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Characterization of Fly Ash from Coal-fired Steam Power Plant Tarahan, Lampung, and Its Potential as a Soil Amendment

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ABSTRACT

Background: Fly ash, a byproduct of coal combustion in steam power plants, has significant potential for utilization, particularly as a soil amendment. However, in Indonesia, including at the Tarahan coal-fired steam power plant (PLTU Tarahan), most fly ash remains underutilized and is primarily disposed of in landfills.
Aims: This study aimed to analyze the characteristics of fly ash produced at PLTU Tarahan and evaluate its potential for recycling through three utilization pathways: biosilica production, application as a soil-stabilizing agent, and incorporation into compost mixtures.
Methods: Samples were collected from three distinct locations and analyzed at a certified laboratory using standardized procedures. The resulting data were subsequently compared with values reported in existing literature and interpreted using a descriptive analytical approach.
Result: Characterization results indicated that the fly ash belongs to Class F, with high silica (SiO_2) content and low calcium oxide (CaO), making it pozzolanic but non-cementitious. Each reuse pathway was assessed in terms of technical compatibility, infrastructure readiness, pretreatment requirements, market potential, and environmental risk mitigation. The findings showed that biosilica production offers high added value but requires advanced chemical extraction technology. Soil stabilization using fly ash and lime is technically feasible for internal infrastructure and land reclamation projects, offering immediate benefits with minimal pretreatment. When mixed with organic materials such as press mud or combined with garbage enzyme, fly ash also enhances compost maturity, nutrient content, and enzymatic activity. Based on these results, a phased implementation strategy is recommended, beginning with applications that are low-risk and compatible with existing infrastructure. These findings contribute to the development of more adaptive and sustainable fly ash management strategies within coal-fired power plants. To support practical implementation, further laboratory- and field-scale studies are needed to validate long-term performance. Additionally, future research should incorporate multicriteria decision-making approaches, such as the Analytic Network Process (ANP), to comprehensively evaluate technical, environmental, social, and economic factors in selecting the most appropriate utilization pathway.

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1. Introduction

Coal-fired Steam Power Plants (PLTUs) are among the main sources of electrical energy in Indonesia. Most of these power plants are operated under the management of the Perusahaan Listrik Negara (PLN) Group, the national electricity provider. One of its subsidiaries, PT PLN Nusantara Power Unit Pembangkitan Tarahan, operates two PLTU units located on Jalan Lintas Sumatera KM15, Tarahan, South Lampung Regency, Lampung Province, occupying an area of approximately 35.69 hectares (PT PLN Nusantara Power Unit Pembangkitan Tarahan, 2025).

The combustion system at PLTU Tarahan utilizes a Circulating Fluidized Bed (CFB) boiler operating at temperatures between 850–900°C. This technology is categorized as environmentally friendly because it optimizes the combustion process and controls emissions (PT PLN Nusantara Power Unit Pembangkitan Tarahan, 2025). The coal combustion process produces solid residues consisting of two main types: fly ash, which is carried with the flue gas, and bottom ash, which accumulates at the bottom of the furnace. Collectively, these residues are known as FABA (Fly Ash and Bottom Ash).

To enhance combustion efficiency, PLTU Tarahan applies a cyclone separator system that recirculates unburned ash particles back into the furnace, allowing for more complete combustion. This system results in a relatively small volume of bottom ash, with annual production approaching zero tons. Meanwhile, fly ash generated in the flue gas stream is handled using a baghouse filter system designed to capture fine particles before the flue gas is released into the atmosphere, thereby minimizing particulate emissions and air pollution. The captured fly ash is then stored in dedicated silos for potential use as raw material in the cement industry, while unutilized fly ash is temporarily stored in an ash disposal area for further management and study.

The growing reliance on coal-based energy has led to a significant increase in fly ash generation (Gollakota *et al.,* 2019). Improper management and disposal of fly ash can cause serious environmental damage (Liu *et al.,* 2022). Open dumping of fly ash can contaminate groundwater and pose risks to public health (Rafieizonooz *et al.,* 2022). Utilizing fly ash can transform waste into a valuable resource, thus mitigating waste disposal problems while conserving natural resources and protecting the environment (Taupedi & Ultra, 2022). Based on its chemical characteristics, the most common utilization of fly ash is as a substitute material in the construction industry (Rafieizonooz *et al.,* 2022). However, the rate of fly ash generation still far exceeds its utilization rate. Therefore, many researchers have explored alternative uses of fly ash across various sectors (Mathapati *et al.,* 2022), including applications in construction and agriculture (Liu *et al.,* 2022).

Fly ash has great potential in agriculture due to its ability to improve soil health and enhance crop performance (Hanum *et al.,* 2023). According to Tejasvi (2021), fly ash combined with organic fertilizers serves as an excellent soil amendment, significantly increasing soil productivity through Fly Ash Soil Amendment Technology (FASAT). Consistent application of fly ash-based amendments can increase maize yields by more than 10% over three years (Ou *et al.,* 2020). When applied in appropriate proportions based on soil type and texture, fly ash can improve various soil physical properties—such as texture, water-holding capacity, bulk density, particle density, and porosity—thereby enhancing overall soil quality (Kumar *et al.,* 2024). A review by Johnson Jeyaraj and Sankararajan (2025) also highlighted that using fly ash in combination with other solid wastes can improve key soil properties, including neutralizing acidic pH, enhancing water infiltration and aeration, supplying essential nutrients for plant growth, and improving soil structure. Furthermore, it can promote microbial activity and nutrient cycling while reducing nutrient leaching and greenhouse gas emissions.

According to the internal report of PLN Nusantara Power (2025), PLTU Tarahan generated 37,814 tons of fly ash in 2024. Currently, its utilization is limited to serving as a raw material substitute in the cement industry. However, a substantial portion of fly ash remains stored in the Temporary Storage Facility (TPS). Prolonged environmental exposure has altered some of its physical characteristics—such as moisture content and particle size—rendering it noncompliant with ASTM C618 standards for cementitious materials. This condition highlights the need to explore alternative utilization strategies in the coming years to reduce fly ash accumulation in the TPS. In line with this, PLN Nusantara Power plans to expand FABA utilization by piloting its use as a fertilizer and soil amendment to enhance agricultural productivity while supporting sustainable farming practices (PLN Nusantara Power, 2025).

Although previous studies have shown the potential of fly ash to improve soil quality and crop productivity through various techniques—such as composting, biosilica extraction, and integration with organic amendments—most of these studies were conducted under different geographical and operational contexts. There remains limited evaluation of their practical applicability to specific facilities such as PLTU Tarahan. Therefore, this study aims to fill that gap by analyzing the potential and challenges of utilizing fly ash as a soil amendment based on data from PLTU Tarahan and relevant scientific literature.

2. Methods

This study employed a descriptive design with a qualitative approach aimed at analyzing the characteristics of fly ash from PLTU Tarahan and evaluating its potential as a soil amendment. The research was conducted in four main stages: (1) evaluation of existing management practices, (2) analysis of fly ash characteristics, (3) literature review on fly ash utilization in agriculture, and (4) descriptive analysis to assess the suitability and opportunities for its application at PLTU Tarahan. Figure 1 presents the flowchart of the research stages:

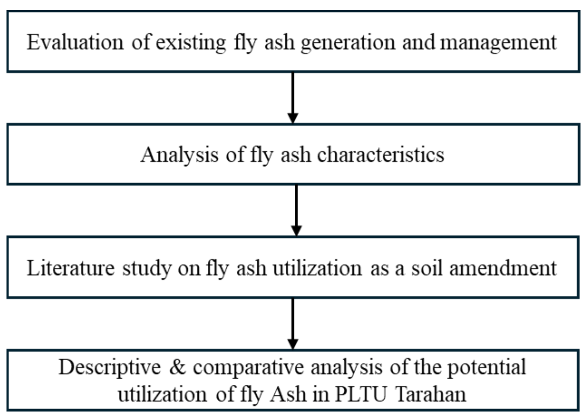

Figure 1. Research Flow Diagram

2.1 Evaluation of Existing Fly Ash Generation and Management

The evaluation of the FABA generation and management system was conducted to understand the existing conditions at PLTU Tarahan, serving as a basis for determining the needs and urgency of developing fly ash utilization. The research site was focused on PLTU Tarahan in Lampung (Figure 2), one of the steam power plants operating with Circulating Fluidized Bed (CFB) technology.

Data on FABA generation were obtained from the 2024 internal waste management report of PLTU Tarahan. The volume of fly ash produced, along with the proportions that had been utilized or stored in the Temporary Storage Facility (TPS) and landfill, was analyzed to illustrate the extent of FABA accumulation. In addition, other relevant documents—such as permit records and descriptions of waste management infrastructure (e.g., TPS capacity, landfill capacity, and distribution flow of FABA utilization to the cement industry)—were reviewed to assess the effectiveness of the existing system.

To ensure the credibility and reliability of the data, this information was further validated through an in-depth interview with the environmental management leader at PLTU Tarahan.

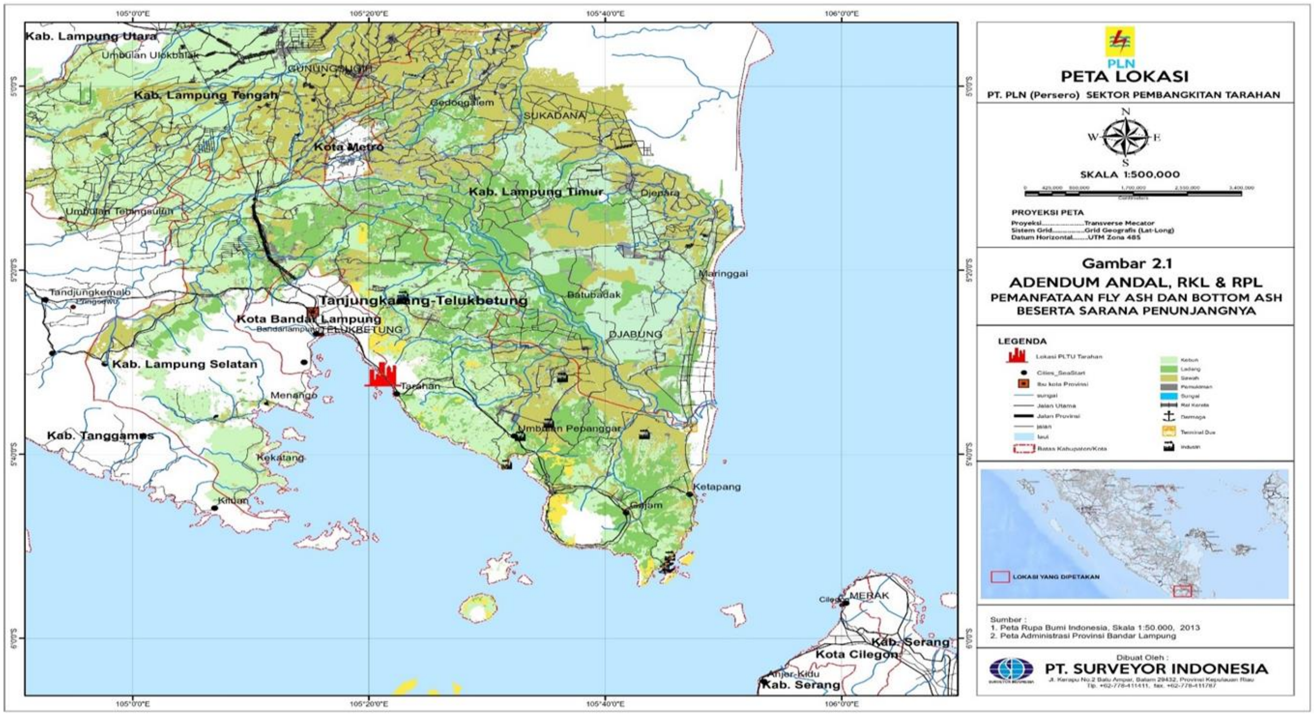

Figure 2. PLTU Tarahan Location
Source: PLN Nusantara Power UP Tarahan (2025)

2.2 Analysis of Fly Ash Characteristics

Fly ash samples were collected from four different points (a composite of three sub-samples per point) within the ash disposal area, as described in Table 1. Sampling was conducted by certified laboratory personnel in 2024. The analyzed parameters included physical properties (moisture content, density, particle size, and fineness-45), chemical properties (pH, SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, and K_2O contents), and toxicity determined using the Toxicity Characteristic Leaching Procedure (TCLP) method, which measures the concentrations of heavy metals such as Pb, Cd, As, Hg, and others. Sample testing was performed in an accredited laboratory, and the results—sourced from the internal waste management report of PLTU Tarahan—were analyzed using descriptive statistical methods in Microsoft Excel. The characterization results served as the basis for evaluating the safety of fly ash for agricultural applications and its suitability as a soil amendment material.

Table 1. Fly Ash Sampling Location.

No	Sample ID	Sampling Point Position
1	Sample-1	Cell 1: 0-55 meters from the ash disposal gate with a depth of 3 meters
2	Sample-2	Cell 2: 55-80 meters from the ash disposal gate with a depth of 3 meters
3	Sample-3	Cell 3: >80 meters from the ash disposal gate with a depth of 3 meters
4	Sample-4	Maximum depth of 50 cm, taken 3 composite samples from Cell 1, 2 and 3

2.3 Literature Study on Fly Ash Utilization Potential as a Soil Amendment

After identifying the characteristics of fly ash from PLTU Tarahan, a literature study was conducted to evaluate its potential utilization as a soil amendment. The literature sources were purposively selected from reputable journals indexed by Scopus and SINTA within the last five years (2020–2025). All articles were obtained from recognized scientific publishers, such as Elsevier and Scientific Research Publishing.

2.4 Descriptive & Comparative Analysis of Potential Utilization

After obtaining data from the characterization of fly ash from PLTU Tarahan and conducting a literature review on fly ash utilization methods as a soil amendment, descriptive and comparative analyses were performed to assess the feasibility of applying these methods in the local context. Comparisons were made between the characteristics of fly ash from PLTU Tarahan and the conditions reported in the reference studies, as well as among the technical aspects of each utilization method. The aspects compared included the compatibility of local fly ash characteristics with the requirements of each method, availability of supporting local resources, technical and infrastructure needs, expected product outcomes, and potential application schemes. Each method was described narratively in the discussion section and analyzed using a comparison matrix.

3. Results and Discussion

3.1 Evaluation of Existing Fly Ash Generation and Management

According to the Environmental Approval document, PLTU Tarahan is equipped with an ash disposal area as part of its FABA management facilities, which include a Temporary Storage Site (TPS) and a designated landfill area (Figure 3). The licensed Non-Hazardous Waste TPS covers an area of 47,000 m², with a maximum storage height of 5.5 meters and a total capacity of 258,500 m³. Meanwhile, the landfill for Non-Hazardous Waste occupies an area of 39,500 m², with a maximum waste pile height of 12 meters from the base of the embankment and a total storage capacity of 434,500 m³ (PLN Nusantara Power UP Tarahan, 2025).

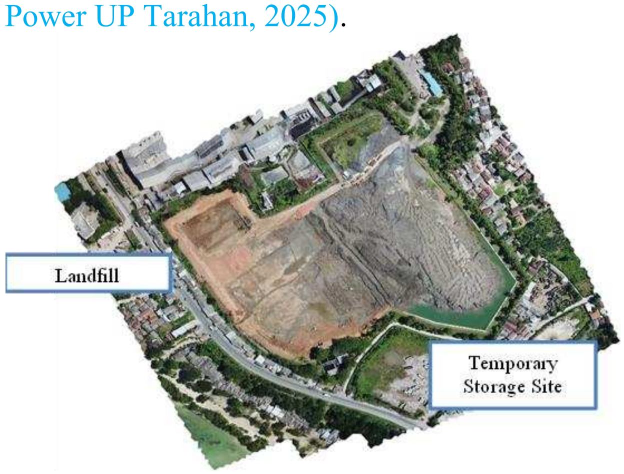

Figure 3. Layout of FABA Management Facility of PLTU Tarahan.
Source: PLN Nusantara Power UP Tarahan (2025)

Fly ash management at PLTU Tarahan is carried out in accordance with the registered non-hazardous waste handling procedures established by the company (Figure 4). Fly ash (along with bottom ash) generated from the coal combustion process is transported by truck to the ash disposal area, which consists of the Temporary Storage Site (TPS) and the FABA landfill. In addition, fresh fly ash from the silo is directly delivered to third-party partners, particularly in the cement industry, using bulk capsule trucks for further utilization.

Most of the fly ash stored in the TPS is transferred to the landfill before its storage period expires, while a portion is scheduled for technical studies to explore potential utilization—both for internal purposes and external collaboration projects. The ash yard facilities are equipped with monitoring wells that serve to monitor soil and groundwater quality around the site, ensuring that no contamination occurs as a result of FABA management activities.

In 2024, PLTU Tarahan generated a total of 37,814 tons of fly ash. Of this amount, 59% (22,235 tons) was utilized by the cement industry as a raw material substitute, while the remaining 41% (15,579 tons) was directly disposed of in the landfill due to non-compliance with technical specifications. During this period, no additional fly ash was stored in the TPS, as all newly generated fly ash was immediately allocated for external utilization or final disposal. The fly ash currently stored in the TPS consists solely of accumulated residues from periods prior to 2024..

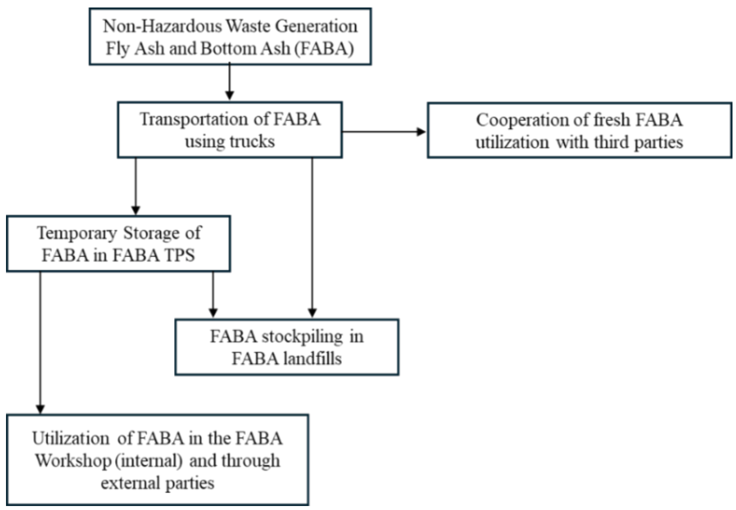

Figure 4. Flow of PLTU Tarahan FABA Waste Management.

3.2 Fly Ash Characteristics Analysis

3.2.1 Physical and chemical properties

The physical characteristics of the analyzed fly ash are presented in Table 2. The fly ash samples were obtained from the ash disposal facility, which is an open area susceptible to environmental exposure, including rainfall. This analysis was important to determine the potential utilization of fly ash that has been stored in the Temporary Storage Site (TPS).

Based on the results (Table 2), the moisture content of the fly ash was relatively high, with an average value of 25.15 ± 4.865%. When compared with the ASTM C618 standard, which specifies a maximum moisture content of <1–3%, the fly ash from the FABA TPS does not meet the requirements for direct use as a concrete mix or other construction material without prior drying treatment. Therefore, an alternative utilization strategy outside the construction sector—better suited to the characteristics of the fly ash—was considered necessary.

Table 2. Analysis Results of Fly Ash Physical Parameters in PLTU Tarahan.

No	Parameter	Sample-1	Sample-2	Sample-3	Sample-4	Average
1	Moisture Content (%)	27.2	31.2	21.5	20.7	25.15 ± 4.865
2	Density (g/cm3)	2.50	2.51	2.50	2.64	2.54 ± 0.067
3	Particle Size (mm)	0.26	0.73	0.951	0.686	0.66 ± 0.283
4	Fineness-45 (% retained)	25.3	27.5	26.0	21.7	25.13 ± 2.412

Source: Sinergi Geoenvi Lab, Bandung (2024), obtained from PT PLN Nusantara Power Unit Pembangkitan Tarahan (2025)

Furthermore, the average density value of fly ash (Table 1) was found to be 2.54 ± 0.067 g/cm³, which is within the general range for fly ash from coal. This parameter is important in mix ratio calculations when fly ash is used as an additive in concrete formulations, fertilizers, or growing media. In general, the particle size distribution of fly ash was in the range of 0.260 mm to 0.951 mm (260-951 μm), with a mean value of 0.66 ± 0.283 mm indicating particles tend to be coarser than fine fly ash typically used in cement and concrete mixtures. However, the fineness value (fineness-45), which shows the percentage of residue retained on the 45-micron sieve, showed a value of 25.13 ± 2.412%. Referring to the ASTM C618 standard which sets a maximum fineness-45 limit of 34%, the fly ash from the FABA TPS of PLTU Tarahan can be categorized as having a good level of fineness and was suitable for various alternative applications.

The analysis of fly ash chemical parameters was contained in Table 3. Based on these results, fly ash from the FABA TPS showed distinctive characteristics and has great potential to be utilized. The high pH value, 8.98 ± 0.198, indicated the alkaline nature of fly ash. This property is useful in neutralizing acidic soil, so it has the potential to be used as an amendment for agricultural land with low pH.

The main composition of fly ash was dominated by silica (SiO_2) content of 56.55 ± 1.093%, followed by alumina (Al_2O_3) of 12.58 ± 0.994%, and iron oxide (Fe_2O_3) of 5.49 ± 0.447%. The total amount of the three main oxides is about 74.62%, which is an important indicator in fly ash classification. Based on the ASTM C618 standard, fly ash with a total content of $SiO_2 + Al_2O_3 + Fe_2O_3$ of more than 70% belongs to class F, which is usually produced by burning anthracite or bituminous coal and has a low calcium (CaO) content.

The CaO content in the fly ash of PLTU Tarahan was 2.52 ± 0.785%, confirming that this fly ash belongs to class F, not class C which has a higher calcium content (>20%). In addition, this fly ash also contained MgO (1.60 ± 0.127%), Na_2O (1.69 ± 0.088%), and K_2O (0.08 ± 0.040%), which although in small concentrations, still contributed to the chemical properties and agronomic potential of fly ash. This chemical composition showed that the fly ash of PLTU Tarahan has alkaline properties and high silica content, making it a suitable candidate to be developed as a soil amendment, especially on lands with high acidity, and used as an ingredient for making biosilica fertilizer.

Table 3. Analysis Results of Chemical Parameters Analysis of Fly Ash in PLTU Tarahan.

No	Parameter	Sample-1	Sample-2	Sample-3	Sample-4	Average
1	pH	8.74	9.2	8.9	9.08	8.98 ± 0.198
2	SiO_2 (%)	58.1	55.9	56.6	55.6	56.55 ± 1.093
3	Al_2O_3 (%)	12.8	12	13.9	11.6	12.58 ± 0.994
4	Fe_2O_3 (%)	5.67	4.97	6.02	5.29	5.49 ± 0.447
5	CaO (%)	1.56	3.32	2.17	3.01	2.52 ± 0.785
6	MgO (%)	1.48	1.54	1.78	1.58	1.60 ± 0.127
7	Na_2O (%)	1.68	1.63	1.82	1.63	1.69 ± 0.088
8	K_2O (%)	0.1	0.13	0.06	0.04	0.08 ± 0.040

Source: Sinergi Geoenvi Lab, Bandung (2024), obtained from PT PLN Nusantara Power Unit Pembangkitan Tarahan (2025)

3.2.2 Leaching properties

The results of the leaching test using the Toxicity Characteristic Leaching Procedure (TCLP) method on fly ash from PLTU Tarahan, as presented in Table 4, showed the concentrations of various heavy metals and dissolved contaminants. This test was conducted to assess the potential of fly ash to release hazardous substances into the environment, especially when utilized or discharged into soil or water.

In general, the results of the analysis showed that the concentration of heavy metals in the leached solution were still below the threshold of TCLP-B pollutant concentration values set by the Government Regulation Number 22 of 2021 in Appendix XI concerning Toxic Characteristic Quality Standards Through TCLP For Determining Hazardous Waste Categories. Based on the results, the fly ash produced by PLTU Tarahan could be considered relatively safe from the risk of leachable heavy metal contamination when disposed of using conventional methods. Consequently, from a toxicity perspective, the fly ash demonstrates potential for utilization—such as in agricultural applications—provided that it also meets other relevant technical requirements.

Table 4. Analysis of Contaminant Concentrations in PLTU Tarahan Fly Ash by TCLP Method.

No	Parameter	Sample-1 (mg/L)	Sample-2 (mg/L)	Sample-3 (mg/L)	Sample-4 (mg/L)	Average (mg/L)	Threshold (mg/L)
1	TCLP Antimony (Sb)	0.003	0.002	0.001	0.003	0.0023 ± 0.001	1
2	TCLP Arsenic (As)	0.003	0.001	0.006	0.001	0.0028 ± 0.002	0.5
3	TCLP Barium (Ba)	0.142	0.119	0.142	0.11	0.1283 ± 0.016	35
4	TCLP Berilium (Be)	0.0005	0.0005	0.002	0.0005	0.0009 ± 0.001	0.5
5	TCLP Boron (B)	4.93	8.14	5.55	10.6	7.3050 ± 2.548	25
6	TCLP Cadmium (Cd)	0.0005	0.0005	0.0005	0.0005	0.0005 ± 0.000	0.15
7	TCLP Copper (Cu)	0.001	0.001	0.001	0.001	0.0010 ± 0.000	10
8	TCLP Lead (Pb)	0.001	0.0005	0.0005	0.0005	0.0006 ± 0.000	0.5
9	TCLP Mercury (Hg)	0.0005	0.0005	0.0005	0.0005	0.0005 ± 0.000	0.05
10	TCLP Molybdenum (Mo)	0.64	0.05	0.018	0.86	0.3920 ± 0.415	3.5
11	TCLP Nickel (Ni)	0.026	0.014	0.023	0.022	0.0213 ± 0.005	3.5
12	TCLP Selenium (Se)	0.066	0.05	0.044	0.079	0.0598 ± 0.016	0.5
13	TCLP Silver (Ag)	0.0005	0.0005	0.0005	0.0005	0.0005 ± 0.000	5
14	TCLP Zinc (Zn)	0.042	0.018	0.024	0.023	0.0268 ± 0.010	50
15	TCLP Chrom Hexavalent (Cr^{6+})	0.03	0.03	0.03	0.03	0.0300 ± 0.000	2.5

Source: Sinergi Geoenvi Lab, Bandung (2024), obtained from PT PLN Nusantara Power Unit Pembangkitan Tarahan (2025)

3.3 Potential Utilization of Fly Ash as Soil Amendment

A review of the current fly ash utilization practices at PLTU Tarahan shows that only one form of utilization has been implemented—namely, as a substitute for cement raw materials. However, there remain many other potential applications that could be further developed. Future development of fly ash utilization methods should primarily focus on fly ash stored in the Temporary Storage Site (TPS), considering that fresh fly ash has already been largely utilized as a raw material substitute in the cement industry.

One promising alternative use of fly ash that has gained increasing attention is its application as a soil amendment. This utilization is based on the chemical characteristics of fly ash, which typically contain macro- and micronutrients such as silica (Si), calcium (Ca), magnesium (Mg), and potassium (K). These elements can help increase the pH of acidic soils and improve soil physical properties. Several previous studies have demonstrated that the application of fly ash in specific amounts and formulations can enhance soil fertility and crop productivity (Chao *et al.,* 2023; Ou *et al.,* 2020).

Considering the characteristics of fly ash produced by PLTU Tarahan and the availability of land around the power plant, implementing a utilization scheme for fly ash as a soil amendment represents a strategic alternative worth exploring, particularly to support the sustainable utilization of non-hazardous waste.

3.3.1 Utilization for biosilica production

Biosilica fertilizer is a type of fertilizer that contains silica (SiO_2) in a form that is easily absorbed by plants. It is typically derived from SiO_2-rich organic and inorganic wastes, originating from natural or biomass sources such as rice husks, straw, or fly ash (Hossain *et al.,* 2022). Amorphous silica is preferred for its high reactivity and safety, unlike the crystalline form, which is inert and thermally stable (Ekwenna & Roskilly, 2023). Specifically, biosilica derived from fly ash can form nanoparticles with a porous structure, large surface area, and hydroxyl functional groups, which enhance its reactivity and potential for various applications, including agriculture and high-value-added materials (Liang *et al.,* 2020).

Various methods have been developed to extract silica from fly ash (Yadav & Fulekar, 2020), including: 1). Chemical extraction, where fly ash reacts with NaOH at 90–100°C for 1–3 hours to dissolve silica as sodium silicate; 2) Alkali fusion, which involves mixing fly ash with NaOH and heating it to 600–1200°C; 3) Sol-gel processing, in which sodium silicate is neutralized with HCl to form silica gel that is subsequently dried into nanoparticles; and 4) Biological extraction, using bacteria or fungi to extract silica with a lower yield but greater environmental friendliness.

Analyses using Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDX), and X-ray Powder Diffraction (XRD) have shown that these processes produce high-quality biosilica (Ekwenna & Roskilly, 2023). Research by Hossain *et al.* (2022) demonstrated that biosilica can enhance soil cation exchange capacity, improve water retention and aeration, reduce heavy metal contamination through adsorption mechanisms, stabilize soil pH, and improve soil structure. Therefore, biosilica has significant potential as a soil amendment to improve both the physical and chemical fertility of soils. The application of silicon-based fertilizers has also proven highly effective in promoting plant growth, improving yields, and enhancing water and nutrient use efficiency in crops such as black soybean, rice, sugarcane, maize, and oil palm (Santi *et al.,* 2021).

In addition, Santi *et al.* (2021) developed an alkaline pretreatment method for fly ash to produce biosilica fertilizer that is more readily absorbed by plants. Pretreatment with NaOH significantly increased the solubility of silica in fly ash, as indicated by changes in particle morphology, resulting in a more porous structure and higher surface activity. The resulting biosilica fertilizer contained substantial soluble silica and showed strong potential for use as a supplementary fertilizer.

The specific characteristics of fly ash from PLTU Tarahan offer favorable conditions for biosilica fertilizer production. Its high silica content supports biosilica formation, while its high pH value enhances silica dissolution in alkaline solutions required for pretreatment. Therefore, the biosilica fertilizer production method has strong potential for adoption at PLTU Tarahan. The availability of basic laboratory facilities, along with ongoing plans to establish a FABA Utilization Workshop, and the potential for collaboration with local research institutions and universities, provide opportunities to implement the NaOH-based fly ash pretreatment process progressively—from the laboratory scale to semi-industrial scale. Furthermore, Lampung Province's extensive agricultural sector presents a high demand for alternative fertilizers that can improve nutrient uptake efficiency, further supporting the feasibility of this approach.

3.3.2 Utilization for soil stabilizing agent

Soil stabilization is the process of improving the physical and engineering properties of soil through the addition of chemical or physical additives (Figure 5), so that the soil has better strength, bearing capacity, and durability. Fly ash has pozzolanic properties that allow chemical reactions with calcium from lime, forming compounds that bind soil particles (Andavan and Pagadala, 2020). Fly ash was used with lime to stabilize local clay soil. The combination of fly ash with lime has been shown to increase the compressive strength (UCS) values of soils, as well as decrease swelling and plasticity. Research from Utkarsh & Jain (2024) also states that fly ash works optimally when combined with lime, creating a LFA (lime-fly ash) mixture that can reduce soil fluffiness and improve soil structural stability, facilitating root penetration and water distribution. This is also in line with other studies which state that the addition of expansive soil with lime and fly ash in a certain percentage can cause a decrease in the plasticity index, optimum moisture content, and differential free swell index. The maximum dry unit weight also increases, thereby increasing the strength of the soil mixture compared to soil alone (Indiramma *et al.,* 2020).

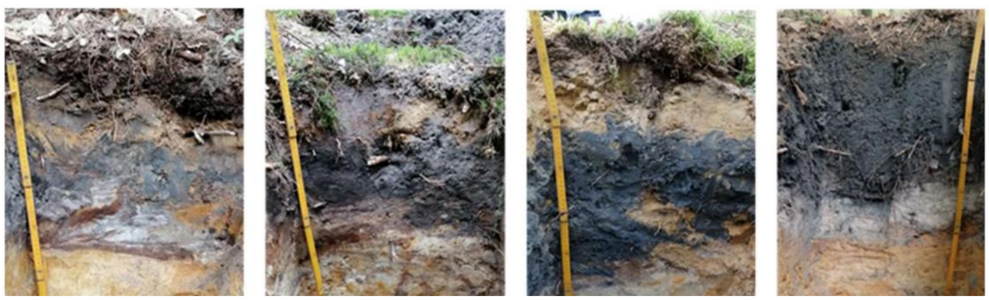

Figure 5. Fly ash Application as Soil Stabilzation Agents in Various Dosages
Source: Bogacz et al. (2024)

Its benefits in agriculture include increasing dry density and decreasing optimum moisture content to support aeration and plant rooting, decreasing the free swell index value which is very beneficial for agriculture in expansive soils (e.g. vertisols) due to its ability to prevent cracking and damage to plant roots, and of course neutralizing the pH of acidic soils which is important for increasing nutrient availability and soil microbial effectiveness (Andavan & Pagadala, 2020).

From the previos section, it was known that the fly ash from PLTU Tarahan was classified as Class F, which possesses pure pozzolanic properties. Although it is not cementitious by itself, it can chemically react with calcium-rich materials, such as lime, to form binding compounds. Due to its relatively slow pozzolanic reactivity compared to Class C fly ash, it is particularly well-suited for soil stabilization applications when combined with lime, offering valuable benefits in both agricultural and civil engineering contexts.

3.3.3 Utilization for incorporation into compost mixtures

Compost is the result of the decomposition of organic matter by microorganisms under aerobic conditions. This process produces nutrient-rich and stable organic matter that is beneficial for plant growth and soil improvement (Poblete *et al.,* 2022). Compost is derived from organic matter from decomposing waste, such as livestock, which contains macro and micronutrients (Febriana *et al.*, 2021). Composting also can be done with a co-composting approach, which is a method that combines two or more types of organic materials to accelerate the decomposition process and produce a more stable and nutrient-rich final product (Mandpe *et al.*, 2021). It can be done in in-vessel composting (Figure 6). The addition of garbage enzyme (GE), a solution of fermented organic kitchen waste (such as leftover fruits, vegetables, and sugar) in water that contains various active enzymes, microorganisms, and bioactive compounds, can enhance microbial activity and significantly improve the physicochemical stability and overall maturity of the final compost product. In the case of vermicompost, the decomposition process is also aided by the presence of earthworms (Karwal & Kaushik, 2020). Even in the simplest method, organic ameliorant from waste like cowdung can also be applied together with fly ash directly without the fermentation process, as done by Febriana *et al* (2021) in their research.

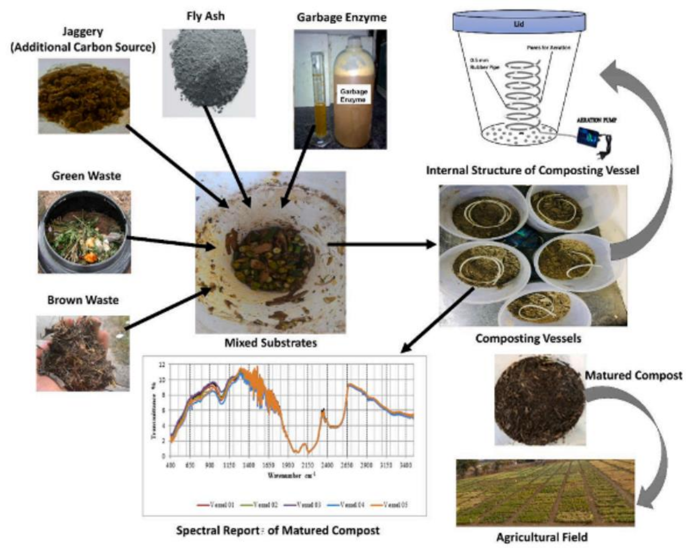

Figure 6. Scheme of Fly Ash Utilization with In-Vessel Composting System
Source: Mandpe et al. (2021)

Fly ash serves as a mineral ameliorant in the composting process, as it contains micro and macro elements such as Ca, Mg, K, and Si. When combined with garbage enzyme (GE), fly ash can stabilize pH, increase microbial and enzyme activity, accelerate the decomposition of organic matter, and reduce odor (Pasalari *et al.*, 2024). In Febriana *et al.* (2021), fly ash was added to the planting medium (acid soil) along with cowdung compost to neutralize pH and improve soil structure.

Compared to before being given fly ash, the incorporation of fly ash into compost induces notable changes in its characteristics, including a shift in pH toward neutral to slightly alkaline levels, a more balanced C/N ratio, a transformation in color to dark gray, a reduction in unpleasant odors resulting in a more natural "earthy" scent, and an enhancement in enzymatic activities such as cellulase and nitrogenase (Pasalari *et al.*, 2024). Also, Mandpe *et al.* (2021) reported that the addition of 20% FA and 5% GE in in-vessel composting resulted in mature compost with a neutral pH (8) and optimal C/N ratio (13.68). Vermicomposting and co-composting press mud with fly ash can improve the quality of compost, in terms of nutrition, biological activity, and stability, and reduces the potential toxic hazards of fly ash (Karwal & Kaushik, 2020). Furthermore, other research also states that fly ash can be used as an adsorbent material to capture CO_2 released during the vermicomposting process, so in addition to being useful in agriculture, the addition of fly ash can also play a role in reducing greenhouse gas emissions (Poblete *et al.,* 2022).

Although rich in nutrients, fly ash also contains heavy metals, so the dosage must be used carefully (Febriana *et al.,* 2021). Looking at the heavy metal leaching test results, fly ash from PLTU Tarahan has a very low concentration of heavy metals and was far below the threshold. The characteristics of fly ash from the PLTU Tarahan showed a more alkaline nature, with a pH value reaching 8.98 ± 0.198. This property has the potential to provide benefits in agricultural land applications, especially in improving acidic soil conditions and increasing the availability of certain nutrients. Fly ash from PLTU Tarahan also showed a high moisture content, with an average of 25.15 ± 4.865%. This condition provided an advantage in the context of fly ash application as a mixed material in the composting process. As stated by Mandpe *et al.* (2021), the moisture content in the initial phase of composting should not be less than 60% to support optimal microbial activity, which usually could be obtained from water added to the process. Thus, the characteristics of PLTU Tarahan fly ash, which has a relatively high initial moisture content, can significantly reduce the need for additional water in the preparation stage of compost materials.

Compost enriched with fly ash has great benefits, both for the soil and for plants. For soil, fly ash content in compost can improve soil structure, water retention, nutrient availability, and cation exchange capacity (CEC). For plant growth, the presence of fly ash can support growth, strengthen roots, improve nutrient absorption efficiency, and increase yield and resistance to environmental stress (Pasalari *et al.,* 2024). In certain doses, fly ash can also affect the better growth of kangkung plants (Febriana *et al.,* 2021).

Beyond that, the method of utilizing fly ash by composting was an applicable and achievable method in PLTU Tarahan. Household waste was certainly available in abundance considering the high activity of employees with a total of 500 people and the size of the operational area which contributes to a large volume of domestic waste. The method of utilizing fly ash by co-composting using press mud material combined with vermicomposting was also a method that has the potential to be implemented. The application of this method was very possible considering the availability of raw materials and the potential for supportive local partnerships. PLTU Tarahan, as one of the major power plants in the Lampung region, produces a significant amount of fly ash as waste from coal combustion. Meanwhile, Lampung Province is one of the national sugar production centers, with several sugar factories such as PTPN VII, PG Gunung Madu, and Sugar Group Companies that produce press mud as organic waste from the sugar cane juice clarification process, so that a partnership can be proposed. By utilizing these multiple types of waste simultaneously, PLTU Tarahan could adopt a circular economic approach to reduce waste piles while producing value-added products in the form of compost or soil amendment.

3.3.4 Comparative analysis of fly ash utilization methods as soil amendment at PLTU Tarahan

In line with efforts to promote circular economy practices and minimize waste generation, several fly ash utilization methods have been critically reviewed by considering both relevant literature and the site-specific characteristics of PLTU Tarahan. Three principal approaches—biosilica production, application as a soil stabilizing agent, and incorporation into compost mixtures—were identified as the most promising. Each method offers distinct benefits and implementation challenges. A comparative analysis of these approaches is presented in Table 5, encompassing key aspects such as material compatibility, infrastructure readiness, pretreatment requirements, implementation feasibility, and associated risk mitigation strategies within the operational context of PLTU Tarahan.

Table 5. Comparative Evaluation of Fly Ash Utilization Methods for Implementation at PLTU Tarahan.

No	Aspects	Utilization Method as a Soil Amendment		
		Biosilica	**Soil stabilizer**	**Compost mixtures**
1	Material Suitability	Highly suitable (Class F; high SiO_2 content, amorphous, low CaO)	Suitable (pozzolanic reactivity effective when combined with lime)	Suitable (alkaline pH supports microbial and enzymatic activity)
2	Infrastructure & Technology Availability	Not yet available – requires chemical extraction units and controlled thermal systems	Commonly used – feasible using standard soil mixing and compaction equipment	Available – compatible with existing composting setups (e.g., windrow, in-vessel, vermicompost)
3	Pretreatment Requirements	High – requires calcination, acid/alkali leaching, and neutralization	Minimal – requires mixing with lime and optional moisture content adjustment	Moderate – requires mixing with organic matter and controlled composting process
4	Product Marketing Potential	Niche products: agricultural biosilica, industrial silica, potential for export	Primarily internal use; potential supply for local construction projects	Easy to distribute locally: organic compost for farmers and PLTU landscaping
5	Risk Mitigation Measures	Chemical waste management from extraction; post-process treatment of residues	Ensure homogeneous mixing to prevent structural segregation	Regular monitoring of C/N ratio, pH, and heavy metals; Control of fly ash dosage to avoid phytotoxicity
6	Added Value	High-value product with industrial relevance; Supports innovation and waste-to-resource transformation	Supports in-house infrastructure, agriculture, and land improvement	Reinforces circular economy via local resource loops; Contributes to community engagement and sustainable agriculture
7	Implementation Scheme at PLTU Tarahan	Development of pilot plant for silica extraction using NaOH/HCl process	Application in site-level infrastructure and plantation area (e.g., internal roads, land reclamation)	Integration with domestic organic waste composting for Corporate Social Responsibility (CSR) use

The comparative overview presented above highlights the relative feasibility, benefits, and constraints of each fly ash utilization pathway within the operational context of PLTU Tarahan. This synthesis provides a foundation for prioritizing strategies that are both technically viable and environmentally responsible. The subsequent conclusion outlines key insights derived from the analysis and offers recommendations for practical implementation and future research. Collaboration between PLTU, research institutions, and local governments are also important in developing technical guidelines for the safe utilization of fly ash in accordance with local characteristics, to prevent long-term negative impacts on the environment and public health.

4. Conclusions

Based on the results of the study, the fly ash produced by PLTU Tarahan exhibits physical and chemical characteristics that demonstrate strong potential for use as a soil amendment, particularly due to its high silica content, alkaline properties, and texture that supports the decomposition process. The three utilization methods examined—biosilica production, incorporation into compost mixtures, and application as a soil-stabilizing agent—showed promising results in enhancing nutrient availability and soil quality. These methods can be implemented at PLTU Tarahan by considering the site-specific characteristics and the availability of local resources. Each method possesses its own advantages, challenges, and implementation strategies.

Further research is required through laboratory and pilot-scale testing to evaluate the practical performance and long-term sustainability of these three methods under field conditions. In addition, the findings of this study indicate the need for a comprehensive assessment to determine the most appropriate utilization approach among the three. One possible framework for this evaluation is multicriteria analysis, which integrates various technical, environmental, social, and economic factors in the decision-making process—such as through the Analytic Network Process (ANP) method..

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