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Optimization of the Utilization of Registered Non-Hazardous Waste (Fly Ash and Bottom Ash from Coal-Fired Power Plants) Based on Their Physical and Chemical Properties

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ABSTRACT

Energy supply plays a critical role in national development, with coal-fired power plants (PLTU) serving as a primary energy source in Indonesia. However, PLTU operations generate significant volumes of coal combustion residues, namely Fly Ash and Bottom Ash (FABA), which present both environmental challenges and economic opportunities. This study examines the Optimization of the Utilization of Registered Non-Hazardous Waste (Fly Ash and Bottom Ash from Coal-Fired Power Plants) Based on Their Physical and Chemical Properties. The research highlights the essential role of energy supply in national development, emphasizing the growing demand for energy, particularly from coal-fired power plants in Indonesia. It discusses the generation and management of coal ash waste, including Fly Ash and Bottom Ash, along with recent policy changes that classify these materials as non-hazardous waste. The study outlines sustainable strategies for utilizing this waste, addressing environmental concerns while unlocking economic potential. Using a quantitative approach, data were collected from coal-fired power plants, providing insights into waste management practices and the potential to enhance the sustainability of FABA utilization. The findings aim to enrich the body of knowledge on waste management and deliver practical benefits for industries engaged in energy production and waste utilization. Theoretically, this research advances the understanding of waste characterization and its relationship to utilization potential. Practically, it offers technical guidance for PLTU operators and related industries in selecting appropriate FABA utilization strategies based on specific waste characteristics, thereby supporting circular economy principles and environmental sustainability.

KEYWORDS *Bottom Ash, Coal Ash, Fly Ash, Indonesia, Sustainability, Waste Management*

INTRODUCTION

Energy security remains a fundamental pillar of economic development in developing nations, with coal-fired power plants continuing to dominate the energy landscape in many Asian countries, particularly Indonesia (Zhang et al., 2020;

Wang & Chen, 2021). The global environmental impact of coal-based power plant waste has become increasingly significant, with annual worldwide coal ash production exceeding 1.2 billion tons (Yao et al., 2015; Ahmaruzzaman, 2010). Countries heavily dependent on coal-fired power plants, such as China, India, and Indonesia, face mounting challenges in managing these waste streams sustainably (Sharma & Bhattacharya, 2021; Kumar et al., 2022). In Indonesia, the environmental burden is further compounded by rapid industrialization and urbanization, necessitating innovative approaches to waste management that align with circular economy principles (Wijaya et al., 2023; Prasetyo & Gunawan, 2022).

The total coal demand for electricity generation in coal-fired power plants (PLTU) in Indonesia amounts to 58.6%, or approximately 153 million tons of coal, according to the energy mix in the 2021–2030 Electricity Supply Business Plan (RUPTL 2021). PLTU operations generate around 10% solid waste in the form of coal combustion residues known as fly ash and bottom ash, with fly ash accounting for 80% and bottom ash 20% (Sharma et al., 2020).

The physical and chemical characteristics of FABA waste directly influence its utilization potential and determine appropriate waste management strategies (Rafieizonooz et al., 2022; Blissett & Rowson, 2012). Understanding these characteristics is crucial because particle size distribution, chemical composition, and mineralogical properties significantly affect the technical feasibility and economic viability of various utilization applications (Ahmaruzzaman, 2010; Kutchko & Kim, 2006). For instance, fine-grained fly ash with high pozzolanic properties is particularly suitable for cement and concrete applications, while coarser bottom ash serves better as an aggregate material in construction (Yao et al., 2015; Singh & Siddique, 2013). Therefore, comprehensive characterization of FABA waste is essential for developing targeted utilization strategies that maximize resource recovery while minimizing environmental impacts.

Fly ash is generally a fine particulate matter produced from the combustion of coal in boilers. These particulates are gray to white in color and contain mineral components such as silica, alumina, and calcium oxide (Sutrisno et al., 2023). Previous research has extensively documented various approaches to fly ash and bottom ash management and utilization, particularly in construction materials and environmental remediation. Internationally, studies have demonstrated successful applications of fly ash in geopolymer concrete production (Provis & Van Deventer, 2014; Singh et al., 2015), soil stabilization (Kolias et al., 2005; Syed & Gupta, 2018), and heavy metal removal from wastewater (Wang et al., 2008; Jha et al., 2008).

In the Indonesian context, several researchers have investigated FABA utilization in cement production (Triwulan et al., 2020; Nurwidayati et al., 2021), road construction materials (Pradana et al., 2019; Setyawan et al., 2020), and agricultural applications as soil amendments (Kurniawan & Hadiyarto, 2020; Sari et al., 2021). However, research gaps remain regarding the optimization of utilization strategies based on comprehensive physical and chemical characterization, particularly for Indonesian coal sources, which exhibit distinct properties compared to coal from other regions (Ekaputri & Bari, 2021; Damayanti et al., 2018). Furthermore, limited studies have explored the integration of recent policy changes regarding FABA reclassification with practical utilization technologies, especially considering the variability of waste characteristics across different PLTU facilities in Indonesia (Asof et al., 2022; Sutrisno et al., 2023). In contrast, bottom ash consists of coarse particles or unburned coal fragments remaining after combustion in PLTUs, typically dark in color with a rough texture (Sutrisno et al., 2023).

The national estimate for FABA (Fly Ash and Bottom Ash) waste generation, based on 2018 calculations, is projected to range between 87 and 139 million tons by 2028 (MKI, 2021). Another estimate predicts that fly ash waste generation will increase by 10.7 million tons per year by 2027 (Ekaputri & Bari, 2021).

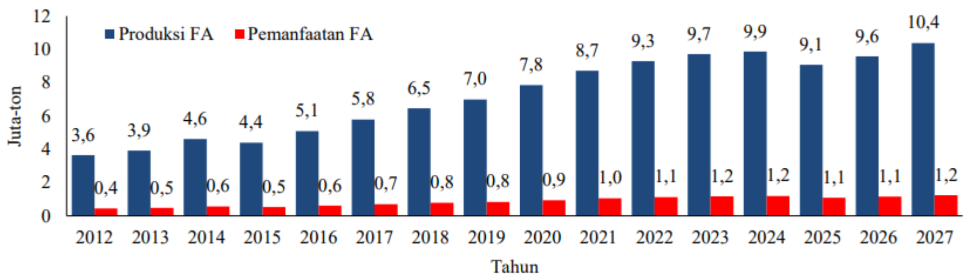

Figure 1 Estimated Fly Ash Waste Generation in Indonesia
(Source: Ekaputri & Bari, 2021)

In 2021, the Government of Indonesia removed FABA from the list of hazardous and toxic waste (B3), as regulated in Government Regulation No. 22 of 2021 concerning the Implementation of Environmental Protection and Management. The classification is now divided into Fly Ash with code N106 and Bottom Ash with code N107, both originating from coal combustion processes in coal-fired power plants (PLTU) or other activities using technologies other than stoker boilers and/or industrial furnaces.

This policy change represents a significant innovation in Indonesia's waste management framework, enabling the application of advanced technologies such as alkali-activated materials, geopolymer synthesis, and mineral carbonation for FABA valorization (Abdullah et al., 2021; Gunawan et al., 2022). The reclassification facilitates broader industrial applications, including zeolite synthesis for environmental remediation (Mushtaq et al., 2019; Inada et al., 2020), rare earth element recovery (Franus et al., 2015; Zhang et al., 2020), and advanced ceramic production (Xu et al., 2014; Koukouzas et al., 2021). Moreover, emerging technologies in Indonesia are now exploring FABA utilization in carbon capture and storage applications, contributing to climate change mitigation efforts (Rahman et al., 2022; Hidayat et al., 2023).

The economic and environmental impacts of FABA waste are substantial and multifaceted. Economically, improper management of approximately three million tons of annual FABA waste from PLN-managed facilities incurs significant costs associated with land acquisition for disposal sites, environmental monitoring, and potential environmental remediation (PLN, 2023; Nugroho & Santoso, 2021). Studies indicate that effective utilization could generate economic value ranging from USD 15 to 50 per ton of FABA, depending on the application, potentially creating a multi-million-dollar industry while reducing disposal costs (Pandey & Singh, 2010; Yao et al., 2015).

Environmentally, the accumulation of FABA in disposal sites poses risks, including groundwater contamination from leachate containing heavy metals, soil degradation, air pollution from dust emissions, and the loss of valuable land resources (Izquierdo & Querol, 2012; Gollakota et al., 2019). Furthermore, inefficient management contradicts sustainable development goals and circular economy principles, resulting in missed opportunities to conserve natural resources and reduce carbon footprints through material substitution in construction and other industries (Hemalatha & Ramaswamy, 2017; Xu et al., 2020). Therefore, developing efficient management strategies is critical not only from an environmental perspective but also for economic sustainability and regulatory compliance (Directive, 2008; Singh & Siddique, 2016).

According to PLN data, there are currently 46 coal-fired power plants under PLN's management throughout Indonesia. These plants generate approximately three million tons of FABA waste per year that must be managed (PLN, 2023). The policy change reclassifying coal combustion ash waste as registered non-hazardous waste presents both an opportunity and a challenge for waste producers, namely PLTUs, to implement broader and more sustainable waste utilization strategies.

The aim of this study is to identify the most effective ways to utilize fly ash and bottom ash waste from PLTUs more efficiently by leveraging information on the physical and chemical properties of the waste. Theoretically, this research contributes to the body of knowledge on waste characterization and sustainable waste management by establishing clear correlations between FABA physical–chemical properties and optimal utilization pathways, thereby enriching the scientific understanding of coal combustion residue valorization in tropical contexts. Practically, this study provides actionable technical guidance for PLTU operators, construction material manufacturers, and environmental managers in selecting appropriate FABA utilization strategies based on specific waste characteristics, supporting the implementation of circular economy principles, reducing environmental burdens, and generating economic value from industrial waste streams. Furthermore, the findings offer empirical evidence to support policy development and industrial standards for sustainable FABA management in Indonesia and similar developing nations.

RESEARCH METHOD

The approach used in this study is a quantitative approach, combined with both quantitative and qualitative methods. This research was conducted at Power Plant A, one of the coal-fired power plants under PLN management in Indonesia, selected based on its representative FABA production capacity and accessibility for data collection. The research population consists of all FABA waste generated by Power Plant A during the 2021-2024 period, with sampling conducted using purposive sampling technique to ensure representation across different production periods and operational conditions.

Data collection was performed through two primary techniques: (1) laboratory testing of FABA samples to determine physical and chemical properties according to Indonesian National Standards (SNI) and ASTM standards, and (2) document review of plant operational records, environmental monitoring reports, and waste management data. Primary data sources include laboratory test results from accredited testing facilities, while secondary data sources comprise plant documentation, previous research, government regulations, and industry standards. Data analysis was conducted using descriptive statistical methods to characterize physical and chemical properties, comparative analysis against established standards (SNI 2460:2014, ASTM C618), and content analysis to identify potential utilization pathways based on the observed characteristics. The analytical framework integrates quantitative measurements with qualitative assessment of utilization potential, ensuring comprehensive evaluation of FABA management opportunities.

RESULT AND DISCUSSION

The characteristics of waste depend on its physical and chemical properties. This is consistent with the research by Rafieizonooz (2022), which states that these characteristics can influence the behavior, potential management approaches, and the resulting impacts of the waste. Understanding waste characteristics is crucial as it is the initial step in identifying utilization potential and the most suitable handling methods.

Table 1 Physical Characteristics of Registered Non-Hazardous Waste (Non-B3) FABA from Power Plant A

Physical Characteristics	Fly Ash Waste	Bottom Ash Waste
Color	Gray	Black
Particle size variation (%)	97.29% of particles are smaller than 0.18 mm	90.72% of particles are larger than 0.18 mm, with details: • 64.72% >0.85 mm • 74.56% >0.50 mm • 79.83% >0.30 mm
Moisture Content (%)	0.19 – 0.53	2.92 – 5.16
Unburned Carbon (%)	0.05	0.18

Source: Monitoring Data of XYZ Power Plant

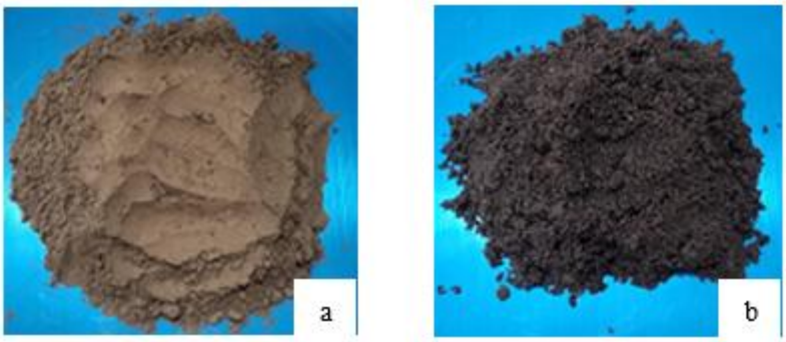

Figure 2 Registered Non-Hazardous Waste (FABA) from Power Plant A
(a) Fly Ash Waste (b) Bottom Ash Waste

Fly ash tends to have a lighter and brighter color compared to bottom ash, influenced by the type of coal used and the amount of unburned carbon in the combustion process. Fly ash particles are finer than bottom ash. The fine particles of fly ash are well-suited for further management, such as utilization in technical applications like concrete production. This fine quality contributes to performance stability. The particle size characteristics from Power Plant A indicate strong potential for use in construction applications and as raw material in cement production.

On the other hand, bottom ash naturally has a larger and more irregular particle shape, making it suitable for civil engineering applications that do not require fine materials—such as fill material, road construction aggregate, non-structural concrete mix, and land reclamation. The moisture content in FABA should be maintained at a low level, as low moisture content optimizes its use in various engineering applications.

Chemical Characteristics of Registered Non-Hazardous Waste (FABA) from Power Plant A

The chemical characteristics of FABA depend on the minerals present in the coal source and combustion conditions. The results are compared with the Indonesian National Standard (SNI) 2460:2014, which refers to ASTM C618-08a, concerning the specification for fly ash and raw or calcined natural pozzolan used in concrete.

Table 2 Chemical Characteristics of FABA from Power Plant A

Parameter	**SNI 2460 Kelas F-C**	***Fly Ash***				***Bottom Ash***			
		2021	**2022**	**2023**	**2024**	**2021**	**2022**	**2023**	**2024**
SiO_2 %	-	50.07	34.83	41.19	34.72	48.95	38.11	43.88	39.17
Al_2O_3		20.04	13.45	9.79	23.05	20.03	11.23	7.31	15.68
Fe_2O_3		2.29	11.02	9.10	12.17	0.84	10.61	10.62	12.51
CaO	>18	8.86	10.73	9.48	9.17	3.19	9.02	8.51	7.93
MgO		1.44	4.68	4.80	3.79	0.92	4.33	2.56	3.41
SO_3		1.25	0.8	0.53	0.70	0.73	0.32	0.29	0.25
Na_2O		0.41	5.80	2.85	1.32	0.36	4.36	4.01	1.36
K_2O		0.37	1.31	0.52	0.72	0.33	0.53	0.13	0.45
Loss Of Ignition (LOI) %	<6	1.68	0.32	1.76	0.41	2.54	2.99	4.05	4.0
SiO_2 + Al_2O_3 + Fe_2O_3 %	>50 %	72,4	59,3	60.08	69.94	69.82	59,95	61,8	67,36

Based on Table 2, the chemical content in FABA from Power Plant A consists of SiO_2 (silica), Al_2O_3 (alumina), Fe_2O_3 (iron oxide), Ca, K, and Na. This aligns with Damayanti (2018), which found that Indonesian FABA mainly contains oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and SO_3. These minerals are influenced by the type of coal and combustion process. Fly ash has a combined oxide content (SiO_2 + Al_2O_3 + Fe_2O_3) ranging from 59.3% to 72.4%, classified as Class F to Class C, indicating strong pozzolanic characteristics.

According to SNI 2460:2014 and ASTM C618, fly ash is classified into:

1. Class F – Pozzolanic, with oxide content >70%
2. Class C – Pozzolanic and cementitious, with oxide content >50%
3. Class N – Natural pozzolan, raw or calcined

The CaO (calcium oxide) content in fly ash is relatively stable (8–10%), slightly higher than in bottom ash (7–9%). CaO is essential for pH neutralization, especially in acid mine drainage treatment, and serves as a pH stabilizer for soil in agriculture and land rehabilitation, as supported by Saputra (2024). It also plays a role in concrete binding, waste treatment, and pollution control. High calcium content also indicates potential for use as a soil conditioner, forming silicates, oxides, sulfates, and carbonates (Asof, 2022).

MgO (magnesium oxide) in both fly ash and bottom ash contributes to acid neutralization, soil pH improvement, and has significant roles in waste processing, pollution control, and construction. It can also be used in durable concrete, chemical catalysts, and agricultural applications.

SO_3 (sulfur trioxide) remains below the 5% threshold during the 2021–2024 test period. It helps regulate quality in cement substitutes, lowers pH in wastewater treatment, and is used in flue gas desulfurization systems to reduce SO_2 emissions.

FABA contains Na_2O (sodium oxide), consistent with Yao (2015), which notes its role in durable building materials, metal and chemical processing, and wastewater treatment.

LOI (Loss on Ignition) in fly ash ranges between 0.32%–1.76%, while in bottom ash it ranges from 2.54%–4.05%. LOI measures the mass lost during high-temperature combustion (typically around 750–1000°C). High LOI indicates the presence of unburned carbon.

Table 3 Potential Utilization of Registered Non-Hazardous Waste (FABA) from Power Plant A Based on Chemical Characteristics

Potential Utilization (Fly Ash and Bottom Ash)	**Key Characteristics**	**Reference Standards**
Cement Raw Material Substitute	SiO_2, Al_2O_3, Fe_2O_3	1. SNI 15-0302:2004 2. SNI 2460:2014 (ASTM C618-08a)
Batching Plant Raw Material Substitute	SiO_2, Al_2O_3, Fe_2O_3	SNI 974:2011, 7833:2012, 2847:2013, 4433:2016
Concrete, Paving Block, Brick	SiO_2, Al_2O_3, Fe_2O_3	SNI 03-0691:1996, 03-0349:1989
Selected Fill Material	$SiO_2 + Al_2O_3 + Fe_2O_3 > 50\%$, LOI $\leq 6\%$	SNI 1744:2012, 1742:2012, 9092:2022
Foundation Layer	$SiO_2 + Al_2O_3 + Fe_2O_3 > 50\%$, LOI $\leq 6\%$	SNI 6427:2012, 6887:2012, 9092:2022
Soil Conditioner	SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O	Agriculture Ministerial Decree No.261/2019
Acid Mine Drainage Neutralizer	CaO, MgO, SiO_2	SNI 9264:2014

Source: Researcher, 2025

The findings from this study corroborate and extend previous research on FABA characterization and utilization. The particle size distribution observed in Power Plant A's fly ash, with 97.29% finer than 0.18 mm, aligns with international studies by Ahmaruzzaman (2010) and Blissett & Rowson (2012), who reported similar fineness characteristics in Class F fly ash, confirming its suitability for pozzolanic applications. This fine particle structure enhances the material's reactivity in cementitious systems, as demonstrated by Hemalatha & Ramaswamy

(2017) in their investigation of fly ash-based geopolymers. The chemical composition, particularly the combined oxide content (SiO_2 + Al_2O_3 + Fe_2O_3) ranging from 59.3% to 72.4%, is consistent with findings by Yao et al. (2015) and Singh & Siddique (2013), who established that such composition levels are optimal for concrete and cement applications. Furthermore, the low LOI values (0.32%--1.76% in fly ash) support the conclusions of Kutchko & Kim (2006), who argued that low unburned carbon content is critical for achieving desirable concrete performance, particularly regarding air entrainment and strength development.

The study's identification of multiple utilization pathways is supported by theoretical frameworks in circular economy and industrial ecology. The resource recovery hierarchy proposed by the European Union's Waste Framework Directive (2008) emphasizes maximizing value extraction from waste materials, which this research operationalizes through comprehensive characterization and targeted application matching. The application of FABA in construction materials aligns with the sustainable construction paradigm articulated by Xu et al. (2020), who advocated for substituting virgin materials with industrial by-products to reduce environmental footprints. Additionally, the potential use of FABA in agricultural applications as soil conditioners is grounded in soil science principles discussed by Syed & Gupta (2018), who demonstrated that fly ash can improve soil structure, water retention, and nutrient availability in degraded lands.

The variation in chemical composition across different sampling periods (2021-2024) reflects the influence of operational parameters and coal quality variations, as theorized by Wang & Chen (2021) in their study of coal combustion dynamics. This temporal variability underscores the importance of continuous monitoring and adaptive management strategies, consistent with the adaptive capacity framework in environmental management literature (Gollakota et al., 2019). The study's findings on CaO content and its role in acid mine drainage neutralization extend the work of Koukouzas et al. (2021), who explored similar applications in European contexts, demonstrating the universal applicability of FABA in environmental remediation despite regional coal source differences.

Moreover, the research contributes to the growing body of evidence supporting policy reforms in waste classification. The reclassification of FABA from hazardous to non-hazardous waste in Indonesia, as analyzed by Ekaputri & Bari (2021), is validated by this study's characterization data, which demonstrates that Power Plant A's FABA meets safety standards for broader industrial applications. This finding has significant implications for regulatory frameworks in other developing nations facing similar waste management challenges, as discussed by Wijaya et al. (2023) in their comparative analysis of waste regulations in Southeast Asian countries.

CONCLUSION

The registered non-hazardous waste (FABA) from PLTU A has chemical characteristics that include SiO_2 (silica), Al_2O_3 (alumina), Fe_2O_3 (iron oxide), Ca, K, and Na, indicating a high potential for utilization through various methods. Based on these characteristics, the possible applications include use as raw material for cement, batching plant materials, concrete production, paving blocks, and bricks. In addition, it can be used for selected fill, road foundation, land reclamation, and acid mine drainage neutralization. The comprehensive physical and chemical characterization conducted in this study demonstrates that FABA from Power Plant A possesses properties suitable for multiple value-added applications, supporting circular economy implementation in Indonesia's energy sector. The low LOI values, appropriate particle size distribution, and balanced chemical composition position this waste stream as a valuable resource rather than a disposal burden. Future research should explore long-term performance evaluation of FABA-based products, life cycle assessment of different utilization pathways, and economic feasibility studies to support industrial-scale implementation of the identified utilization strategies.

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