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Circular Waste Management Through Sustainability Governance in the Energy Industry

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ABSTRACT

The rising electricity demand has increased industrial waste generation in the energy industry, particularly Fly Ash and Bottom Ash (FABA), which pose environmental risks if not managed sustainably. Circular waste management offers an effective approach to reduce environmental impacts and improve resource efficiency; however, its success depends on the quality of sustainability governance, which integrates environmental protection, social participation, and institutional coordination. This study examines the governance-related factors influencing the external utilization of industrial waste and develops a sustainable and replicable management strategy for the energy industry. A mixed-method design was employed, combining quantitative analysis using exploratory factor analysis (EFA) of survey data from 115 respondents with qualitative interviews with power plant operators and local government officials. The results identify two key factors shaping circular waste management performance: infrastructure and institutional support for waste utilization, and promotion and regulatory mechanisms. The analysis also revealed five major challenges: financial constraints, infrastructure limitations, regulatory barriers, weak stakeholder engagement, and limited multi-stakeholder collaboration. This study proposes an integrated sustainability governance framework that strengthens circular waste management practices and provides practical guidance for policymakers and industry stakeholders, particularly in developing countries.

1. INTRODUCTION

The expansion of coal-fired power generation in Indonesia has resulted in a substantial increase in combustion-derived solid waste, particularly Fly Ash and Bottom Ash (FABA). At the national level, the annual generation of FABA has exceeded 11 million tons, underscoring the magnitude of waste management challenges associated with coal-based energy systems [1]. This growing volume presents both environmental risks and opportunities for resource recovery if managed within a circular economy framework. In response to these challenges, the Government of Indonesia enacted Government Regulation of the Republic of Indonesia Number 22 of 2021, which reclassified FABA from hazardous and toxic waste (B3) to non-B3 waste. This regulatory reform was intended to facilitate wider utilization of FABA, particularly in construction materials and other industrial applications. However, a critical implementation gap persists between regulatory intent and actual industrial practice, as empirical evidence from field observations suggests that this regulatory shift has not yet translated into effective implementation. FABA continues to be predominantly treated as a low-value combustion residue, with limited economic utilization and persistent reliance on disposal-based management practices [2].

This discrepancy between regulatory intent and operational practice is evident in the case of PLTU Asam-Asam, a state-owned coal-fired power plant located in South Kalimantan Province, Indonesia. With an installed capacity of 65 MW, the facility operates using sub-bituminous coal, which generates considerable quantities of FABA annually. According to operational records from 2024, total FABA production at PLTU Asam-Asam reached 104,805 tons. Despite the substantial volume generated, FABA utilization at the plant remains minimal. Only approximately 553 tons, equivalent to 0.53% of total FABA production, were utilized through external channels (Table 1). The remaining majority was stockpiled in internal disposal facilities without further processing or value-added applications. Such a management pattern indicates a low level of material circularity and highlights inefficiencies in transforming combustion by-products into secondary resources. This case provides concrete empirical evidence of the implementation gap between national regulation and operational practice, reflecting a broader structural issue within Indonesia's coal-based energy sector, where regulatory advancements are not yet supported by sufficient technical readiness, market demand, or institutional coordination. Enhancing FABA utilization therefore requires not only technical solutions but also governance-oriented and multi-actor strategies encompassing policy enforcement, technological innovation, and cross-sector collaboration to enable the transition from disposaloriented waste management toward a more circular and resource-efficient energy system.

Table 1. Fly Ash and Bottom Ash (FABA) utilization at PLTU Asam-Asam

Month	Internal Utilization (tons)	External Utilization (tons)
January	5,127	0
February	3,544.4	0
March	1,987.04	0
April	13,089.04	0
May	15,885.03	0
June	2,483.78	0
July	11,904.35	0
August	33,720	0
September	13,875	0
October	1,500	0
November	830.69	285.74
December	858.91	268.07
Total	104,805.2481	553.81

Source: Authors

The accumulation of FABA waste in landfills poses serious environmental problems, including potential air, soil, and water pollution, and confirms the weak application of circular economy principles in the national energy sector [3]. The FABA problem is not only related to the accumulation of combustion residues but also reflects the lack of integration of the Environmental, Social, and Governance (ESG) dimensions in industrial waste management. In this study, sustainability governance is conceptualized as the interaction between environmental feasibility (technology and ecological impact), social acceptance (public perception, literacy, and participation), and governance capacity (policy frameworks, incentives, and institutional coordination). From an environmental perspective, FABA has great potential as a cement substitution material in the manufacture of concrete, soil stabilization material, and raw material for making geopolymers. This utilization can contribute to the reduction of carbon emissions and the conservation of natural resources [4, 5]. However, various obstacles still hinder the development of FABA's added value, including the limitations of rare earth metal extraction technology, the absence of national quality standards for its derivative products, and the lack of an integrated and accountable environmental impact monitoring system [6]. In the social dimension, the economic potential of FABA should encourage the creation of business opportunities for small and medium business actors, especially in the building materials sector and alternative material-based creative industries. In addition, increasing public awareness of sustainable waste management is necessary for the FABA value chain to be formed inclusively [7]. Unfortunately, the lack of public access to technical training, low environmental literacy, and a strong negative perception of waste are the main obstacles to strengthening public participation [8]. In terms of governance, regulatory changes have not been accompanied by widely accessible technical guidelines, adaptive licensing mechanisms, or clear incentive structures. Information disclosure in FABA's supply chain is still limited, and multistakeholder collaboration forums involving governments, industry players, academics, and communities have not been permanently established [9]. These interrelated dimensions demonstrate that FABA utilization is not solely a technical issue but a governance challenge requiring integrated ESG-based analysis.

This study focuses on identifying and analyzing crucial factors in the ESG dimensions that influence external demand for FABA utilization at the Asam-Asam coal-fired power plant. To achieve this, the study adopts a mixed analytical approach combining quantitative factor prioritization with qualitative stakeholder insights, capturing the interaction between the government, industry, and local communities as key actors in sustainable FABA governance. The study aims to develop an actionable and replicable ESG-based strategy that is relevant not only for the Asam Asam context but also for other coal-fired power plants in Indonesia and comparable developing countries facing similar waste management challenges.

The problem-solving strategy in this study emphasizes the importance of implementing ESG principles in industrial waste management systems, particularly in the national energy sector. From an environmental perspective, the application of the zero-waste principle is a fundamental element in reducing industrial waste and strengthening circular economy practices. This principle prioritizes a systematic approach through the efficient reduction, reuse, and recycling of materials [10]. In the context of FABA management, this principle opens up significant opportunities for building material substitution, carbon emission reduction, and natural resource conservation [11]. However, in practice, structural and regulatory barriers remain the main barriers, especially in developing countries [12]. Operationally, the ESG framework in this study was applied by grouping the influencing factors and FABA utilization strategies into three main dimensions that are integrated with each other. From an environmental perspective, the focus is on the exploration of FABA utilization technology and the effectiveness of reducing ecological impacts through the substitution of conventional materials. The social dimension is examined through public perception, the level of public waste literacy, and MSME participation in the alternative material supply chain. The governance aspect is analyzed through sectoral policies, the availability of incentives, licensing mechanisms, and coordination structures between stakeholders. Each dimension of ESG is measured based on the perception of local multiactors, namely, regulators, industry players, and impacted communities.

This research also fills the scientific gap that has been missed in previous literature discussions. Most previous studies have tended to limit the analysis to only one dimension, either environmental [13, 14], social [15-18], or economic [19]. There remains a lack of integrative analysis that captures the interaction between these dimensions within a governance framework. Moreover, existing research rarely examines the implementation gap between regulatory frameworks and actual industrial practices, particularly in the context of FABA utilization in coal-fired power plants. In addition, participatory ESG approaches that incorporate stakeholder perceptions remain underexplored, despite their importance in shaping sustainable waste management outcomes. By integrating environmental feasibility, social acceptance, and governance capacity, this study provides a more comprehensive and context-sensitive analytical framework [15-18]. This approach is particularly relevant for developing countries such as Indonesia, where institutional limitations, market barriers, and public trust issues significantly influence the success of circular economy initiatives [17, 20].

This research integrates information technology within the governance dimension to improve the efficiency, transparency, and accountability in waste management systems [20]. In addition, human resource risk management is emphasized as the main prerequisite for corporate sustainability and corporate governance, which is adaptive to external environmental pressures [18]. This study contributes by providing empirical evidence of the regulatory implementation gap in FABA utilization, applying a governance-oriented ESG framework rather than a purely technical perspective, and integrating quantitative and qualitative approaches to identify actionable priorities for stakeholders. The findings aim to support the transformation of FABA from a low-value residue into a strategic ESG-based resource that contributes to sustainable energy transition policies.

2. METHODOLOGY

The research approach used in this study was a mixed method, which is a methodological framework that integrates quantitative and qualitative methods to answer the research objectives. This approach was chosen to gain an in-depth understanding of complex issues, namely the evaluation of the implementation of ESG standards in the management of FABA waste in the national energy sector, especially in the Asam-Asam coal-fired power plant. The research was conducted in three sequential stages: quantitative analysis, qualitative exploration, and data integration. The development of the 18 indicators followed a systematic three-step process. First, indicators were systematically derived from prior literature on ESG, waste management, and circular economy practices. Second, each indicator was explicitly mapped into the ESG dimensions, where environmental indicators represent technological feasibility and ecological impact, social indicators capture public awareness and participation, and governance indicators reflect policy support, institutional coordination, and regulatory effectiveness. Third, the indicators were validated through expert judgment and contextualized to the Asam-Asam setting, considering local industrial characteristics, MSME involvement, and existing regulatory conditions. The quantitative stage aimed to identify key factors influencing external demand for FABA utilization. Each indicator was designed to measure respondents' perceptions across ESG dimensions in an integrated manner. Perception measurements were conducted using a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) to ensure structured and interpretable data. A detailed list of indicators and their sources is provided in Table 2 to enhance transparency and replicability.

Table 2. The indicators of Fly Ash and Bottom Ash (FABA) implementation

Indicators	Statement Items
Knowledge of FABA [1, 3] • Understanding of the physical and chemical properties of FABA • Information about FABA applications in construction	• I have a basic understanding of FABA as a product of power generation. • I know that FABA can be used for various construction needs.
Economic Benefits of FABA [4, 16] • Potential construction cost reduction • Job creation opportunities	• I learned that FABA can help reduce costs in construction projects. • I believe that FABA management can support the opening of local business opportunities.
Infrastructure Support [9] • Availability of FABA processing facilities • Availability of transportation facilities	• Processing facilities to support the use of FABA are not widely available in my area. • Access to transportation is a major challenge to utilize FABA widely in my area.
Accessibility and Distribution [10] • Ease of distribution of FABA-based products • Distribution costs	• I feel that it is difficult to distribute FABA-based products to the local market. • The cost of distributing FABA is too expensive for the surrounding community.
Government Policy [12, 18] • Regulatory clarity • Policy effectiveness in supporting the use of FABA	• I feel that the government's policy on FABA management has not been fully understood by the public. • The current government policy is quite effective in supporting the optimal use of FABA in my area.
Environmental Awareness [17] • Concern for FABA's environmental impact • Support for environmental programs	• I feel that the public does not understand the environmental impact of FABA which is not managed properly. • I support the existence of an environmental education program to increase public understanding of FABA.
Processing Technology [20] • Innovations in FABA processing technology • Availability of technology training	• I feel that FABA processing technology is not yet widely available in my area. • Training on FABA processing technology needs to be improved in my area.
Education and Socialization [17] • The level of public education about FABA • Frequency of socialization activities	• I feel that socialization related to the benefits of FABA has not been done much in my area. • FABA education and socialization activities need to be carried out more often in the local community.
Local Economic Support [18] • Improving the economy of local communities • Strengthening small and medium enterprises	• I feel that the use of FABA can provide economic opportunities for the people in my area. • I believe that MSMEs can benefit from the management and use of FABA.
Public Trust [14] • Confidence in the benefits of FABA • Risk perception of FABA use	• I believe that FABA is safe to use if it is properly managed. • I feel that people are still hesitant to use FABA due to the lack of clear information.
Stakeholder Collaboration [12] • Cross-sector coordination • Community involvement	• I feel that the government, society, and industry need to collaborate more in the use of FABA. • I feel that the community needs to be more involved in the FABA management process.

Regulation and Supervision [18] • Effectiveness of regulatory oversight • Consistency of regulatory implementation	• I feel that the government's supervision of FABA management has not been optimal. • I feel that the regulations related to the management of FABA are not consistent in my area.
Risk Perception [21, 22] • Perception of social risk • Perception of economic risk	• I feel that the public is still worried about the social impact of the use of FABA. • I feel that the use of FABA does not pose a significant economic risk to the community.
Community Engagement [22] • Participation in management programs • Support for local policies	• I feel that the community needs to be encouraged to actively participate in the management of FABA. • I support the existence of a local policy that focuses more on FABA management.
Program Sustainability [21] • Ongoing support • Commitment of all parties	• I believe that the FABA utilization program needs to be continued to support the environment. • I feel that the success of the FABA management program depends on the commitment of all parties involved.

Source: Authors

The research population consists of key actors surrounding the operational area of the Asam-Asam coal-fired power plant, including: 1) local communities within the Ring-1 radius, 2) MSME actors with potential to utilize FABA, and 3) local government and regulatory representatives responsible for environmental management. Respondents were grouped based on these three roles to reflect their position within the FABA value chain. The sampling technique used was purposive sampling, selecting respondents based on direct involvement in FABA-related activities. A minimum sample size of 100 was targeted, with a final sample of 115 respondents, ensuring adequacy for multivariate analysis. Given the inclusion of heterogeneous actor groups, this study explicitly acknowledges differences in perspectives arising from variations in knowledge, interests, and institutional roles. However, pooling the data is methodologically justified because all respondent groups are structurally interconnected within the FABA value chain and collectively influence external utilization outcomes. Furthermore, the objective of the analysis is to identify underlying latent factors (via exploratory factor analysis (EFA)) at the system level rather than to compare group-specific perceptions. To address potential bias, differences between actor groups were further examined during the interpretation stage and triangulated using qualitative findings, ensuring the robustness of cross-actor insights.

Quantitative data were analyzed using EFA to identify underlying latent factors representing ESG dimensions. Instrument validity was assessed using the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy (threshold > 0.5) and Bartlett's Test of Sphericity ($p < 0.05$). Factor extraction was conducted using Principal Component Analysis (PCA), with eigenvalues greater than 1 as the selection criterion. Varimax rotation was applied to enhance interpretability, with factor loadings above 0.4 considered significant. The interpretation of extracted factors was explicitly linked to ESG dimensions, ensuring that each factor reflects an integrated combination of environmental feasibility, social acceptance, and governance capacity. The qualitative phase aimed to provide in-depth insights into challenges and opportunities in FABA utilization. Data were collected through semi-structured interviews with key informants, including local government representatives, MSME actors, and PLTU management. The interview guide was directly derived from the same 18 indicators used in the quantitative phase, ensuring methodological consistency and strong linkage between datasets. Interviews included structured ESG-based questions as well as open-ended discussions to capture contextual insights. Data were analyzed using thematic analysis, involving coding, theme development, and interpretation. This approach enabled triangulation between quantitative findings and stakeholder perspectives, strengthening the validity of ESG-based interpretations.

The final stage involved integrating quantitative and qualitative findings using a sequential explanatory design. Quantitative results from EFA were first established, followed by qualitative interpretation to explain the underlying context. The EFA produced two main constructs: 1) economic and infrastructure support and 2) social and regulatory support. Integration was performed using a connecting and merging approach, where qualitative themes were mapped onto quantitative factor structures, enabling a comprehensive ESG-based interpretation. This process is illustrated in Figure 1 and aims to bridge statistical findings with real-world contextual dynamics.

The sample consisted predominantly of male respondents, reflecting the gender distribution in technical and construction sectors. This potential bias is explicitly acknowledged and considered during interpretation to avoid overgeneralization. Instrument validity was assessed through a pilot test ($n = 29$), followed by full data collection ($n = 115$). The dataset met EFA requirements, with KMO values exceeding 0.7 and Bartlett's Test showing statistical significance ($p < 0.05$). These results confirm the adequacy of the sample and the reliability of the instrument. The final integrated findings were used to develop a strategic ESG-based model, which was further validated through a Focus Group Discussion (FGD) involving multi-stakeholder participants. This step ensured the practical relevance and feasibility of the proposed model.

The expected outcome of this study is the development of a comprehensive ESG-based evaluation framework for FABA utilization in the national energy sector. The study identifies both enabling and constraining factors across ESG dimensions and formulates actionable strategies for stakeholders. By integrating quantitative factor prioritization and qualitative stakeholder insights, the study provides a robust basis for policy formulation and practical implementation. The environmental dimension emphasizes sustainable and productive utilization, the social dimension focuses on stakeholder participation, and the governance dimension supports policy alignment and institutional coordination.

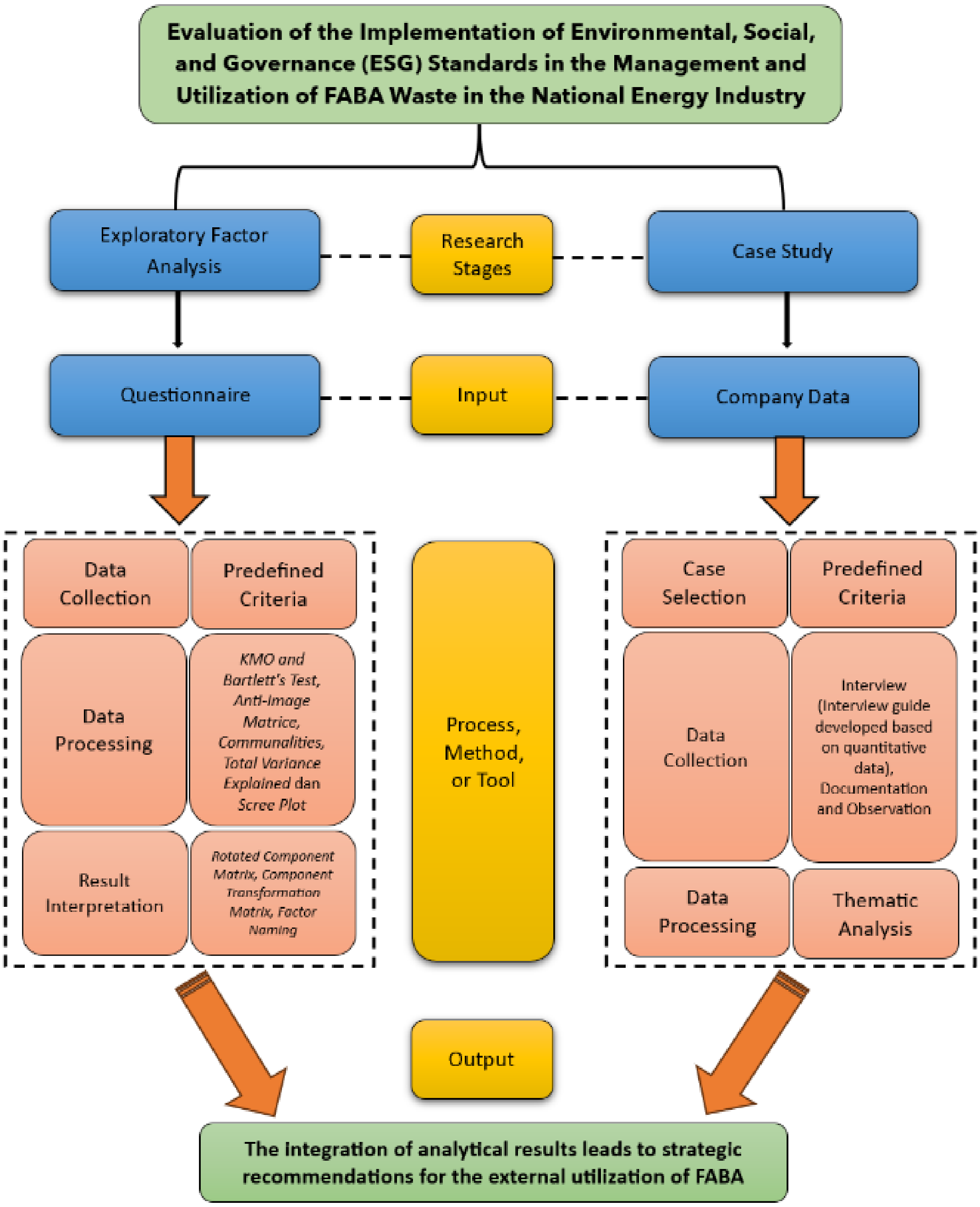

Figure 1. Research flowchart

3. RESULTS AND DISCUSSION

The respondent profile in this study provides valuable insights into the demographic characteristics influencing the utilization of FABA at the Asam-Asam coal-fired power plant. The sampling technique employed was purposive sampling, whereby the respondents were selected based on predetermined criteria. The criteria were as follows: (1) community members residing within the "Ring-1" radius of the Asam-Asam power plant who possess basic knowledge of FABA; (2) local government officials involved in monitoring or managing regional development and environmental impacts; (3) external companies and MSMEs with the potential to use FABA as a raw material for their products. Of the 115 respondents, the majority were male (96.5%), comprising 111 individuals, while only four respondents (3.5%) were female. This imbalance reflects the dominance of male participation in technical and construction-related sectors rather than differences in knowledge, and it is acknowledged as a potential source of bias in interpretation. The age distribution was diverse, with an average age of 30.56 years and a range of 18-54 years. This age diversity indicates that FABA utilization encompasses individuals from various age groups.

In quantitative research, validity and reliability are critical aspects that ensure the quality and dependability of a measurement instrument. Validity refers to the extent to which an instrument accurately measures what it is intended to measure, whereas reliability assesses the consistency of the results when the instrument is applied under similar conditions. Instrument validity was tested using the Pearson Product-Moment Correlation technique, which evaluates the strength of the relationship between each indicator and the total score of its construct. Pilot testing. Prior to the main survey, a pilot test was conducted with 29 respondents to evaluate item clarity, preliminary item-total validity, and initial reliability. This pilot size aligns with scale development recommendations suggesting 10-30 participants as an appropriate range for preliminary studies. The pilot findings were used to refine the wording and filter items before the main data collection. Following instrument refinement, data were collected from 115 respondents and analyzed using EFA. This sample size satisfies the general guidelines (≥ 100-200; N : variable ratio of 3–10) and was deemed adequate based on the high KMO index (≈ 0.94) and significant Bartlett's test, both indicating the factorability of the correlation matrix. All final reliability reporting (factor-level alpha) and factor interpretation were based on the main survey (n = 115) rather than pilot data. Based on the calculations, the pilot test involved 29 respondents, yielding degrees of freedom (df) = n - 2 = 29 - 2 = 27 for the correlation test. At a significance level of $\alpha = 0.05$, the critical r-value used as a reference was 0.3673, which was obtained from the Pearson statistical distribution table. The validity test results demonstrated that all indicators, from I1 to I18, had Pearson Correlation values greater than 0.3673. Furthermore, each indicator had a significance value (Sig. 2-tailed) below 0.05, indicating that the correlations between each indicator and the total score were statistically significant (Table 3). Thus, it can be concluded that all indicators employed in this research instrument are valid, as they met the significance criteria and demonstrated sufficiently strong correlations with the total scores of the variables measured.

Table 3. The validation results

Indicator	Pearson Correlation	R-Table	Description
I1	0.726	0.3610	Valid
I2	0.667		Valid
I3	0.655		Valid
I4	0.892		Valid
I5	0.772		Valid
I6	0.860		Valid
I7	0.793		Valid
I8	0.764		Valid
I9	0.882		Valid
I10	0.831		Valid
I11	0.783		Valid
I12	0.849		Valid
I13	0.722		Valid
I14	0.507		Valid
I15	0.746		Valid
I16	0.548		Valid
I17	0.746		Valid
I18	0.603		Valid

Source: Authors

Once the validity of the instrument was confirmed, the next step was to test its reliability using Cronbach's alpha, a widely applied method for measuring the internal consistency of a scale. Cronbach's alpha values ranged from 0 to 1, with higher values indicating greater reliability. An instrument can be categorized as moderately reliable when Cronbach's alpha falls within the range of 0.6–0.7, reliable when between 0.7–0.8, and highly reliable when it exceeds 0.8. In this study, the reliability test yielded a Cronbach's alpha value of 0.951, indicating that the instrument possessed exceptionally high reliability. This result demonstrates that the research instrument has a very strong internal consistency, meaning that each indicator consistently and stably measures the intended construct. Overall, the findings of this study confirm that the instrument used is both valid and reliable, thereby ensuring that data collection can be conducted with a high degree of confidence and accuracy. These results highlight the importance of conducting validity and reliability tests to guarantee the quality of research instruments, particularly in studies that involve measuring psychological and behavioral dimensions.

The suitability of the dataset for factor analysis was evaluated using the KMO Measure of Sampling Adequacy and Bartlett's Test of Sphericity. The KMO value obtained was 0.940, indicating excellent sampling adequacy. Bartlett's Test of Sphericity produced a significant result ($\chi^2 = 1306.367$; $p < 0.05$), confirming that the correlation matrix is not an identity matrix (Table 4). These results indicate that the dataset is suitable for factor analysis (factorability), rather than testing data normality. The analysis of the Anti-Image Correlation results within the framework of EFA demonstrates that all indicators in this research instrument meet the requirements for sample adequacy Measure of Sampling Adequacy (MSA). Theoretically, an indicator is considered suitable for inclusion in further analysis if its Anti-Image Correlation value exceeds the threshold of 0.50. This criterion was applied to ensure that each variable made an adequate contribution to the factor structure to be established. Based on the calculations, all MSA values for the respective indicators were above the 0.50 threshold. These findings provide a strong basis for concluding that all indicators are statistically appropriate for further analysis in the factor extraction process. Consequently, none of the indicators needed to be eliminated at this stage, and all variables could be included in the development of valid and reliable constructs.

Table 4. The communalities results

Indicator	Initial	Extraction
I1	1	0.545
I2	1	0.528
I3	1	0.447
I4	1	0.713
I5	1	0.588
I6	1	0.562
I7	1	0.648
I8	1	0.638
I9	1	0.649
I10	1	0.663
I11	1	0.570
I12	1	0.765
I13	1	0.618
I14	1	0.528
I15	1	0.673
I16	1	0.439
I17	1	0.638
I18	1	0.567

Source: Authors

In the process of EFA, one critical step is the evaluation of the communality's values for each indicator. The criterion applied to assess the adequacy of indicators at this stage is the extraction communalities value, whereby an indicator is considered acceptable if its extraction value exceeds 0.50. This value represents the proportion of variance in each variable that can be explained by the factors in the model. Based on the results of the calculations, two of the 18 indicators analyzed, I3 and I16, had extraction values below the 0.50 threshold. Accordingly, these two indicators were deemed insufficient to represent the latent construct under investigation and were therefore excluded from the subsequent stages of the analysis. The remaining 16 indicators demonstrated adequate extraction values and were retained for further factor analysis. These findings indicate that the indicators in this study significantly contribute to explaining the factor structure that was established.

The analysis of the variance exploration results indicated that two principal factors emerged from the 16 indicators analyzed. The first factor had an eigenvalue of 8.890 and contributed significantly to explaining 55.561% of the variance in the dataset. This finding suggests that more than half of the information contained within the indicators can be represented by one dominant factor. The second factor had an eigenvalue of 1.115, accounting for an additional 6.967% of the variance. Cumulatively, these two factors explained 62.529% of the total variance, which is considered highly satisfactory in factor analysis, as it exceeds the minimum threshold for model interpretability. The presence of these two factors was further supported by the visual pattern observed in the scree plot, which illustrates the relationship between eigenvalues and the number of extracted factors. The scree point, where the slope of the curve began to level off, was observed immediately after the first two factors (Figure 2). This indicates that these two factors constitute the optimal number within the data structure, whereas subsequent factors contribute negligibly to explaining the additional variance.

The Rotated Component Matrix in this study was used to identify the factor structure of the 16 indicators that had passed the validity and reliability tests (Table 5). The criterion applied in this process was the factor loading value, whereby a variable was considered significant if its loading exceeded 0.55 and was clustered within a specific component. This value reflects the strength of the relationship between an indicator and the factor. Based on the rotation results, two principal components were identified. The first component consisted of 12 indicators with factor loading values above 0.55, all consistently grouped within a single dimension. This indicates that the 12 indicators demonstrated strong correlations and collectively formed a coherent factor, which was subsequently interpreted as Factor 1. The second component comprised the remaining four indicators, each with factor loading values above 0.55, which consistently clustered within Component 2. This consistent grouping suggests that these four indicators represent a construct distinct from that of the first group, thereby forming Factor 2.

Table 5. The rotated component results

Indicator	Component 1	Component 2
I4	0.808	
I17	0.776	
I1	0.732	
I5	0.730	
I9	0.724	
I8	0.697	
I2	0.678	
I15	0.676	
I18	0.664	
I10	0.652	
I17	0.625	
I14	0.614	
I12		0.827
I13		0.738
I11		0.722
I16		0.700

Source: Authors

These findings reinforce the structural validity of instrument measurement, as each indicator successfully converged into the factor to which it theoretically belongs (Table 6).

Table 6. The exploratory factor results

Factor	Indicator
1	I4, I7, I1, I5, I9, I8, I2, I15, I18, I10, I17, I14
2	I12, I13, I11, I6

Source: Authors

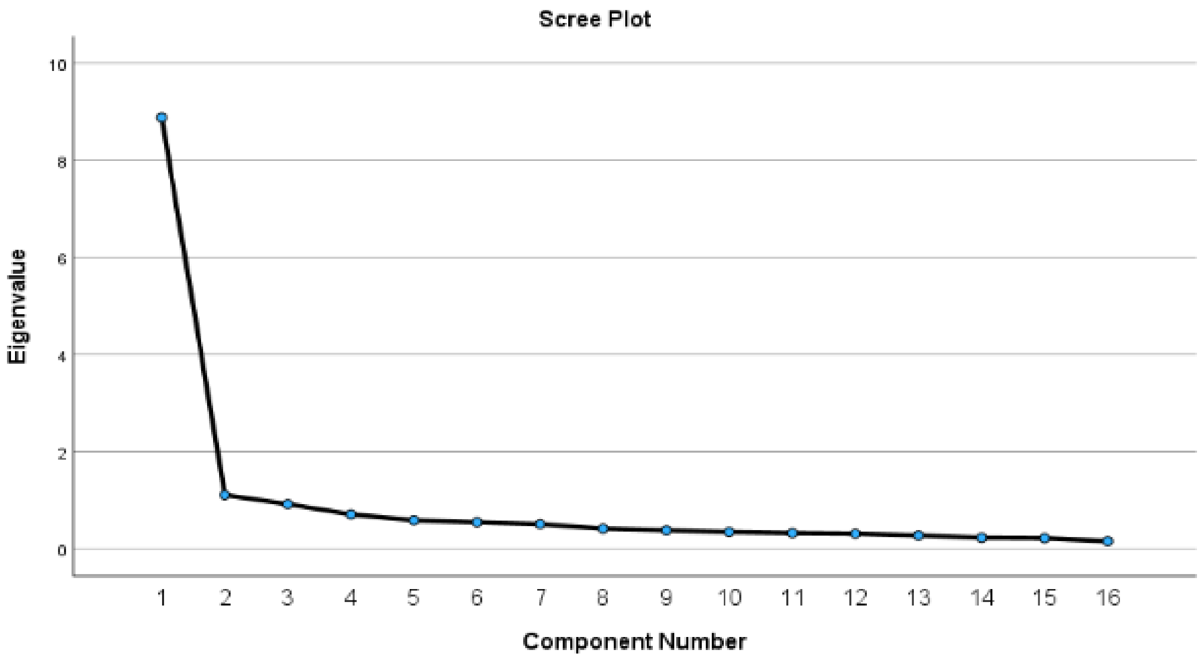

Figure 2. Scree plot

The first factor reflects the structural and institutional dimensions that underpin the overall success of FABA utilization. The indicators included in this factor highlight the importance of adequate infrastructure as a foundational prerequisite to support the distribution and FABA use. Moreover, the level of public understanding on FABA benefit as a construction material directly contributes to its acceptance and adoption at the local level. Community potential for active participation, the technological readiness of small-scale industries, as well as educational programs and information campaigns, reinforce collective awareness FABA usage importance. Additional supporting elements identified include collaborative forums as spaces for innovation, the availability of structured implementation guidelines, the presence of local markets ready to absorb FABA-based products, simplified licensing procedures, and synergy among government, business, and local communities, all of which jointly foster a conducive and sustainable utilization ecosystem. The second factor emphasizes aspects of promotion, regulation, and the strengthening of interactor relationships within the FABA value chain. The indicators grouped under this factor include effective promotion and marketing strategies to expand FABA market acceptance. The commitment of both government authorities and coal-fired power plants to support the implementation of FABA-related regulations serves as a crucial pillar for the continuity of these initiatives. The level of integration between power plants as producers and industrial sectors as end-users represents a crucial factor; when reinforced, it can significantly accelerate the process of utilization. Finally, technical training targeted at MSME actors serves as an important bridge for transferring practical skills and expanding community production capacity in transforming FABA waste into economically valuable products.

Qualitative data analysis in this study employed case-study approach, with the objective of inductively developing themes and concepts derived from field data. The analysis was carried out in three main stages: open coding, axial coding, and selective coding. Semi-structured interviews were conducted with two strategic informants: Pahrinnor, representing Asam-Asam power plant management, and Zainal Arifin, the Village Secretary of Pandansari. The interviews were analyzed using manual coding techniques. Each transcript was carefully examined to extract “core ideas” and “keywords,” which were then developed during the open coding process. The results of open coding were subsequently advanced into the axial coding and selective coding stages to formulate conceptualization, categorization, and thematization of the interview findings (Table 7). Open coding constituted the initial stage of qualitative analysis, conducted by thoroughly reviewing the entire interview transcripts of the two key informants, both of whom held strategic roles in the context of FABA management and utilization. This stage aimed to identify and separate each data segment containing significant meaning into basic units of information. These units of meaning were interpreted as direct representations of the informants’ experiences, perceptions, and perspectives regarding field realities. The process was both descriptive and interpretative, as the researcher systematically organized information into preliminary categories that captured recurring thematic patterns. This analysis produced fourteen major categories, which provided the initial basis for developing broader conceptual categories in the subsequent stage. From the open coding results, units of meaning that shared substantive similarities and thematic tendencies were consolidated during the axial coding stage. This process was performed to construct more meaningful relational patterns among the data units, which were then organized into broader and more structured conceptual categories. Axial coding enabled the researcher to identify relationships among causal conditions, contexts, interventions, strategies, and consequences of the phenomena under study. Through this process, fragmented data was organized into ten thematically significant categories with deeper conceptual meaning. These categories were subsequently employed to understand more complex dynamics in the context of FABA utilization, leading toward data integration in the selective coding stage. Axial coding was then restructured into a broader and more systematic thematic framework that reflected the primary focus of this research. This process resulted in five core elements representing the conceptual framework for understanding critical aspects of FABA management and utilization: economic support, infrastructure, regulation and licensing, socialization, and multi-stakeholder collaboration. Each of these elements serves as an analytical pillar for understanding the dynamics of the system involved. Of the five elements considered, economic support emerged as the most pressing priority, given its direct bearing on the ability of local communities to secure business opportunities, mobilize capital, and sustain operational viability in the utilization of industrial waste. This coding structure offers a robust conceptual framework for advancing the analysis of interrelated factors in ESG context.

Findings from the qualitative analysis reveal that challenges in FABA utilization arise not only from technological readiness but also from inequities in economic access, infrastructure, and governance. Economic support emerged as the central theme, shaped by systemic issues including the lack of equipment subsidies, training opportunities, and micro-financing schemes (Table 8). These findings underscore that the sustainability of FABA utilization projects is highly dependent on the presence of contextual and well-targeted economic interventions. Furthermore, the interviews confirmed that rural communities demonstrate strong willingness to participate. However, they are constrained by limited access to capital, technology, and market. This reflects a gap between local enthusiasm and the systemic support required. Without adequate interventions, the economic potential of FABA will remain untapped within a fragmented supply chain.

The findings of this study show that the success of the external utilization of FABA is largely determined by the alignment between infrastructure support, regulatory effectiveness, community engagement, and collaborative governance schemes. The quantitative analysis identified two main constructs, namely 1) economic and infrastructure support and 2) social and regulatory support, while the qualitative analysis revealed five key themes: economic support, infrastructure, regulation and licensing, socialization, and multi-stakeholder collaboration. These findings are explicitly interconnected, where Factor 1 corresponds to economic support and infrastructure readiness, while Factor 2 aligns with socialization, regulatory frameworks, and stakeholder collaboration. This integration demonstrates strong convergence between quantitative factor structures and qualitative thematic insights, reinforcing the robustness of the findings. The divergent perceptions between community members and MSME actors reflect structural asymmetries in knowledge, access, and institutional support. Communities tend to perceive FABA as low-value waste due to limited exposure and lack of demonstration projects, whereas MSMEs recognize its economic potential but face operational barriers such as logistics costs, licensing complexity, and limited technical assistance [2]. These findings suggest that the main constraint is not merely technological, but lies in "last-mile" governance challenges, including weak coordination, insufficient policy incentives, and gaps in knowledge transfer at the local level. Therefore, intervention strategies must be differentiated: community-focused programs should emphasize awareness and social legitimacy, while MSMEs require targeted support in supply chain efficiency, financing, and regulatory facilitation [2, 20].

Table 7. Manual coding

Open Coding	Axial Coding	Selective Coding (Element)
Significant initial production expenses necessitate subsidies for raw materials and essential equipment.	Barriers of Initial Capital and Production Costs	Economic Support
Non-monetary incentives are required, including paving molds, trucks, and training.	Types of Productive Incentives	Economic Support
Currently, there are no direct subsidies from the government or PLN for firms based on FABA.	Lack of Formal Incentive Programs	Economic Support
Access to micro-grants is essential for launching small-scale firms.	Access to Microfinance	Economic Support
FABA-based goods are more economical; nonetheless, they have not yet attracted interest due to their aesthetic.	Discrepancy Between Economic Value and Product Aesthetics	Economic Support
The power plant infrastructure is sufficient; nonetheless, the hamlet is deficient in equipment, roadways, and storage facilities.	Disparities in Infrastructure	Infrastructure
The power plant utilizes sophisticated technology and substantial apparatus; conversely, the community necessitates fundamental tools and education.	Preparedness of Industrial Facilities in Relation to Local Requirements	Infrastructure
The power plant functions under a Memorandum of Understanding; however, village MSMEs face obstacles due to environmental and administrative licensing constraints.	Variations in Judicial Processes	Regulation and Licensing
A comprehensive service is required to aid small enterprises in acquiring permits.	Legal Complications for Micro, Small, and Medium Enterprises	Regulation and Licensing
Community outreach is inconsistent, but the industry already has a comprehensive understanding.	Disparities in Access to Information	Socialization
The village's marketing approach is predominantly passive, depending mainly on formal invites.	Deficiencies in Local Information Strategies	Socialization
A coordinating forum exists, although it has not yet facilitated economic transformation.	Magnitude and Orientation of Collaboration	Multi-Stakeholder Collaboration
Synergy necessitates a primary facilitator and financial resources for efficient implementation.	Requirement for Cooperative Endeavors	Multi-Stakeholder Collaboration
The local authority is prepared to spearhead the project contingent upon the provision of equipment and training.	Preparedness of Local Government as a Principal Actor	Multi-Stakeholder Collaboration

Source: Authors
Note: FABA = Fly Ash and Bottom Ash

Table 8. Economic support element

Element	Respondent	Interview Excerpts
Economic Support	RT1	FABA products are more economical but are constrained by aesthetic limits.
Economic Support	RT2	Elevated initial production expenses hinder people from commencing without assistance in the form of tools and materials.
Economic Support	RT2	No financial assistance have been obtained, despite considerable business potential.
Economic Support	RT2	Local actors require access to micro-grants or corporate social responsibility funds to establish small-scale firms.
Economic Support	RT1	The power plant supplies FABA at no cost; yet, the town encounters transportation limitations.
Economic Support	RT2	Non-monetary incentives, such paving molds, vehicles, and training, are in greater demand.
Economic Support	RT2	The primary obstacle is the initial capital necessary for equipment and ancillary production materials.
Economic Support	RT2	The local market has potential; nevertheless, purchasing power is limited, and perceptions of FABA product quality are unfavorable.

Source: Authors
Note: FABA = Fly Ash and Bottom Ash

The proposed ESG-based strategy emphasizes that economic support serves as a critical entry point for intervention, complementing environmental and governance dimensions. ESG strategies must be designed as an integrated framework that addresses disparities in access to resources, institutional capacity, and stakeholder coordination within a circular economy system [21, 23]. The findings indicate that although environmental potential (availability of FABA) is high, its utilization is constrained by governance and coordination gaps at the implementation level. Opportunities exist in the readiness of power plants to supply FABA, the presence of emerging local markets, and the institutional capacity of villages (e.g., BUMDes) to drive economic activities. These opportunities highlight that the challenge lies not in resource availability, but in activating an enabling ecosystem through effective governance mechanisms. These findings confirm that the primary barriers to FABA utilization are systemic rather than purely technical, including disparities in economic capacity, institutional limitations, and insufficient support mechanisms. Key challenges include limited access to capital, lack of production equipment, and complex licensing procedures [4, 19]. These constraints reflect a broader "last-mile governance" problem, where policies exist but fail to translate into effective implementation at the local level. However, these limitations also present opportunities, such as the availability of free raw materials, strong local commitment, and village-level institutional readiness. Thus, the success of FABA utilization depends on the ability to bridge policy implementation gaps through targeted, context-specific governance interventions [19, 22].

Previous studies in developing countries such as Ethiopia and India similarly identify legal constraints, infrastructure limitations, and low community participation as key barriers [17, 19]. This study extends these findings by demonstrating that such challenges are interconnected within an ESG-based governance framework, rather than isolated issues. The results show that environmental potential alone is insufficient without supportive social acceptance and governance capacity. In particular, governance acts as a mediating factor that links environmental feasibility with social adoption. Weak institutional coordination, absence of collaborative platforms, and non-adaptive regulatory systems hinder the formation of an effective FABA utilization ecosystem. Conversely, the presence of clear incentives, technical guidance, and coordinated stakeholder engagement significantly enhances both social participation and environmental utilization outcomes. These findings highlight that ESG integration is not merely conceptual but has practical implications for addressing complex, multi-dimensional challenges. The framework developed in this study is applicable to other coal-fired power plants with similar characteristics and provides a replicable model for advancing circular economy-based waste management in developing countries.

Previous research results have shown similar patterns in the context of other developing countries. Research in Ethiopia and India highlights legal barriers, limited infrastructure, and low community participation as the main obstacles in industrial waste management [17, 19]. Nevertheless, this research contributes added value by situating these dynamics within an integrated ESG framework. Whereas previous studies tended to isolate a single dimension such as technical or social concerns, this study demonstrates that the ESG dimensions are interdependent and exert systemic influence on one another [4, 13, 14, 19]. For instance, limitations in physical infrastructure, often regarded as purely technical issues, directly affect social outcomes, including citizen participation and MSMEs' access to raw materials. Governance weaknesses such as the absence of collaborative forums have an impact on the slow transformation of the local waste-based business ecosystem. This research reveals how non-adaptive regulations weaken people's motivation to engage in interactions between ESG dimensions, while also burdening MSMEs in building supply chains. On the contrary, when clear policy incentives and technical guidance are in place, social participation tend to increase and thereby expanding opportunities for environmental utilization. ESG integration is not only conceptual but has proven to have a real impact in managing the complexities that arise in FABA utilization practices [4]. The findings in this study can be adopted by other power plants in Indonesia with similar characteristics, namely locations adjacent to dense communities, high volume of waste, and limited village infrastructure. Patterns of interaction between stakeholders, governance challenges, and reliance on regulatory incentives are common challenges in FABA waste-producing areas. ESG-based strategies built from the results of this data integration have the potential to be replicated to other regions, both at the national and international levels, especially in developing countries that are transitioning to waste management based on circular economic principles.

4. CONCLUSION

This study provides empirical insights from the case of the Asam-Asam coal-fired power plant into the application of an ESG framework in industrial waste management, particularly for FABA utilization. The findings suggest that ESG can function not only as a normative concept but also as an analytical framework to examine the interlinkages between environmental feasibility, social acceptance, and governance capacity in the waste utilization chain. This research integrates quantitative and qualitative analysis offering a context-specific understanding of the interaction between policy and practice within a circular economy perspective. The results indicate that infrastructure and regulatory support alone are insufficient; effective implementation depends on coordinated social interventions, economic incentives, and multi-stakeholder collaboration. Importantly, the findings highlight that the primary constraints are not purely technical, but relate to "last-mile" governance challenges, including coordination gaps, limited incentives, and barriers to local implementation. The practical implications of the findings of this study can be used by energy sector policymakers, coal-fired power plant managers, and local governments in developing strategies to increase the use value of FABA waste in a sustainable manner. The ESG-based approach can serve as a guiding framework for identifying implementation barriers, setting policy priorities, and designing interventions that are adaptive to local needs. The strategic recommendations developed, such as strengthening the capacity of MSMEs, developing shared infrastructure, and improving information dissemination are derived from the case context and may require adaptation before application in other settings. The scope of this study is limited to one study location, namely PLTU Asam-Asam in South Kalimantan, which has certain geographical and social characteristics so that the potential for generalization of findings to other regions is limited. Accordingly, the findings should be interpreted as context-bound, and their transferability to other regions requires careful consideration. In addition, the collection of regulatory data is carried out through document review and limited interviews, which risks ignoring the dynamics of government policies and regulations at the local level. The sample composition was predominantly male, reflecting the demographic profile of respondents in technical and industrial sectors; this may limit the representation of diverse perspectives, particularly in relation to social and participatory dimensions. Future research is therefore recommended to conduct comparative studies across multiple locations with varying socio-economic and governance contexts. Comparative analysis across power plants in different regions of Indonesia, as well as in other developing countries, would help to test the robustness and generalizability of the ESG-based framework proposed in this study. Further research could also explore the development of ESG-based policy models that incorporate local institutional dynamics, incentive structures, and governance capacity. Such efforts would contribute to validating and refining the applicability of ESG-based strategies in supporting inclusive and sustainable industrial waste management systems.

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