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Comparative Analysis of FABA Waste Composition in Various Coal-Fired Power Plant Industries in Several Countries and Indonesia: A Review

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Abstract—Fly Ash and Bottom Ash (FABA) is the waste from burning coal in coal-fired power plants and consists of chemical compounds, such as SiO_2, Al_2O_3, Fe_2O_3, and CaO. This waste poses an environmental challenge and an opportunity for the construction industry. This study conducted a comparative analysis of the composition of FABA from several coal-fired power plants in Indonesia and other countries, such as Thailand, China, Malaysia, France, Italy, and Portugal. In particular, this study assessed the XRF data from several other references. The XRF test data showed significant variations in the FABA content, influenced by coal type, combustion method, and emission management technology. The high SiO_2 content in the Cirebon and Teluk Sirih coal-fired power plants showed potential for pozzolanic applications. Meanwhile, the high Fe_2O_3 in Tanjung Enim and Sudimoro had the potential for metallurgical applications. In addition, the high CaO content of Teluk Sirih allowed its use in lime production and soil stabilization. However, high levels of SO_3, especially in Cirebon, required more attention in processing because of its impact on concrete quality and environmental pollution. With proper processing, FABA could be a valuable resource in various industries, reducing reliance on natural raw materials. This study highlighted the potential for the sustainable use of FABA and proposed management measures to address environmental challenges. The optimal use of FABA reduced negative environmental impacts and opened up significant economic opportunities, supporting the circular economy in the energy and construction sectors.

Keywords— *Characteristic XRF; Fly ash bottom ash; Metal oxide; Power plant industries.*

1. INTRODUCTION

Waste ash from coal-fired power plants, known as Fly Ash and Bottom Ash (FABA), is a by-product of coal combustion process and is generated in large quantities all over the globe [1]. As energy consumption increases, especially in developing countries, the volume of FABA waste continues to rise, posing considerable challenges in management and utilization [2]. This waste consists of various chemical compounds, such as SiO_2, Al_2O_3, Fe_2O_3, and CaO [3], whose composition highly depends on the type of coal used, combustion technology, and the ash management method in each power plant.

FABA has excellent potential [4] to be used in a wide range of industrial applications, especially in the construction [5] and materials sectors, given its high silica [6], alumina, and calcium content. If disposed of carelessly, improper management of FABA waste can negatively impact the environment, including soil and water pollution, and increase greenhouse gas emissions. The use of FABA as a raw material in the production of cement [7], concrete [8], and other building materials not only can reduce environmental impacts but also contribute to the reduction of carbon emissions by partially replacing the use of energy-intensive conventional cement.

Nevertheless, the composition of FABA varies significantly in various power plants around the world, leading to differences in the physical and chemical characteristics of these wastes. This variation is caused by several factors, such as coal type, plant operational conditions, combustion technology, and emission management systems. Therefore, it is pivotal to conduct

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a comparative analysis of the composition of FABA waste from various power plants to understand its specific characteristics and maximize its potential use in multiple industrial applications.

This study identifies differences in the chemical composition of FABA from various sources and explores its potential use in the construction industry and other sectors. With a better understanding of the composition and characteristics of FABA, this waste could be managed and used more efficiently. Therefore, providing sustainable economic and environmental benefits sustainably. In this study, a comparative analysis of the composition of FABA from various coal-fired power plants in several countries, including Indonesia and Malaysia, is examined.

If FABA waste is left untreated without proper management, its negative impact on the environment and human health can be serious. One of the main problems is the potential for environmental pollution, especially in soil and groundwater. FABA contains a variety of harmful compounds, including heavy metals, such as arsenic, mercury, and lead, which can dissolve and contaminate water sources if not managed properly. In addition, very fine-sized FABA dust can be inhaled by humans, causing respiratory problems, such as lung disease and asthma[9], especially in areas near power plants or dumps.

The solution to overcoming the dangers of FABA is to implement this waste reuse strategy. One of the most common approaches is the use of FABA as a construction material, such as a mixture in the manufacture of concrete and cement because its high silica and alumina content allows for pozzolanic reactions [10]. FABA can also be used as a material for soil stabilization in infrastructure projects, replacing more expensive and hard-to-obtain natural materials. FABA treatment can also include emission reduction technologies, such as flue gas desulfurization (FGD) systems, to reduce the sulfur content in waste. In addition, chemical stabilization techniques can be applied to minimize the mobility of heavy metals, thereby making the waste safer for use in construction projects or disposal at controlled waste disposal sites.

A more integrated approach to FABA management is needed to ensure that this waste is not only managed safely but also used optimally. In this way, the environmental and health risks posed by FABA waste can be minimized, while the waste is converted into useful resources, supporting the principles of a more sustainable circular economy.

2. CHARACTERIZATION XRF FLY ASH BOTTOM ASH (FABA)

The chemical compositions of prepared fly ash and bottom ash samples were analyzed using an X-ray fluorescence (XRF) spectrometer. The Other data on chemical compositions used data from some articles on the Mae Moh power plant in the north of Thailand ([11]), the Tanjung Bin power plant, Johor, [12], ENEL (coal-fired power plant Federico II, Brindisi, Italy) [13], Power Plant China, France, and Portugal [14], a coal-fired power plant in Teluk Sirih, Malaysia [16], and a coal-fired power plant in Indonesia [15], including a coal-fired power plant in Cirebon [17], a coal-fired power plant in Kutai Kartanegra [18], Tanjung Jati [19], Tanjung Enim [20], Sudimoro [21], and Tuban [22].

3. COMPARATIVE ANALYSIS OF FABA WASTE COMPOSITION IN SEVERAL COUNTRIES

The XRF was used to analyze the Chemical Composition of the FA (Fly Ash) and BA (Bottom Ash) from waste from steam power plants in several countries like Indonesia, China, France, Italy, Japan, Portugal, Thailand, and Malaysia. The chemical composition results are presented in Error! Reference source not found. and Error! Reference source not found.. Chemical Compositions include: SiO_2, Fe_2O_3, CaO, Al_2O_3, MgO, SO_3, TiO_2, P_2O_5, Na_2O, K_2O, SrO, MnO, Sc_2O_3, BaO, NiO, Cr_2O_3, and ZnO. FA and BA have almost similar contents because they come from the same process and materials used in the performance of steam power plant systems.

The highest metal oxide content in FABA waste is attributed to SiO_2 compounds, whereas the remaining compounds have different metal oxide contents. Generally, the metal oxide compounds that are most commonly identified are Al_2O_3, Fe_2O_3, CaO, and MgO. The lowest metal oxide content differs by country. This is because the materials used in steam power plant processes are of different origins [23], resulting in different metal oxide contents in several countries.

Fly ash and bottom ash (FABA) from coal-fired power plants significantly impact human health and the environment. Environmentally, fly ash contains heavy metals (e.g., arsenic, mercury) that, when deposited on soil, can lead to contamination and affect plant growth by altering soil pH and nutrient balance. The ash's alkaline nature can increase soil salinity, disrupt microbial communities, and affect nearby water bodies through leaching.

For human health, the inhalation of fly ash particles is linked to respiratory issues, cardiovascular problems, and potential genotoxic effects due to toxic elements like silica and trace metals. Long-term exposure to ash has been associated with higher risks of cancer and chronic lung disease, especially in those living near ash disposal sites. Efforts to manage these risks include the use of FABA in construction materials and soil stabilization, which helps reduce the environmental footprint while using its properties effectively.

Fly Ash is very fine coal ash that comes from coal-burning activities in the furnace of a generator boiler. The highest chemical composition of Fly Ash is SiO_2. Indonesia has the highest SiO_2 content and the lowest in

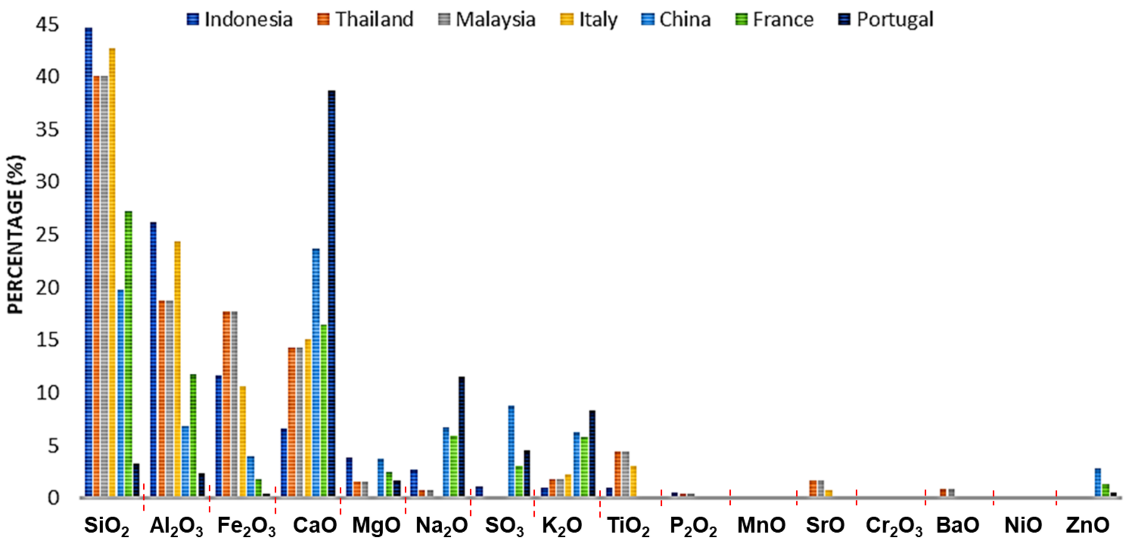

Fig. 1. Chemical composition chart fly ash from several countries [11-14]

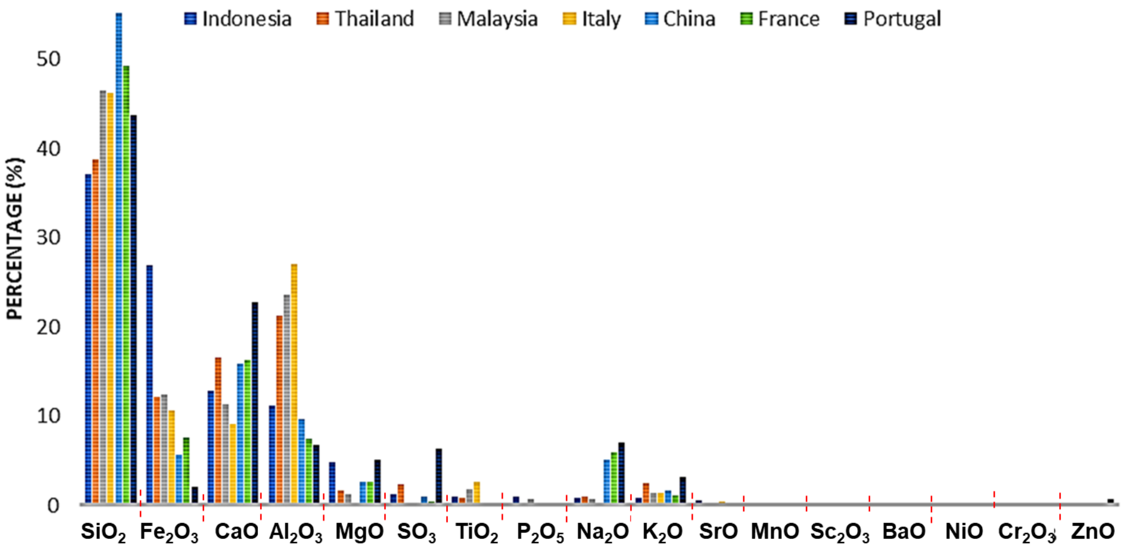

Fig. 2. Chemical composition chart bottom ash from several countries

Portugal. In several countries, MnO, SrO, Cr_2O_3, BaO, NiO, and ZnO have been identified. However, not all countries have identified them. Fly ash for metal extraction in another application can be reused and recycled [24]. Silicon can be used for electronic circuits [25], and aluminum and ferrous are used in household tools [26]. The composition of fly ash varies greatly depending on the waste source, incineration method, and purification system. Fly ash is mostly composed of Ca, Si, Al, Fe, and other elements, with SiO_2, CaO, Al_2O_3, Na_2O, and K_2O serving as its primary constituents. It contains certain soluble salts; therefore, after washing, its composition changes. Fly ash includes heavy elements, such as Zn, Cr, Cu, and other components.

Bottom Ash is ash formed from the combustion process in the furnace in the form of solids that are not carried away by the flue gas [27]. The highest chemical composition of the bottom ash is SiO_2. Indonesia has the highest composition of SiO_2 and the lowest is Portugal. In several countries its identified MnO, SrO, Cr_2O_3, BaO, NiO, and ZnO but not all countries identified of them.

It can be observed from **Fig. 2** that all countries have a high SiO_2 content, with percentages ranging from 40% to 50%. In contrast, Indonesia and China have slightly higher SiO_2 content compared to other countries. Al_2O_3 and Fe_2O_3 compounds present at significant percentages in almost all countries. Italy and China have slightly larger Al_2O_3 contents, whereas Thailand has higher levels of Fe_2O_3 than other countries.

For CaO, Malaysia and France have higher levels, which could be indicated by the use of coal containing more lime or using different combustion methods. Meanwhile, minor compounds, such as MgO, TiO_2, and Na_2O, show variation between countries but are generally present at lower percentages than major compounds, such as SiO_2, Fe_2O_3, and Al_2O_3.

The content of compounds, such as P_2O_5, K_2O, MnO, and BaO, is very low in all countries. This shows that these components are not the main constituents of fly ash. Overall, the composition of fly ash is similar between countries, with minor differences that may be caused by variations in the type of coal or combustion technology used in each country [28].

4. COMPARATIVE ANALYSIS OF FABA WASTE COMPOSITION IN SEVERAL LOCATION

The XRF (X-ray Fluorescence) test results (**Fig. 3**) exhibit the composition of chemical compounds in fly ash waste from several coal-fired power plants in Indonesia and one in Malaysia (Teluk Sirih). The main compounds contained in fly ash are SiO_2, Al_2O_3, Fe_2O_3, and CaO. The plants in Cirebon, Tanjung Enim, and Teluk Sirih have the highest Silicon oxide (SiO_2) content, indicating the dominance of this compound in the composition of fly ash at these locations. In contrast, Kutai Kartanegara and Tanjung Jati show higher levels of Al_2O_3 (alumina) and Fe_2O_3 (iron oxide), indicating the use of coal with greater levels of iron and alumina minerals.

Interestingly, fly ash from Teluk Sirih (Malaysia) shows a very high content of CaO (calcium oxide) compared to other power plants and a larger "Other" category, indicating the presence of other compounds that are commonly detected at power plant sites in Indonesia. This high CaO content may be due to the use of limestone or differences in the type of coal or combustion technology used.

In addition, minor compounds, such as Na_2O, SO_2, K_2O, TiO_2, P_2O_5, MnO, Cr_2O_3, and BaO have very low concentrations at all locations, suggesting that these components are not the main components in fly ash. Overall, each location has a significant variation in fly ash composition, which can have implications for the potential use of fly ash for various purposes, such as building materials or environmental engineering. For example, a location like Teluk Sirih, with high CaO content, could be better suited for applications that require high lime oxide. Meanwhile, other locations with high silica [25] could be beneficial in the manufacture of cement or concrete[7].

The results of XRF tests on bottom ash waste from several coal-fired power plants in Indonesia and one in Malaysia reveal interesting variations in chemical compound composition. SiO_2 (silicon dioxide) compounds dominate almost all locations, especially in Malaysia and Teluk Sirih, where the content is close to 50% and even exceeds 60% in Cirebon. The content of Al_2O_3 (alumina) is also quite significant, especially in Tanjung Jati, Tanjung Enim, and Sudimoro, with values ranging above 20%, indicating that alumina is an essential component in bottom ash, especially at Indonesian power plant sites. Fe_2O_3 (iron oxide) compounds are prominent in Sudimoro and Tanjung Jati at levels close to 30%. Meanwhile, their content is lower in Malaysia and Teluk Sirih, indicating differences in the type of coal or the combustion process.

The CaO (calcium oxide) content is very high in Teluk Sirih and Tanjung Enim, with Teluk Sirih reaching almost 40%, which may be due to the use of calcium-rich coal or the combustion process with limestone additives. In contrast, Cirebon has a very high SO_3 (sulfur trioxide) content, indicating the use of coal with a high sulfur content. The "Other" component is also significant in Cirebon and Tanjung Jati, indicating the existence of other minor compounds.

Overall, the composition of this bottom ash varies across power plant locations, with Cirebon prominent in SiO_2 and SO_3 content, and Teluk Sirih (Malaysia) for its very high CaO content. This variation reflects the different types of coal used and the combustion technologies applied. The high SiO_2 and Al_2O_3 content provides potential for the use of bottom ash in cement or concrete [7]. Meanwhile, a location like Cirebon may require special treatment because of their high sulfur content to reduce environmental impacts.

There is a significant variation in the composition of chemical compounds in fly ash and bottom ash from various coal-fired power plants in Indonesia and one in Malaysia (**Fig. 4**). The main compounds found in all locations are SiO_2, Al_2O_3, Fe_2O_3, and CaO. However, the percentage of these compounds varies depending on the locations. Fly ash and bottom ash from Cirebon, for example, tend to have very high SiO_2 content, while Teluk Sirih (Malaysia) has a prominent dominance of CaO. In addition, some locations, such as Tanjung Jati and Sudimoro, have higher Fe_2O_3 content, while SO_3 content is very high in Cirebon. This difference is most likely due to various factors, such as coal quality, the type of combustion technology, and the additives used during the combustion process. For example, limestone is used to reduce the emissions of sulfur dioxide.

In terms of usability, the composition of fly ash and bottom ash rich in SiO_2 and Al_2O_3 offers excellent potential for use in the construction industry, especially as a substitute for cement in concrete manufacture. Fly ash with high silica content, such as those found in Cirebon and Teluk Sirih, can act as a pozzolanic material [29], resulting in improved strength and durability of concrete. High CaO content, as observed in Teluk Sirih, can also be valuable for cement production, aiding in the hydration process, which is essential for material binding. Fly ash with high levels of Fe_2O_3 can be used in the production of refractory building materials.

However, the high SO_2 content in some locations, such as in Cirebon, can be a challenge because these compounds can cause degradation in concrete if not managed properly. Therefore, it is crucial to carry out additional treatment processes, such as chemical stabilization or sulfur reduction before the waste is used in construction applications. In addition, significant "Other" categories in some locations, such as in Teluk

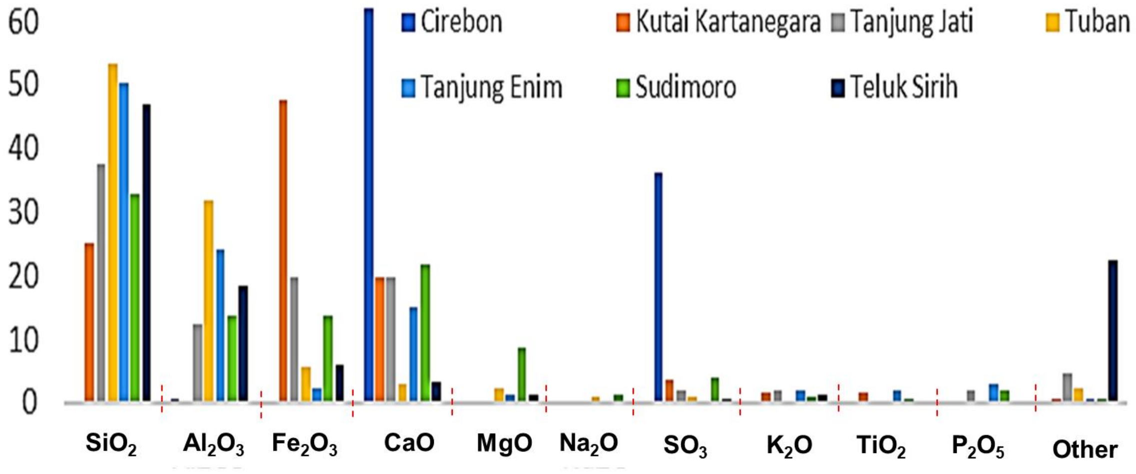

Fig. 3. Chemical composition chart fly ash from several location in indonesia and malaysia

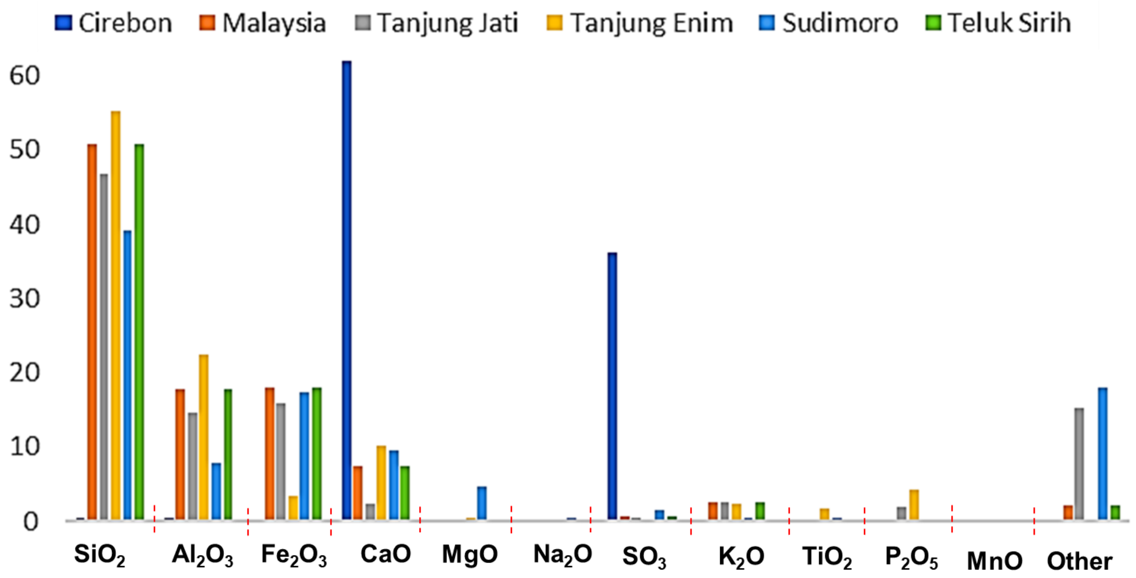

Fig. 4. Chemical composition chart composition ash from several cities in indonesia and malaysia

Sirih and Tanjung Jati, indicate the presence of minor compounds that also need to be further identified to optimize the utilization of these wastes in other industries, such as toxic waste treatment or composite material development.

Overall, fly ash and bottom ash from coal-fired power plants have great potential to be used sustainably in various industrial sectors, provided that proper treatment is carried out to reduce harmful components such as sulfur. The use of this waste can help reduce environmental impacts while providing new economic value from coal-burning waste.

In addition to differences in composition caused by coal type and combustion technology, these differences can also be affected by the specific operational conditions of each power plant, such as the combustion temperature [30], the type of additives used, and the ash management mechanism [31],[32]. For example, coal with different mineral content can produce fly ash and bottom ash that have significant variations in compounds, such as SiO_2, Al_2O_3, and Fe_2O_3. More efficient combustion technologies or those that use emission controllers, such as desulfurization systems can also affect the sulfur content in the ash, as observed from the high levels of SO_3 in Cirebon.

In addition, the high Fe_2O_3 content in bottom ash can also be used in the iron recovery process for metallurgical applications [33]. Thus, this waste has the potential to be a source of raw materials for the metal industry. With the right separation and purification technology, iron compounds can be extracted from the bottom ash, resulting in a material that can be reprocessed for industrial purposes.

Fly ash and bottom ash with high calcium oxide (CaO) content, as observed in Teluk Sirih, can be used in lime production or as a soil stabilizer in road construction projects. CaO is also beneficial in wastewater treatment processes, where these compounds are used to neutralize acidic pH and precipitate heavy metals. However, harmful compounds, such as SO_3 (sulfur trioxide), need to be managed properly. High sulfur content can cause environmental issues [34], such as increased acidity that is harmful to water and soil ecosystems, and accelerated corrosion of concrete infrastructure. Therefore, technologies such as sulfur removal before the use of fly ash or bottom ash should be prioritized to mitigate these negative impacts.

Overall, the use of fly ash and bottom ash waste not only supports environmental sustainability by reducing solid waste discarded but also offers significant economic opportunities. With proper treatment, this waste can be integrated into the production chain of various sectors, from construction to metallurgy and the environment. This not only reduces the need for natural raw materials but also reduces carbon emissions by minimizing reliance on energy-intensive production processes, such as traditional cement manufacturing.

From **Table 1**, it is clear that the chemical composition of FABA (Fly Ash and Bottom Ash) varies greatly depending on the location and type of power plant used. This is due to differences in the type of coal used, combustion technology, and emission and waste management methods at each location. In this case, Fly Ash (FA) and Bottom Ash (BA) are by-products that have great potential to be utilized in various industries, especially in construction, manufacturing, and other environmental applications.

Table 1. Utilization method of FABA

Utilization Method	Sector	Benefits	Description
Cement and Concrete Production	Construction	Reduces need for raw materials, lowers carbon footprint	FABA is mixed with cement as a supplementary material, enhancing strength and durability of concrete.
Road Base and Subbase Layers	Infrastructure	Improves road durability, reduces waste disposal	FABA is used in road construction as a stabilizing agent, reducing reliance on natural aggregates.
Soil Amendment	Agriculture	Enhances soil properties, improves plant growth	Treated FABA is added to soil to increase water retention and provide essential nutrients.
Metal Recovery	Metallurgy	Recovers valuable metals, minimizes waste	Extracts metals like aluminum and iron from FABA, allowing them to be reused in production processes.

One of the main factors that affect the variation in the composition of FABA is the type of coal used. Coal from different regions contains different mineral compositions, which ultimately affects the content of SiO_2, Al_2O_3, Fe_2O_3, CaO, and other compounds in FA and BA. In addition, incineration technologies, such as the use of flue gas desulfurization (FGD) and emission control, play a significant role in determining the sulfur content (SO_3) in ash. For example, the Cirebon PLTU shows quite high SO_3 levels, which can be a challenge in the use of FABA in the construction sector due to the potential for concrete degradation if not managed properly.

High SiO_2 content in FA, especially in the Cirebon, Teluk Sirih, and Tanjung Enim coal-fired power plants, shows fabulous potential for pozzolanic applications in the cement and concrete industries. SiO_2 is a primary component required in cement production due to its ability to react with free lime, forming compounds that reinforce concrete. In addition, the high content of Al_2O_3 and Fe_2O_3 in several locations, such as Tanjung Enim and Sudimoro, opens up opportunities for the utilization of FABA in metallurgical applications, especially as a feedstock in the metal refining process.

In construction applications, FABA rich in SiO_2 and Al_2O_3 can be used as a partial replacement of cement in concrete mixtures, which can reduce the use of conventional cement raw materials that require large amounts of energy in their production. In addition, the high CaO content, such as in the Teluk Sirih coal-fired power plant can be used in lime production or as a soil stabilizer for infrastructure projects. FABA can also be used as a base material and subbase in highway projects, and in the manufacture of paving blocks or bricks.

CaO-rich FABAs, such as those found in Teluk Sirih, also have potential in the environmental field, particularly for wastewater treatment and neutralization of contaminated soil. CaO content can help neutralize acidic pH and precipitate heavy metals in wastewater, thereby improving environmental quality.

SO_3 Management Challenges High SO_3 content, such as those found in Cirebon coal-fired power plants, can cause serious problems in FABA applications, especially in concrete construction. SO_3 can lead to the formation of etringite in concrete, which can result in expansion and cracking. Therefore, before FABA with a high SO_3 content can be used, it is necessary to carry out a chemical stabilization or sulfur reduction process to ensure its safety and durability in construction applications.

Economic Opportunities in the Utilization of FABA: The use of FABA not only provides environmental benefits but also opens up significant economic opportunities. By utilizing FABA as a raw material in industry, the use of natural resources can be minimized, thus supporting the concept of a circular economy. In addition, the development of technology to extract metals, such as aluminum and iron from FABA, also provides excellent value-added potential in the manufacturing and metallurgy industries.

CONCLUSION

The main components of fly ash and bottom ash in this study were SiO_2, Fe_2O_3, CaO, and Al_2O_3. However, compared with fly ash, bottom ash had higher SiO_2 and Al_2O_3 content and lower heavy metal content. The chemical component could be applied to aggregates for paving blocks, absorbent, soil amendment and agriculture, base and subbase material, subgrade, and prevention of soil erosion in coal mines. A comparison of FABA composition from various coal-fired power plants showed that coal quality, combustion methods, and waste management technologies contributed to the variation of chemical compound composition. With proper processing, FABA showed tremendous potential for use as building materials, metallurgical materials, and other environmental applications. This could reduce the environmental impact of power plant waste and open up opportunities to develop new environmentally friendly and sustainable material technologies. Thus, FABA could be valuable resources, if properly managed and utilized, supporting the concept of circular economy in the energy and construction industries.

Fly ash and bottom ash from coal-fired power plants have great potential to be used sustainably in various industrial sectors, provided that proper treatment is carried out to reduce harmful components, such as sulfur. The use of this waste can help reduce environmental impacts while providing new economic value from coal-burning waste.

Overall, the use of fly ash and bottom ash waste supports environmental sustainability by reducing solid waste discarded and offers significant economic opportunities. With proper treatment, this waste can be integrated into the production chain of various sectors, from construction to metallurgy and the environment. This not only reduces the need for natural raw materials but also reduces carbon emissions by minimizing reliance on energy-intensive production processes, such as traditional cement manufacturing

SUPPORTING INFORMATION

There is no supporting information for this paper.

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CONFLICT OF INTEREST

The authors have no conflict of interest in this publication.

AUTHOR CONTRIBUTIONS

MSNP, LAH, and AEP was conducted the research design, conceptualization, and validation of final revision. AEP, AB, and MZA wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

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