnesium (2.70%), and Calcium (6.87%). Statistical analysis indicated that most nutrient parameters showed significant differences at the 5% significance level. Boiler ash has strong potential to be utilized as an alternative nutrient source to support sustainable oil palm plantation systems and reduce dependence on inorganic fertilizers.

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INTRODUCTION

The palm oil industry is one of the most strategic agribusiness sectors and plays an important role in the Indonesian economy as the largest palm oil producer in the world. The increasing global demand for palm oil has encouraged higher production capacity and the expansion of palm oil mills (POMs) in various plantation areas. Along with the increasing processing activities of fresh fruit bunches (FFB), the amount of biomass waste generated has also increased significantly. These wastes include empty fruit bunches, fiber, shell, liquid waste, and boiler ash (Agustiar, 2022).

Boilers are important units in palm oil processing plants that function to generate steam as an energy source for mill operations. The primary fuel for boilers comes from biomass by-products such as fiber and shell. The combustion process produces boiler ash residue, which is still not optimally utilized and is mostly stockpiled around factory areas (Hikmawan et al., 2020). Continuous accumulation of boiler ash may lead to environmental pollution, including reduced air quality, changes in soil chemical properties, and environmental disturbances around the factory (Erwinson et al., 2023).

On the other hand, boiler ash contains nutrients beneficial for plant growth. Boiler ash contains macronutrients such as Potassium (K), Phosphorus (P), Magnesium (Mg), and Calcium (Ca), which are essential for the growth and development of oil palm plants (Isra et al., 2024). Potassium is the dominant nutrient that plays an important role in fruit formation, photosynthate translocation, and increasing palm oil production. In addition, Calcium and Magnesium in boiler ash can improve soil

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chemical properties and increase the pH of acidic soils commonly found in tropical oil palm plantations (Effendi et al., 2022).

The utilization of boiler ash as an alternative nutrient source can support sustainable agricultural systems and environmentally friendly industrial waste management. The use of boiler ash as a soil ameliorant and alternative fertilizer has the potential to reduce dependence on inorganic fertilizers, which are relatively expensive and may reduce soil quality if excessively applied over the long term (Handajaningsih et al., 2024). Furthermore, biomass waste utilization supports the circular economy concept in the palm oil industry through the conversion of waste into value-added products.

Several previous studies reported that boiler ash has significant potential to improve soil fertility and plant growth.Veranika et al. (2019) reported that boiler ash application increased soil pH and Potassium availability in plantation soils. Other studies also showed that nutrient content in boiler ash is influenced by biomass type, combustion temperature, and boiler operational efficiency (Tri & Sasongko, 2023). However, studies comparing boiler ash characteristics based on different palm oil mill capacities are still limited.

Palm oil mills with different processing capacities are expected to produce boiler ash with different characteristics. Palm oil mills with capacities of 30 ton/hour and 60 ton/hour are commonly used in Indonesia. Differences in processing capacity affect the amount of biomass burned and the operational intensity of the boiler, thereby influencing the quantity and quality of boiler ash produced (Sri Wahyuni et al., 2024). Therefore, studying the characteristics and potential of boiler ash based on mill capacity is important for more effective and efficient waste management. This study aimed to evaluate the potential of boiler ash from palm oil mills with capacities of 30 ton/hour and 60 ton/hour as nutrient sources in oil palm plantations through analysis of boiler ash production quantity, macro and micronutrient contents, and statistical differences between both mill capacities.

Previous studies have primarily focused on the application of boiler ash as a soil amendment or alternative fertilizer for improving soil fertility and plant growth. However, limited studies have compared the production quantity and nutrient characteristics of boiler ash generated by palm oil mills with different processing capacities. Variations in mill capacity may influence biomass consumption, combustion efficiency, and ultimately the nutrient composition of boiler ash. Therefore, this study provides a comparative evaluation of boiler ash produced by 30 ton/hour and 60 ton/hour palm oil mills. The novelty of this research lies in the integration of mass balance analysis, nutrient characterization, and statistical comparison to assess the potential utilization of boiler ash as an alternative nutrient source for sustainable oil palm plantation management.

RESEARCH METHOD

Research Location and Period

This study was conducted at two palm oil mills with different processing capacities, namely Adolina Palm Oil Mill with a capacity of 30 ton FFB/hour and Bah Jambi Palm Oil Mill with a capacity of 60 ton FFB/hour. Nutrient analyses were conducted at the Research and Development Centre Laboratory of PT. Nusa Pusaka Kencana Analytical and QC Bahilang, Tebing Tinggi, North Sumatra, Indonesia, which is accredited by the National Accreditation Committee (KAN) under ISO/IEC 17025:2017 standards. The study was carried out from April 2025 to April 2026.

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The research locations were selected purposively because they represent two commonly used processing capacities in the Indonesian palm oil industry, namely 30 ton/hour and 60 ton/hour. These mills were chosen to evaluate whether differences in processing capacity affect boiler ash production and nutrient characteristics. Boiler ash samples were collected from each mill with three replications under normal operating conditions, resulting in six total observations used for laboratory and statistical analyses.

Research Design

This study employed a quantitative descriptive approach to evaluate the potential of boiler ash as an alternative nutrient source for oil palm plantations (Effendi et al., 2022). The independent variable in this study was the capacity of the palm oil mill, consisting of 30 ton/hour and 60 ton/hour mills, while the dependent variables were the macro and micronutrient contents of boiler ash. Macronutrients analyzed included Nitrogen (N), Phosphorus (P), Potassium (K), Magnesium (Mg), and Calcium (Ca), whereas micronutrients included Boron (B), Copper (Cu), Zinc (Zn), Iron (Fe), and Manganese (Mn).

Boiler Ash Sampling

Boiler ash samples were collected using purposive sampling under normal mill operating conditions. Samples were taken directly from the dust collector outlet of each palm oil mill with three replications. The collected samples were weighed and converted into boiler ash production per minute, hour, and day. The average value of the three replications was used to estimate total boiler ash production. The estimation of boiler ash production was calculated using the following equation:

$$AB = \frac{W_s}{t} \times T$$

Where:

- AB = estimated boiler ash production (kg/day)
- W_s = sample weight collected (kg)
- t = sampling time (second)
- T = operational time conversion factor

The mass balance approach used in this study follows the law of conservation of mass, which states that the total mass entering the system is equal to the total mass leaving the system plus mass losses during processing (Bayu et al., 2023)

$$\sum M_{in} = \sum M_{out} + \sum M_{loss}$$

Where:

- $\sum M_{in}$ = estimated boiler ash production (kg/day)
- $\sum M_{out}$ = sample weight collected (kg)
- $\sum M_{loss}$ = mass loss during processing

Sample Preparation

Sample preparation was carried out according to standard methods for soil and fertilizer preparation (Keiter, 2019). Boiler ash samples were dried in an oven at 105°C for 2–4 hours until

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constant weight was achieved to remove moisture content. The dried samples were then ground using a porcelain mortar and sieved through a 0.5 mm sieve to obtain homogeneous particle sizes. Homogeneous samples were stored in airtight containers prior to laboratory analysis.

Nutrient Analysis

Nitrogen (N) analysis was conducted using the Kjeldahl method, which consists of destruction, distillation, and titration stages (Setyaningrum et al., 2024). Approximately 0.5 g of boiler ash sample was mixed with 10 mL concentrated H_2SO_4 and a catalyst mixture of K_2SO_4:$CuSO_4$ (10:1), then heated until a clear solution was obtained. The digest was distilled using 40% NaOH, and the released ammonia was trapped in 4% H_3BO_3 solution and titrated using 0.1 N HCl to determine total Nitrogen content. Phosphorus (P) analysis was performed using UV-Visible Spectrophotometry (Musa et al., 2024). Samples were digested using HNO_3:$HClO_4$ (4:1) until clear solutions were formed, followed by reaction with molybdate and ascorbic acid reagents to produce a phosphomolybdenum blue complex. Absorbance was measured at 880 nm using a UV-Visible Spectrophotometer based on NaH_2PO_4 standard curves. Potassium (K), Magnesium (Mg), Calcium (Ca), Iron (Fe), Copper (Cu), and Zinc (Zn) contents were analyzed using Atomic Absorption Spectrophotometry (AAS) (Rangkuti et al., 2021). Samples were digested using HNO_3:$HClO_4$ (4:1) and heated until clear solutions were obtained. Element concentrations were determined using standard calibration curves according to the AAS method (Nurventi, 2019).

Statistical Analysis

The laboratory analysis results were presented as mean values and standard deviations from three replications. Data analysis consisted of descriptive and inferential statistical analyses. Inferential analysis was performed using the Independent Samples T-Test at a significance level of α = 0.05 using IBM SPSS software to determine differences in nutrient contents between boiler ash from the 30 ton/hour and 60 ton/hour palm oil mills. The Independent Samples T-Test equation used in this study is presented as follows:

$$t = \frac{X_1 - X_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

Where:

- X_1 = mean nutrient content of boiler ash from the 30 ton/hour mill
- X_2 = mean nutrient content of boiler ash from the 60 ton/hour mill
- s_1^2 = variance of nutrient content in the 30 ton/hour mill
- s_2^2 = variance of nutrient content in the 60 ton/hour mill
- $n_1 \; and \; n_2$ = number of samples in each group

The Independent Samples T-Test was selected because the study compared the mean nutrient contents of boiler ash obtained from two independent groups, namely the 30 ton/hour and 60 ton/hour palm oil mills. This statistical method is widely used to determine whether significant differences exist between the means of two unrelated groups at a specified confidence level

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RESULTS AND DISCUSSION

Boiler ash production in palm oil mills was influenced by the amount of fresh fruit bunches (FFB) processed and the operational capacity of the mill. Fiber and shell generated during palm oil processing were utilized as boiler fuel to produce thermal energy and steam required for factory operations. The combustion process generated solid residues in the form of boiler ash, which potentially contains nutrients beneficial for oil palm plantations. The mass balance analysis showed that the 60 ton/hour palm oil mill produced a higher quantity of boiler ash than the 30 ton/hour mill due to greater biomass consumption and higher combustion intensity. Larger mill capacities required more fiber and shell as fuel, thereby increasing the amount of combustion residue generated. Similar findings were reported by Agustiar (2022), who stated that higher palm oil mill capacities contribute to increased biomass waste generation and ash production.

Table 1. Boiler Ash Production of Palm Oil Mills

Month	30 Ton/Hour Mill (ton)	60 Ton/Hour Mill (ton)
September	3.276,42	5.909,72
Oktober	2.837,43	5.463,62
November	2.510,55	5.339,41
Total	**8.624,40**	**16.712,75**

Based on Table 1, the total boiler ash production during September–November 2025 reached 8,624.40 tons in the 30 ton/hour mill, while the 60 ton/hour mill generated 16,712.75 tons. The highest production occurred in September for both mills, whereas lower production in October and November was associated with reduced FFB processing and fewer operational days. These findings indicate that operational intensity directly affects biomass combustion and ash generation. The large quantity of boiler ash produced demonstrates its significant potential for reutilization as an alternative nutrient source in oil palm plantations, supporting sustainable waste management and circular economy practices (Cerya et al., 2024).

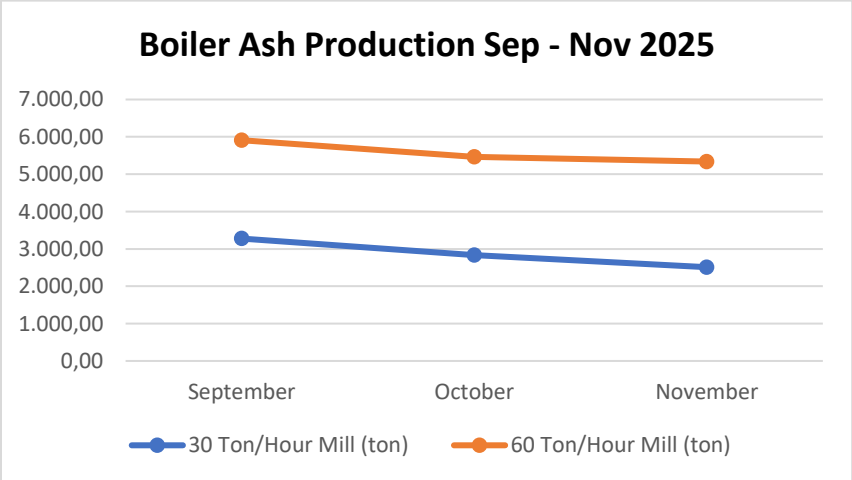

Figure 1. Boiler Ash Production from September to November 2025

Figure 1 illustrates the comparison of boiler ash production between the 30 ton/hour and 60 ton/hour palm oil mills during September–November 2025. The 60 ton/hour mill consistently

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produced higher boiler ash quantities than the 30 ton/hour mill because of greater fresh fruit bunch processing capacity and biomass combustion intensity. The highest production was observed in September, while production gradually decreased in October and November due to lower processing activities. These findings indicate that operational intensity directly affects biomass combustion and ash generation. The large amount of boiler ash produced demonstrates considerable potential for reutilization as an alternative nutrient source in oil palm plantations, supporting sustainable waste management and circular economy practices.

Laboratory analysis revealed that boiler ash from both palm oil mills contained considerable amounts of macro and micronutrients required for oil palm growth and development. However, nutrient composition differed between mill capacities due to differences in combustion efficiency and biomass utilization.

Table 2. Average Nutrient Content of Boiler Ash

Parameter	Unit	30 Ton/Hour Mill	60 Ton/Hour Mill
N	%	0,36	0,18
P	%	1,64	2,17
K	%	3,81	4,79
Mg	%	2,01	2,70
Ca	%	5,43	6,87
B	ppm	51,52	48,72
Cu	ppm	82,81	173,85
Zn	ppm	55,21	87,46
Fe	ppm	7973,75	8950,41
Mn	ppm	782,07	1208,77
pH	-	10,76	12,28

The results demonstrated that boiler ash from the 30 ton/hour mill contained higher Nitrogen concentrations than the 60 ton/hour mill. Higher Nitrogen content may indicate incomplete biomass combustion, leaving residual organic matter within the ash. Residual Nitrogen may contribute to vegetative growth by improving nitrogen availability in plantation soils. Conversely, boiler ash from the 60 ton/hour mill exhibited higher concentrations of Potassium, Phosphorus, Magnesium, and Calcium. Potassium was identified as the dominant nutrient and plays an essential role in photosynthate translocation, fruit formation, and oil palm productivity.

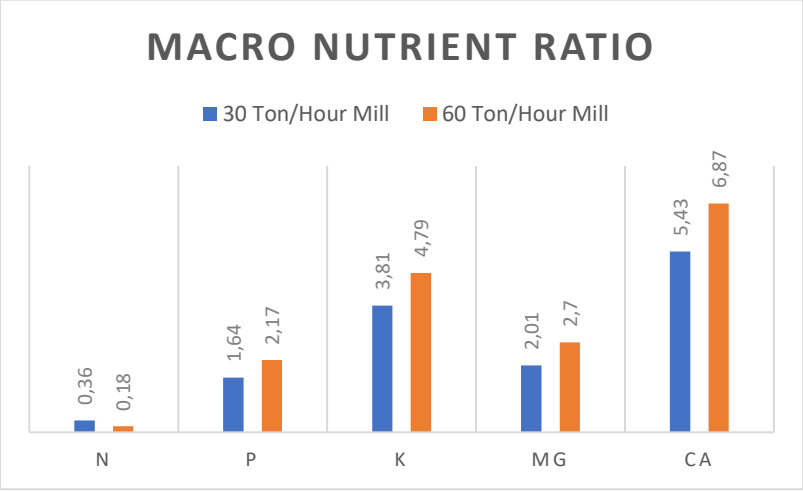

Figure 2. Comparison of Macronutrient Content in Boiler Ash

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Figure 2 presents the comparison of macronutrient contents in boiler ash produced by the two palm oil mill capacities. Boiler ash from the 60 ton/hour mill contained higher concentrations of Potassium (K), Phosphorus (P), Magnesium (Mg), and Calcium (Ca), while the 30 ton/hour mill exhibited higher Nitrogen (N) content. These differences indicate that processing capacity and combustion efficiency strongly influence the chemical characteristics of boiler ash. Higher mineral nutrient concentrations in the 60 ton/hour mill were likely associated with more efficient biomass combustion processes.

The observed differences in nutrient composition between the two mill capacities were likely associated with variations in biomass combustion efficiency and operational intensity. Higher-capacity mills generally require larger quantities of fiber and shell fuel, resulting in more complete combustion processes and greater mineral concentration in ash residues. Similar findings were reported by Tri and Sasongko (2023), who found that combustion conditions significantly influence the nutrient characteristics of boiler ash. These results support the theory that operational parameters in biomass combustion systems directly affect the quality and agronomic value of the resulting ash.

Micronutrient analysis indicated that Iron (Fe) and Manganese (Mn) were present in relatively high concentrations in both mill capacities. These micronutrients are essential for chlorophyll formation, enzyme activation, and photosynthesis. In general, the 60 ton/hour mill produced higher micronutrient concentrations than the 30 ton/hour mill, indicating that larger processing capacities and more efficient combustion systems may enhance mineral accumulation in boiler ash residues. Furthermore, the alkaline characteristics of boiler ash, indicated by pH values above 10, suggest strong potential as a soil ameliorant capable of improving acidic plantation soils.

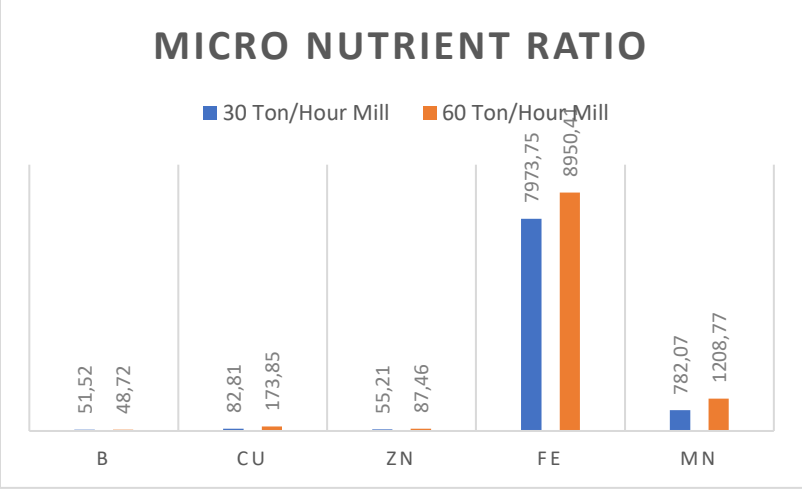

Figure 3. Comparison of Micronutrient Content in Boiler Ash

Figure 3 shows the micronutrient composition of boiler ash produced by the two palm oil mill capacities. Iron (Fe) and Manganese (Mn) were identified as the dominant micronutrients in both samples. The 60 ton/hour mill generally produced higher concentrations of Copper (Cu), Zinc (Zn), Iron (Fe), and Manganese (Mn) than the 30 ton/hour mill, indicating greater mineral accumulation resulting from higher combustion intensity and operational efficiency. Statistical analysis using the Independent Samples T-Test was performed to determine whether nutrient contents differed significantly between the two mill capacities.

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Table 3. Independent Samples T-Test Results

Parameter	p-value	Description
N	<0,05	Significantly different
P	<0,05	Significantly different
K	<0,05	Significantly different
Mg	<0,05	Significantly different
Ca	<0,05	Significantly different
Mn	<0,05	Significantly different
Cu	<0,05	Significantly different
Zn	<0,05	Significantly different
Fe	<0,05	Significantly different
B	>0,05	Not Significantly different

The statistical analysis revealed that most nutrient parameters differed significantly between boiler ash from the 30 ton/hour and 60 ton/hour mills at the 5% significance level. These findings indicate that mill processing capacity significantly influences the chemical characteristics of boiler ash. The 60 ton/hour mill generally produced ash with higher mineral nutrient concentrations due to more intensive and efficient biomass combustion. More complete combustion likely increased mineral concentration while reducing residual organic matter. In contrast, the 30 ton/hour mill produced ash with higher Nitrogen content because incomplete combustion left more organic residues. The Boron (B) concentration did not differ significantly, suggesting that this micronutrient was less influenced by processing capacity and combustion intensity.

The findings of this study demonstrate that boiler ash possesses substantial potential as an alternative nutrient source in sustainable oil palm plantation systems. The high concentrations of Potassium, Calcium, Magnesium, and Phosphorus indicate that boiler ash may function both as an alternative fertilizer and as a soil ameliorant. The alkaline properties of boiler ash can improve acidic soils, increase nutrient availability, and support oil palm growth. From a practical perspective, the 60 ton/hour mill offers greater potential for large-scale boiler ash utilization because it produces larger quantities of ash with higher mineral concentrations. However, boiler ash from the 30 ton/hour mill may be more suitable during vegetative growth stages due to its higher Nitrogen content. Therefore, boiler ash application can be adjusted according to plantation nutrient requirements and growth phases. These findings support environmentally sustainable plantation management by reducing industrial waste accumulation and minimizing dependence on synthetic fertilizers, thereby contributing to circular economy implementation in the palm oil industry. From a practical perspective, boiler ash can be utilized as an alternative nutrient source to partially substitute inorganic fertilizers in oil palm plantations. The high concentrations of Potassium, Calcium, and Magnesium suggest that boiler ash may contribute to improving soil fertility and reducing fertilizer costs. Furthermore, its utilization can minimize waste accumulation around palm oil mills and support environmentally sustainable plantation management practices.

This study has several limitations. The analysis was conducted on boiler ash samples collected from only two palm oil mills representing different processing capacities, which may not fully represent the variability of all palm oil mills in Indonesia. In addition, the study focused on nutrient characterization and did not evaluate the direct effects of boiler ash application on soil properties or oil palm growth under field conditions. Therefore, future research should investigate long-term field applications of boiler ash to assess its agronomic effectiveness and environmental impacts.

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CONCLUSION

Boiler ash produced by palm oil mills with capacities of 30 ton/hour and 60 ton/hour has considerable potential as an alternative nutrient source for oil palm plantations. The 60 ton/hour mill generated a larger quantity of boiler ash and generally contained higher concentrations of Potassium, Phosphorus, Magnesium, Calcium, and micronutrients, whereas the 30 ton/hour mill exhibited higher Nitrogen content. Statistical analysis confirmed significant differences in most nutrient parameters between the two mill capacities. These findings indicate that mill processing capacity influences the nutrient characteristics of boiler ash and its potential utilization in plantation systems. The application of boiler ash may contribute to sustainable waste management, improved soil fertility, and reduced dependence on inorganic fertilizers in the palm oil industry.

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