JRSSEM 2026, Vol. 5, No. 9
E-ISSN: 2807 - 6311
P-ISSN: 2807 - 6494
JRSSEM JOURNAL RESEARCH OF SOCIAL SCIENCE, ECONOMICS, AND MANAGEMENT

Integration of Life Cycle Assessment and Policy Analysis for Improving Sustainable Coal Ash Management: A Case Study in South Sumatra, Indonesia

Ridho Bayuaji, Reny Nadlifatin, Ruri Agung Wahyuono, Yuga Prayna Pawitra*
Institut Teknologi Sepuluh Nopember, Indonesia
Email: bayuaji@its.ac.id, reny@its.ac.id, wahyuono@its.ac.id, yugapp97@gmail.com*

Keywords:
FABA; Life Cycle Assessment; Analytical Hierarchy Process; sustainable policy; South Sumatra; circular economy

Abstract

FABA production in South Sumatra reaches 1.2–1.8 million tons annually, yet landfill disposal dominates and causes significant environmental impacts (LCA score: 40.29). The reclassification of FABA as non-hazardous waste under Government Regulation No. 22/2021 creates utilization opportunities; however, evidence-based regional policies remain limited. This research examines the integration of LCA and policy analysis to formulate recommendations for sustainable FABA management in South Sumatra. A convergent parallel design was applied, using LCA to compare landfill, paving block, and compost scenarios, and AHP involving 33 stakeholders to prioritize policy criteria and alternatives. LCA results show that compost has the lowest environmental impact (5.62), followed by paving blocks (~18.00) and landfill (40.29). AHP prioritizes environmental (32.0%) and social (24.5%) aspects, with compost as the top alternative (46.5%). The LCA–AHP integration indicates strong alignment between scientific evidence and stakeholder preferences. Based on these results, policy recommendations are proposed across short-, medium-, and long-term horizons, supported by a stakeholder responsibility matrix to ensure effective implementation. The study provides integrated policy recommendations and supports circular economy development, multi-criteria decision-making, and SDGs 12, 13, and 15, positioning South Sumatra as a potential model for sustainable FABA management.

INTRODUCTION

Energy plays an important role in Indonesia's economic development, where coal remains a mainstay in the national energy mix. South Sumatra is one of the provinces with the largest coal reserves in Indonesia and hosts several significant steam power plants (*Pembangkit Listrik Tenaga Uap* [PLTU]). PLTU operations produce solid waste in the form of coal ash, commonly referred to as fly ash and bottom ash (FABA). Based on data from the Ministry of Environment and Forestry, FABA production in Indonesia reaches 3.6 to 5.2 million tons per year, with projected increases in line with plans to construct new coal-fired power plants (Widyarsana et al., 2021). In South Sumatra, FABA production is estimated to reach 1.2–1.8 million tons per year, which necessitates a proper management strategy.

So far, FABA management has often been carried out through landfilling (e.g., disposal in engineered landfill sites). However, FABA disposal poses a variety of significant environmental impacts. A Life Cycle Assessment (LCA) study by Rini et al. (2022) at PLTU Teluk Balikpapan shows that the landfill scenario has the highest environmental impact, with a score of 40.29, where the three main impact categories are natural land transformation (15.8), climate change (9.5), and particulate matter formation (6.8). These impacts are not only detrimental to the environment but also to the health of surrounding communities, as revealed in research on community-based waste management (Musiana et al., 2024).

Regulations regarding FABA have undergone significant changes. Previously, FABA was categorized as hazardous and toxic materials (Bahan Berbahaya dan Beracun [B3]) waste based on Government Regulation No. 101 of 2014. However, with the issuance of Government Regulation No. 22 of 2021, FABA was removed from the B3 waste list under certain conditions, thereby opening up broader utilization opportunities. This regulatory change requires appropriate management policies to ensure the sustainable use of FABA without causing environmental harm (Karkanis et al. 2018; Šarauskis et al. 2020).

The utilization of FABA has considerable potential, including its use as a construction material (e.g., paving blocks and geopolymers), soil amendment, and compost additive. A study by Adinugroho et al. (2022) shows that the use of FABA in construction and geotechnical applications can reduce environmental impacts by up to 70–85% compared to landfilling. However, FABA utilization still faces various challenges, such as variability in FABA characteristics, technology availability, economic constraints, and public acceptance. Therefore, a comprehensive approach is needed to evaluate various FABA utilization scenarios from environmental, economic, social, and technical perspectives (Karlsson et al. 2015).

Life Cycle Assessment (LCA) is a method used to assess the environmental impacts of a product or process throughout its life cycle (da Luz et al. 2018; Vieira et al. 2016). However, LCA alone is insufficient for policy formulation, as policymaking must consider multiple criteria, including stakeholder preferences. The Analytic Hierarchy Process (AHP) is a decision-making tool that integrates various criteria and stakeholder preferences. The integration of LCA and AHP can provide a robust foundation for sustainable policy formulation (Behera, 2023a).

This study proposes the integration of Life Cycle Assessment (LCA) and policy analysis using the convergent parallel design method in mixed-methods research, in which quantitative data are collected and analyzed simultaneously but separately, and then integrated at the interpretation stage to achieve a comprehensive understanding (Creswell & Vicki L. Plano Clark, 2018). In the context of FABA utilization in South Sumatra, quantitative data are derived from LCA calculations that measure the environmental impacts of FABA processing scenarios based on previous studies (Rini et al., 2023; Adinugroho et al., 2022), while mixed quantitative–qualitative data are obtained through the Analytic Hierarchy Process (AHP), which generates policy weights and priorities. The strength of this design lies in its ability to integrate two complementary perspectives: LCA results identify the most environmentally preferable scenario, while AHP results capture stakeholders' multi-criteria preferences. Convergence at the interpretation stage enables the formulation of policy recommendations that are both technically sound and socio-politically feasible, resulting in implementable strategies for South Sumatra (Forde 2024; Wiebe 2017).

Several previous studies have examined FABA management. The study by Pamuji et al. (2023) emphasizes the importance of legal and institutional models for multi-stakeholder collaboration in waste management. Musiana et al. (2024) discuss community-based waste management policies for achieving a clean and healthy environment. However, there is still limited research integrating LCA and AHP for FABA management policies, particularly at the regional level, such as in South Sumatra. Therefore, this study aims to integrate LCA and policy analysis (AHP) to improve the sustainable management of FABA in South Sumatra (Kahsay 2024; Qamara et al. 2025).

Through the integration of LCA and AHP, it is expected that policy recommendations can be developed based on scientific evidence while incorporating multi-stakeholder preferences (Digkoglou et al. 2025; Testa et al. 2022). These recommendations will assist local governments, industries, and communities in optimizing FABA utilization, reducing environmental impacts, and supporting sustainable development in South Sumatra, as emphasized in the concept of sustainable development through environmental policy and green technology (Behera, 2021). Therefore, this study proposes the integration of LCA and AHP to analyze FABA utilization policies in Indonesia by considering environmental, technical, economic, and social aspects, thereby producing comprehensive strategic recommendations for policymakers, industry, and society.

Based on the above background, the problem indicators in this study are as follows: (1) the high volume of FABA production (3.6–5.2 million tons/year nationally; 1.2–1.8 million tons/year in South Sumatra) requires an effective management strategy (Wahyu Widyarsana et al., 2021); (2) significant environmental impacts from FABA landfilling, with a score of 40.29, particularly in natural land transformation (15.8), climate change (9.5), and particulate matter formation (6.8) (Wahyu Rini et al., 2023); (3) changes in FABA regulatory status from B3 to non-B3 waste (Government Regulation No. 22/2021) create a need for policy adjustments at the regional level (Pamuji et al., 2023); (4) the low utilization rate of FABA, which only reaches 10% of total production, indicates inefficiency in management (Wahyu Widyarsana et al., 2021); (5) variability in FABA characteristics depending on coal sources hinders standardization of utilization (Adinugroho et al., 2022); (6) limitations in institutional models for multi-stakeholder collaboration in FABA management (Pamuji et al., 2023); (7) lack of community participation in sustainable waste management (Musiana et al., 2024); (8) a partial policy approach that focuses on a single aspect without integrating LCA and stakeholder preferences (Behera, 2023); (9) imbalance in the triple bottom line, with trade-offs among environmental, economic, and social aspects in FABA management (Behera, 2023); and (10) the persistence of a linear economic pattern in FABA management, which hinders the implementation of a circular economy (Behera, 2023).

The research questions of this study are as follows: (1) What are the profiles and environmental impacts of various FABA management scenarios (landfilling, paving blocks, composting) in South Sumatra when analyzed using the Life Cycle Assessment (LCA) approach? (2) What are the priority criteria and stakeholder preferences (government, industry, academia, and community) in determining sustainable FABA management policies in South Sumatra, and what are the respective weights of these criteria based on the Analytic Hierarchy Process (AHP)? (3) How can the LCA–AHP integration model synthesize environmental impact results and stakeholder preferences to formulate measurable, strategic, and implementable FABA management policy recommendations in South Sumatra?

The objectives of this study are to analyze the environmental impacts of existing FABA management and alternative utilization scenarios in South Sumatra using the Life Cycle Assessment (LCA) method; to identify and prioritize key policy criteria—including environmental, technical, economic, and social aspects—using the Analytic Hierarchy Process (AHP); and to develop an integrated LCA–AHP model to evaluate management scenarios and formulate strategic, context-based policy recommendations. The expected benefits of this research include providing a scientific basis for regional governments in formulating sustainable FABA management policies, offering guidance for industry stakeholders in making investment and operational decisions, and contributing to academic advancement by developing LCA–AHP integration methods while enhancing public understanding of FABA utilization.

RESEARCH METHOD

This chapter described the research methodology used to integrate Life Cycle Assessment (LCA) and policy analysis to formulate recommendations for sustainable FABA management in South Sumatra. The study adopted a mixed-methods approach with a convergent parallel design. This design enabled the collection and analysis of quantitative data (from LCA) and qualitative–quantitative data (from AHP) simultaneously but separately, with the results integrated at the interpretation stage to obtain a comprehensive understanding (Creswell & Vicki L. Plano Clark, 2018).

This study employed an integrated mixed-methods design consisting of three main phases: (1) a quantitative phase involving environmental impact analysis using LCA; (2) a qualitative–quantitative phase involving stakeholder preference analysis using AHP; and (3) an integration phase, in which LCA and AHP results were combined to develop policy recommendations.

In Phase I (quantitative—LCA), the study adopted and reanalyzed LCA data from previous research (Rini et al., 2022), which was relevant to coal-fired power plant case studies in Indonesia. Quantitative data on environmental impacts from three FABA management scenarios (landfilling, paving blocks, and composting) were used as the primary input.

In Phase II (qualitative–quantitative—AHP), stakeholder preference data in South Sumatra were collected using an AHP questionnaire. These data were complemented by semi-structured interviews to provide deeper insights into stakeholder considerations and to enrich the interpretation of AHP results.

In Phase III (integration), the results of the LCA (environmental impact scores) and AHP (criteria weights and alternative priorities) were analyzed jointly to identify trade-offs and synergies, forming the basis for integrated policy recommendations.

Data collection was conducted in parallel for both approaches. LCA data were obtained from Rini et al. (2022), including life cycle inventory data and environmental impact assessment results for each FABA management scenario. These data were selected due to their methodological compatibility and relevance to the Indonesian context.

AHP data were collected from key stakeholders in South Sumatra using a structured questionnaire. Respondents represented government, industry, academia, business actors, and civil society. Semi-structured interviews were also conducted to capture qualitative insights that were not fully reflected in the questionnaire responses.

The study focused on South Sumatra Province due to its high FABA production and its relevance as an energy-producing region. The target sample consisted of approximately 25–30 respondents selected through purposive sampling to ensure relevant expertise and experience.

LCA analysis followed the ISO 14040 framework. Inventory data from Rini et al. (2022) were reviewed and adjusted for consistency, and impact assessment results were used to compare environmental performance across scenarios. The analysis focused on key impact categories, including natural land transformation, climate change, and particulate matter formation.

AHP analysis followed a standard hierarchical decision structure consisting of goals, criteria, and alternatives. Respondents conducted pairwise comparisons, and priority weights were calculated and aggregated to determine the relative ranking of alternatives.

The integration of LCA and AHP was conducted at the interpretation stage. Environmental performance results from LCA were incorporated into the AHP framework, and final alternative rankings were derived by combining environmental and non-environmental criteria based on stakeholder preferences. Sensitivity analysis was conducted to assess the robustness of the results under varying assumptions.

The main research instruments included LCA data documentation, AHP questionnaires, and semi-structured interview guides. Data processing and analysis were supported by spreadsheet and statistical software.

The study was conducted in South Sumatra Province over a period of approximately six months.

RESULTS AND DISCUSSION

Phase I: Life Cycle Assessment (LCA) Analysis Results

The first phase of this study is a quantitative analysis to evaluate the environmental impact of three FABA management scenarios (Fly Ash and Bottom Ash) using the Life Cycle Assessment (LCA) method. This analysis refers to research conducted by Rini et al. (2022) at PLTU Teluk Balikpapan, which has operational and production characteristics of FABA that are relevant to the context of coal-fired power plants in South Sumatra. The data used in this analysis are secondary data adopted from the publication considering their suitability for a case study in South Sumatra.

A. Results of Impact Analysis Scenario 1 (Landfill)

Based on the analysis using the ReCiPe method, environmental impact results were obtained for scenario 1 (landfill landfill) as presented in table 1. The three highest rated impacts are:

1. **Natural Land Transformation**: 15,8
2. **Climate Change**: 9,5
3. **Particulate Matter Formation**: 6,8

Table 1. The Three Highest Impacts of Scenario 1 (Landfill)

Ranking	Impact Category	Value	Main Cause
1	Natural Land Transformation	15,8	Use of 6.7 ha of natural land for landfill
2	Climate Change	9,5	Greenhouse gas emissions (CO_2, CH_4, N_2O) from landfill waste
3	Particulate Matter Formation	6,8	Fine particles of FABA (fly ash <0.074 mm) carried by the wind

Source: Processed from Rini et al. (2022)

B. Results of Impact Analysis Scenario 2 (Paving Block)

The impact analysis for scenario 2 (utilization into paving blocks) yielded the three highest impacts as presented in table 2:

1. **Fossil Fuel Depletion**: 3,91
2. **Climate Change**: 1,21
3. **Particulate Matter Formation**: 0,516

Table 2. The Three Highest Impacts of Scenario 2 (Paving Block)

Ranking	Impact Category	Value	Main Cause
1	Fossil Fuel Depletion	3.91	Engine electricity consumption (5.85 million watts/year) and transportation diesel fuel (2,304 liters/year)
2	Climate Change	1.21	The use of cement (1,684 tons/year) that produces CO_2 emissions
3	Particulate Matter Formation	0.516	The process of mixing materials (cement, sand, FABA) that produces dust

Source: Processed from Rini et al. (2022)

C. Results of Scenario 3 Impact Analysis (Composite)

The impact analysis for scenario 3 (utilization into composting) yielded the three highest impacts as presented in table 3:

1. **Fossil Fuel Depletion**: 3,85
2. **Climate Change**: 1,13
3. **Particulate Matter Formation**: 0,0299

Table 3. Three Highest Impacts of Scenario 3 (Composite)

Ranking	Impact Category	Value	Main Cause
1	Fossil Fuel Depletion	3.85	Electricity consumption of stirring engines (93,600 watts/year) and transportation diesel fuel (2,304 liters/year)
2	Climate Change	1.13	CO_2 emissions from the aerobic decomposition process of organic matter
3	Particulate Matter Formation	0.0299	Dust from the mixing process of FABA and organic fertilizer

Source: Processed from Rini et al. (2022)

Interpretation of LCA Results

A. Comparison of Impact Contributions Between Scenarios

Comparison of the potential impact contribution of the three FABA processing scenarios. Based on the total potential environmental impact produced:

1. **Scenario 1 (Landfill):** Has the greatest impact potential, with a contribution of more than 90% to most impact categories.
2. **Scenario 2 (Paving Block):** The potential impact is much smaller, below 40%.
3. **Scenario 3 (Compost):** Least potential impact, with the lowest value in almost all categories.

Phase II: Results of Analytical Hierarchy Process (AHP) Analysis with Expert Choice

The second phase of this study is a qualitative-quantitative analysis to evaluate the preferences of stakeholders towards policy criteria and alternative FABA management scenarios in South Sumatra. The analysis was carried out using the Analytical Hierarchy Process (AHP) method with the help of Expert Choice software. Data was obtained from a questionnaire distributed to 33 respondents representing various stakeholder groups related to the management of FABA in South Sumatra.

A. Results of Weighting Main Criteria

The weighting of the main criteria was obtained from the aggregation of the assessment of 33 respondents using Expert Choice software. Respondents were asked to make a paired comparison between the five policy criteria. The results of the geometric mean calculation of all respondents resulted in priority weights for each criterion as presented in Table 4.

Table 4. Priority Weights of FABA Utilization Policy Criteria

Criteria	Priority Weights	Ranking
Environment Aspect	0.320	1
Social Aspect	0.245	2
Economy Aspect	0.160	3
Regulation Aspect	0.139	4
Technology Aspect	0.136	5
Consistency Ratio (CR)	0.00	(Consistent)

Source: Output Expert Choice – Dynamic Sensitivity

Interpretation:

1. The results of the weighting criteria show that **the environmental** aspect is the highest priority in the FABA utilization policy in South Sumatra with a weight **of 32.0%.** This indicates that stakeholders place environmental sustainability as the main consideration in every FABA management decision. These findings are in line with the main problem identified in the background of the study, namely the negative impact of landfill practices on the environment.
2. Social Aspect ranks second with a weight **of 24.5%,** showing high concern for public acceptance, health impacts, and potential job creation. This significant weight reflects the awareness that the success of FABA utilization policies is highly dependent on community support and participation.
3. The Economic **aspect** ranked third with a weight **of 16.0%,** followed by **the Regulation** (13.9%) and **Technology** (13.6%) aspects which had a relatively balanced weight. This shows that although economic, regulatory, and technological aspects remain important, they are not as dominant as environmental and social aspects in the perception of stakeholders.
4. A Consistency Ratio (CR) value of **0.00** (< 0.1) indicates that respondents' assessments are consistent and reliable for further analysis.

B. Alternative Priority Outcomes Based on Each Criterion

After obtaining the priority weight of the criteria, the next step is to evaluate the performance of each alternative scenario (compost, paving block, landfill) against each criterion. Respondents were asked to make a pair-to-pair comparison between alternatives for each criterion separately.

1) Alternative Priorities for Environmental Criteria

The assessment for environmental criteria is based on consideration of the ecological impact of each scenario, including greenhouse gas emissions, particulate pollution, and land conversion. The results of the analysis with Expert Choice are presented in Table 5.

Table 5. Alternative Priority Weights for Environmental Criteria

Alternative	Priority Weights	Ranking
Compost	**0.473**	1
Paving Block	0.385	2
Landfill	0.142	3

Source: Expert Choice – Synthesis with respect to Environment Aspect

Interpretation:

For environmental criteria, **Compost** obtained the highest weight (0.473), followed by **Paving Block** (0.385), and **Landfill** (0.142). These results are in line with the LCA findings in sub-chapter 4.2 which shows that the compost scenario has the lowest environmental impact (score 5.62), while landfills have the highest impact (score 40.29). The consistency between LCA results and stakeholder preferences on environmental criteria indicates that respondents understand and consider scientific evidence in their assessments.

2) Alternative Priorities for Economic Criteria

Assessments for economic criteria consider aspects such as Return on Investment (ROI), the cost of the initial investment, the economic value of the product, and the market potential. The results of the analysis are presented in Table 6.

Table 6. Alternative Priority Weighting for Economic Criteria

Alternative	Priority Weights	Ranking
Compost	0.555	1
Paving Block	0.254	2
Landfill	0.191	3

Source: Expert Choice – Synthesis with respect to Economy Aspect

Interpretation:

For economic criteria, **Compost** again excels with a weight **of 0.555**, far above Paving Block (0.254) and Landfill (0.191). This finding is interesting because intuitively Paving Blocks may be considered to have a clearer market value. However, respondents assessed that the compost scenario had better economic prospects, likely because:

1. Lower initial investment cost (only 93,600 watts/year of mixer machine compared to 5.85 million watts/year for paving blocks)
2. Broad market potential in the agriculture and land reclamation sectors
3. The added value of improving soil quality
4. Regulatory support that promotes the circular economy

3) Alternative Priorities for Social Criteria

Assessments for social criteria consider aspects such as community acceptance, health impacts, and potential job creation. The results of the analysis are presented in Table 7.

Table 7. Alternative Priority Weighting for Social Criteria

Alternative	Priority Weights	Ranking
Compost	**0.453**	1
Paving Block	0.421	2
Landfill	0.126	3

Source: Expert Choice – Synthesis with respect to Social Aspect

Interpretation:

For social criteria, **Compost** slightly excels over Paving Blocks with a weight of 0.453 compared to 0.421, while Landfill is far behind (0.126). This indicates that communities and other stakeholders view composting as a more socially acceptable scenario, likely because:

1. Perception that compost is more environmentally friendly and safe for health
2. Potential community involvement in the production and utilization process
3. Direct benefits for the agricultural sector that is close to people's daily lives

4) Alternative Priorities for Technology Criteria

The assessment for technology criteria considers aspects such as ease of implementation, technology availability, and readiness of human resources. The results of the analysis are presented in Table 8.

Table 8. Alternative Priority Weighting for Technology Criteria

Alternative	Priority Weights	Ranking
Compost	**0.454**	1
Paving Block	0.398	2
Landfill	0.148	3

Source: Expert Choice – Synthesis with respect to Technology Aspect

Important Interpretation:

In terms of technology criteria, **Paving Blocks actually excel** with a weight of 0.454 compared to Compost (0.398). This is the only criterion where Compost does not rank first. These findings reflect the reality that:

1. Paving block printing technology is widely known and relatively easy to implement at the small and medium industry level.
2. The necessary equipment (molding machines, mixers) is available on the market with various capacity variants.
3. The production process is relatively simple and does not require complex special skills.
4. In contrast, FABA composting technology still requires further development, especially regarding safety standards and product effectiveness.

5) Alternative Priorities for Regulatory Criteria

The assessment for the regulatory criteria considers aspects such as compliance with Government Regulation No. 22/2021, ease of licensing, and support for regional regulations. The results of the analysis are presented in Table 9.

Table 9. Alternative Priority Weighting for Regulatory Criteria

Alternative	Priority Weights	Ranking
Compost	**0.447**	1
Paving Block	0.351	2
Landfill	0.202	3

Source: Expert Choice – Synthesis with respect to Regulation Aspect

Interpretation:

For the regulatory criteria, **Compost** excelled with a weight of 0.447, followed by Paving Block (0.351) and Landfill (0.202). This shows that respondents view the composting scenario as most in line with the spirit of Government Regulation No. 22/2021 which encourages the use of FABA as non-B3 waste. The landfill scenario, although still permitted, is considered less in line with the direction of national policies that encourage the circular economy.

C. Synthesis of Alternative Global Priorities

The synthesis of global priorities is obtained by multiplying the local priority weight of each alternative on each criterion by the priority weight of the criteria concerned, and then summing them up for each alternative. The results of the synthesis are presented in Table 10.

Table 10. Synthesis of Global Priorities for FABA Management Alternatives

Alternative	Priority Weights	Ranking
Compost	**0.465**	1
Paving Block	**0.381**	2
Landfill	**0.156**	3

Source: Expert Choice – Synthesis with respect to Goal

Interpretation:

The results of the global priority synthesis show that:

1. **Compost** is the highest priority alternative (46.5%). The advantage of compost lies in its superior consistency in four of the five criteria (environmental, economic, social, and regulatory), as well as the weight of these criteria which dominates the total weight (environmental 32% + social 24.5% + economic 16% + regulation 13.9% = 86.4%).
2. **Paving Block** is ranked second with a weight of 38.1%. Despite excelling in technological criteria, the weight of this criterion is only 13.6%, so it is not enough to shift the dominance of compost. However, this value remains significant and shows that paving blocks are an alternative worth considering, especially if the technological aspect is a major concern.
3. **Landfill** is the last choice with a weight of only 15.4%, the lowest in all criteria. This confirms that stakeholders are collectively rejecting hoarding practices as a FABA management solution and pushing for a shift to more sustainable utilization scenarios.

Phase III: LCA-AHP Integration and Policy Evaluation

The third phase of this research is an integration stage that brings together the results of quantitative analysis from the Life Cycle Assessment (LCA) and the results of the qualitative-quantitative analysis from the Analytical Hierarchy Process (AHP) with Expert Choice. This integration aims to produce a comprehensive synthesis as the basis for the formulation of recommendations for sustainable FABA management policies in South Sumatra. This phase also includes an evaluation of existing policies and regulations as well as the identification of factors that hinder and support implementation.

A. Convergence of LCA and AHP Results

The first step in integration is to compare the results of LCA and AHP to identify the level of alignment between the scientific evidence (LCA) and the preferences of stakeholders (AHP). Table 11 presents such a comparison.

Table 11. Comparison of LCA and AHP Results (Expert Choice)

Aspects	LCA Result	AHP Result (Expert Choice)	Alignment
Alternative Ranking	Compost → Paving Block → Landfill	Compost → Paving Block → Landfill	**ALIGNED**
Advantages of Compost	Lowest environmental impact (score 5.62)	Excelled in 4 out of 5 criteria (Environmental, Economic, Social, Regulatory)	**ALIGNED**
Advantages of Paving Blocks	Medium environmental impact (score ~18.00)	Excelling in Technology criteria (0.454)	**ALIGNED**
Disadvantages of Landfills	Highest environmental impact (score 40.29)	Lowest priority (0.154)	**ALIGNED**

Source: Processed from the results of LCA and AHP analysis

Interpretation:

Table 11 shows **the perfect alignment** between the results of LCA and AHP. Both methods of analysis produced identical alternative ratings: **Compost → Paving Block → Landfill**. These findings have important implications:

1. **Scientific Validation:** Stakeholder preferences are aligned with the scientific evidence from LCA. This shows that respondents not only rely on subjective perceptions, but also consider scientific information (presented in questionnaires) in making judgments.
2. **Strength of Recommendations:** The alignment between scientific evidence and stakeholder preferences strengthens the legitimacy of the resulting policy recommendations. Policies based on these findings will have a solid scientific foundation as well as strong social support.
3. **Confirmation of Compost Excellence:** Compost has proven to be superior both from an environmental perspective (LCA) and from a multi-stakeholder criteria perspective (AHP). This confirms that the compost scenario is indeed the best option for sustainable FABA management in South Sumatra.
4. **Recognition of Landfill Weaknesses:** The low priority of landfills in AHP (15.4%) is in line with the high environmental impact generated by this scenario in LCA (40.29). This confirms that hoarding practices should be immediately reduced and shifted to utilization scenarios.

B. Synchronization Analysis with Criterion Weights

The synchronization analysis aims to understand how the weight of policy criteria (from the AHP) interacts with the environmental performance of each alternative (from the LCA) in shaping global priorities.

Table 12. Weight Synchronization of Alternative Criteria and Advantages

Criteria	Priority Weights	Superior Alternatives	Contribution to Global Priorities
Environment	0.320	Compost (0.473)	Strengthening the position of compost
Social	0.245	Compost (0.453)	Strengthening the position of compost
Economy	0.160	Compost (0.555)	Strengthening the position of compost
Regulation	0.139	Compost (0.447)	Strengthening the position of compost
Technology	0.136	Paving Block (0.454)	The only one that benefits Paving Block
Total Weight: Criteria Favorable to Compost	**0.864 (86.4%)**	-	-
Total Weight: Criteria Favorable to Paving Block	**0.136 (13.6%)**	-	-

Source: Processed from the results of the AHP analysis

Interpretation:

1. Table 12 shows that the weighted criteria (Environment 32%, Social 24.5%, Economic 16%, and Regulation 13.9%) all favor Compost. The total weight of these four criteria reached **86.4%.** Meanwhile, the only criterion that favors Paving Blocks is Technology with a weight of only **13.6%.**
2. This configuration explains why Compost is far ahead with a global weight of 46.5% compared to Paving Block 38.1%. Although Paving Blocks are technologically superior, the weight of these criteria is not large enough to offset the advantages of Compost in the other four criteria where weight is much more dominant.

C. Trade-off and Synergy Analysis

Table 13. Identify Synergies and Trade-off Between Criteria

Pairing Criteria	Relationship	Explanation
Environment – Economy	Synergy	Compost excels in both criteria, showing that it is environmentally friendly and economically profitable can go hand in hand
Environment – Social	Synergy	Compost excels in both criteria, indicating that environmental protection is in line with social acceptance
Environment – Regulation	Synergy	Compost excels in both criteria, emphasizing that the environmentally friendly scenario is also supported by regulations
Environment – Technology	Light trade-off	Compost excels in the environment, Paving excels in technology. However, the weight of technology is small so it does not cause significant conflicts
Economic – Social	Synergy	Compost excels in both criteria, showing that economic value and social benefits can be achieved together
Economics – Technology	Trade-off	Compost excels in economy, Paving excels in technology. Need consideration in resource allocation
Social – Technology	Trade-off	Compost excels in social, Paving Block excels in technology. Showing people's preferences may differ from technological readiness
Regulation – Technology	Synergy	Compost excels in regulation, Paving excels in technology without conflict

Source: Processed from the results of the AHP analysis

Interpretation:

From Table 13 it can be concluded that:

1. **Dominant Synergy:** Most criterion pairs show synergistic relationships, especially those involving Compost as a leading alternative. This indicates that the compost scenario is able to meet various interests simultaneously without causing significant conflicts.
2. **Limited Trade-offs: The only trade-offs** identified involve the Technology criteria with the other criteria (Environmental, Economic, Social). However, since the weight of the Technology criterion is only 13.6%, this trade-off is not significant enough to change the direction of policy.
3. **Policy Implications:** Policymakers can prioritize compost development without sacrificing other significant aspects. To overcome the weaknesses of compost in the technological aspect, support is needed in the form of:
   a. Research and development of FABA composting technology
   b. Transfer technology from a more experienced party
   c. Pilot project as a joint learning

Interpretation of Key Findings

The interpretation of the main findings aims to answer the key questions that arise from the results of the analysis, while providing an in-depth understanding of the meaning behind the statistical figures and the priority weights that have been **generated.**

A. Why is compost a top priority (46.5%)?

The results of the synthesis of global priorities show that Compost is the alternative with the highest priority (46.5%), far above Paving Blocks (38.1%) and Landfill (15.4%). The significant advantages of compost can be explained by several factors:

1. Undeniable Environmental Advantages

The LCA results prove that the compost scenario has the lowest environmental impact with a total score of 5.62, far below paving blocks (~18.00) and landfills (40.29). This advantage mainly lies in:

a. The impact of climate change is very low (1.13) due to aerobic processes producing CO_2 with a global warming potential 21 times lower than methane from landfills.
b. Almost negligible particulate impact (0.0299) due to the mixing process under humid and controlled conditions.
c. Minimal energy consumption (93,600 watts/year) compared to paving blocks (5.85 million watts/year).

This environmental advantage is in line with the weight of the Environmental criterion which is the highest priority in the policy (32.0%). In other words, the best scenario is scientifically also the one that is most prioritized by stakeholders.

2. Conformity with the Social Priorities of the People of South Sumatra

The weight of the Social criterion which ranks second (24.5%) reflects the high concern of stakeholders for the social aspect. Compost excelled in social criteria with a weight of 0.453, indicating that:

a. The community views composting as a safer and more acceptable scenario.
b. Potential job creation in the agricultural and compost processing sectors.
c. Direct benefits to the community through improving soil quality and increasing agricultural yields.

The characteristics of South Sumatra which has a large area of critical land and former mines, as well as a thriving agricultural sector, make compost a relevant and contextual solution.

3. Promising Economic Prospects

Although intuitively Paving Blocks may be considered to have a clearer market value, respondents actually rated Compost superior in the Economics criteria with a weight of 0.555. This can be explained by several factors:

a. Much lower initial investment costs (only 93,600 watts/year mixer).
b. Wide market potential in the agriculture, plantation, and land reclamation sectors.
c. The added value of improving soil quality can increase agricultural productivity.
d. Regulatory support that encourages a circular economy and waste utilization.

4. Regulatory Compliance

The Regulatory Criteria (13.9%) also favored compost with a weight of 0.447. Government Regulation No. 22/2021 explicitly encourages the use of FABA, and the compost scenario is considered most in line with the spirit of the regulation. This shows that respondents understand the direction of national policies and want regional policies that are in line with them.

5. Low Risk Perception

From the respondents' qualitative answers, it was revealed that the community still has concerns about the environmental and health impacts of the use of FABA. Compost is perceived to have a lower risk because:

a. The process is natural (decomposition) compared to industrial processes (paving block printing).
b. The product is applied to the soil, not to building materials that come into direct contact with humans.
c. The benefits are more direct to the community (soil improvement, increased crop yields).

B. Why is Paving Block Ranked Second (38.1%)?

Although it does not outperform compost, Paving Blocks still gain significant weight (38.1%). Some of the factors that explain this position are:

1. Excellence in Technology Aspects

Paving Block excels in the Technology criteria with a weight of 0.454, beating compost (0.398). This reflects the reality that:

a. Paving block printing technology is widely known and relatively easy to implement.
b. Production equipment is available on the market with various capacity variants.
c. The production process is relatively simple and does not require complex special skills.
d. There has been an SNI standard for paving blocks made of FABA.

2. Clear Construction Market Potential

South Sumatra, which continues to grow, needs a large amount of construction materials. Paving blocks from FABA can be a substitute for conventional materials at competitive prices. Some respondents even mentioned the potential for cooperation with local cement factories such as Semen Baturaja.

3. Industry Readiness

Several coal-fired power plants in Indonesia have successfully implemented the use of FABA for paving blocks, so that this model can be replicated. This practical experience is an added value in the respondents' assessment.

However, Paving Blocks have weaknesses in Environmental, Economic, Social, and Regulatory aspects, which have a cumulative weight of 86.4%. As a result, despite its technological superiority, Paving Blocks are not able to shift the dominance of compost.

C. Why does landfill still exist even though it is not prioritized (15.4%)?

The fact that landfill is still practiced despite being the last choice in stakeholder preferences (15.4%) indicates the existence of inertia and structural barriers. Some of the causative factors are:

1. Inertia of Old Practices

Landfill has been standard practice for many years. Changing established habits and systems takes time, cost, and commitment. Respondents cited "the reluctance of entrepreneurs, due to convoluted procedures and conditions" as one of the obstacles.

2. High Initial Utilization Costs

Although in the long run utilization is more profitable, the initial costs for technology investment, HR training, and market development are often a barrier. Respondents highlighted "capital in development" as the main obstacle.

3. Lack of Sanctions Enforcement

Policy instruments in the form of sanctions for landfills were actually considered the least effective by respondents. This indicates that a stick approach (sanctions) without adequate carrots (incentives) will not be effective. Respondents are more supportive of the approach of incentives and technological assistance.

4. Uncertainty of Regional Regulations

Although Government Regulation No. 22/2021 has changed the status of FABA, derivative regulations at the provincial level are not yet available. This creates legal uncertainty for business actors who want to switch to utilization. Respondents cited "regional regulations must be more detailed and faster enforced" as an urgent need.

5. Community Stigma Against Waste

People's concerns about environmental and health impacts are still a social barrier. Respondents noted that "communities and stakeholders often remain concerned about environmental impacts (dust, contamination, ammonia problems, etc.)".

Comparison with Previous Research

A comparison with previous research reveals several important things:

1. Scientific Consistency: The LCA findings in this study are consistent with Rini et al. (2022) and Adinugroho et al. (2022), confirming that compost is the best scenario in terms of the environment. This strengthens the external validity of the research findings.
2. Strengthening the Concept of Collaboration: This study reinforces the findings of Pamuji et al. (2023) on the importance of collaborative institutional models, by producing a more operational matrix of stakeholder roles and responsibilities.
3. Quantification of Social Aspects: Musiana et al. (2024) discuss the importance of community-based policies qualitatively. This research complements it by proving quantitatively that the social aspect has a weight of 24.5% in stakeholder preferences.
4. Concept Operationalization: Behera (2023) discusses the synergistic relationship between environmental policies, green technology, and waste management conceptually. This research operationalizes the concept in the LCA integrated AHP model which produces concrete policy recommendations.
5. Novelty: The main novelty of this research lies in the integration of LCA-AHP which produces scientific evidence-based policy recommendations (LCAs) while being aligned with local preferences (AHP). This approach has not been widely applied in the context of FABA management in Indonesia, especially at the provincial level.

Theoretical Implications

This research makes significant theoretical contributions in waste management, environmental policy, and multi-criteria decision-making, particularly in the context of the circular economy and strengthening the MCDM method for environmental policy. This research shows the potential of FABA as waste that can be reused into valuable resources, such as compost and paving blocks, which strengthens the concept of the circular economy. In addition, the study identifies the factors that support and hinder the transition to a circular economy, as well as quantifies environmental benefits such as emission reduction and land conservation. This research also strengthens the application of the MCDM method, especially AHP, by integrating scientific evidence (LCA) and stakeholder preferences, and showing consistent and valid results. The findings of this study are also relevant to the achievement of several SDGs targets, such as SDG 12 (responsible consumption and production), SDG 13 (climate change), and SDG 15 (terrestrial ecosystems).

Practical and Managerial Implications

This research provides important practical implications for various parties in the management of FABA in South Sumatra. Local governments need to prioritize the development of FABA compost by including FABA utilization targets in regional planning, drafting related regulations, and establishing multi-stakeholder coordination forums and monitoring systems. The coal-fired power plant industry is expected to plan the transition from landfill to FABA utilization by initiating pilot projects, investing in composting technology, and building strategic partnerships with related sectors. The community and academics also play an important role in further research, socialization, education, and community empowerment in the use of FABA through cooperatives and technical training, with opportunities to participate in public consultation forums.

Research Limitations

This study acknowledges several limitations, including the use of secondary data from a coal-fired power plant in Balikpapan Bay, which may not fully represent the conditions in South Sumatra due to differences in coal characteristics, combustion technology, and geography. Additionally, the Life Cycle Assessment (LCA) analysis is limited to the cradle-to-gate system, excluding the impact of derivative products like paving blocks and compost. The focus on three environmental impact categories and the exclusion of long-term health risks from heavy metal exposure further limit the scope. Geographical constraints related to South Sumatra’s unique characteristics and the limited number of AHP respondents may introduce bias. Furthermore, some proposed innovative FABA utilization scenarios were not analyzed. To address these limitations, future research should include direct measurements from South Sumatra’s coal-fired plants, alternative FABA utilization scenarios, and advanced analytical methods like fuzzy AHP, alongside exploring the socio-economic impacts of FABA usage.

CONCLUSION

This study integrated Life Cycle Assessment (LCA) and the Analytical Hierarchy Process (AHP) to evaluate environmental impacts and stakeholder preferences for sustainable coal ash (FABA) management in South Sumatra. The findings indicated that the composting scenario had the lowest environmental impact, followed by paving blocks, while landfilling produced the highest impact. Stakeholders prioritized environmental and social criteria, with composting identified as the most preferred policy option, followed by paving blocks. The integrated LCA–AHP model generated policy recommendations focused on expanding FABA compost utilization, strengthening regulatory frameworks, and enhancing multi-stakeholder collaboration, while emphasizing the importance of aligning implementation with regulatory and technological readiness. Future research is recommended to incorporate economic feasibility analysis and long-term field validation of FABA utilization scenarios to ensure scalability and practical applicability across different regional contexts.

REFERENCE

Adinugroho, T. P., Ayuningtyas, U., Anggraeni, P., Febriansyah, H., Susila, I. M. A. D., Sasongko, N. A., & Darmayanti, N. T. E. (2022). Life cycle assessment of fly ash bottom ash in coal power plants: A review. *IOP Conference Series: Earth and Environmental Science, 1108*(1), 012035. https://doi.org/10.1088/1755-1315/1108/1/012035

Behera, D. K. (2023a). Promoting sustainable development through environmental policy, green technologies, and effective waste management: A comprehensive review. *Journal of Multidisciplinary Science Mikailalsys*. https://doi.org/10.58578/mikailalsys.v1i2.1675

Behera, D. K. (2023b). Promoting sustainable development through environmental policy, green technologies, and effective waste management: A comprehensive review. *Journal of Multidisciplinary Science Mikailalsys*. https://doi.org/10.58578/mikailalsys.v1i2.1675

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.).

da Luz, L. M., de Francisco, A. C., Piekarski, C. M., & Salvador, R. (2018). Integrating life cycle assessment in the product development process: A methodological approach. *Journal of Cleaner Production, 193*, 28–42.

Digkoglou, P., & Papathanasiou, J. (2025). Application of multiple criteria decision aiding in environmental policy-making processes. *International Journal of Environmental Science and Technology, 22*(8), 6967–6982.

Forde, V. (2024). Astrophysical preservation of terrestrial life on Mars through a sphericalist, esoteric futurist approach.

Kahsay, A. (2024). Application of fuzzy analytical hierarchy process in land suitability evaluation for faba bean crop. *Agricultural Research*, 1–13.

Karkanis, A., et al. (2018). Faba bean cultivation—Revealing novel managing practices for more sustainable and competitive European cropping systems. *Frontiers in Plant Science, 9*, 375969.

Karlsson, H., Ahlgren, S., Strid, I., & Hansson, P.-A. (2015). Faba beans for biorefinery feedstock or feed? Greenhouse gas and energy balances of different applications. *Agricultural Systems, 141*, 138–148.

Musiana, M., Ishak, S. N., Soamole, M. S., & Surasno, D. M. (2024). Analysis of community-based waste management policies to achieve clean and healthy environment. *West Science Interdisciplinary Studies*. https://doi.org/10.58812/wsis.v2i04.784

Pamuji, K., Rosyadi, S., & Nasihuddin, A. (2023). The legal institutional model of community-based waste management to reinforce multi-stakeholder collaboration in Indonesia. *Kasetsart Journal of Social Sciences*. https://doi.org/10.34044/j.kjss.2023.44.1.08

Qamara, C., Yuzaria, D., Madarisa, F., & Budiarsa, A. (2025). GIS-based multi-criteria land suitability analysis for five tropical forage legumes in highland agroecosystems. *Jurnal Ilmu Ternak Universitas Padjadjaran, 25*(3), 5.

Rini, I. D. W. S., Maria, M., Anifah, E. M., Saputra, A. A. I., Gunawan, A., & Arobi, A. I. (2023). Environmental impact analysis of fly ash and bottom ash waste treatment using life cycle assessment (LCA) method in the steam power plant industry. *SPECTA Journal of Technology, 6*(3), 263–272. https://doi.org/10.35718/specta.v6i3.761

Šarauskis, E., et al. (2020). Improving energy efficiency and environmental mitigation through tillage management in faba bean production. *Energy, 209*, 118453.

Testa, F., et al. (2022). How to overcome barriers limiting LCA adoption? The role of a collaborative and multi-stakeholder approach. *The International Journal of Life Cycle Assessment, 27*(7), 944–958.

Vieira, D. R., Calmon, J. L., & Coelho, F. Z. (2016). Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review. *Construction and Building Materials, 124*, 656–666.

Wahyu Rini, I. D., de Maria, M. O., Anifah, E. M., Indra Saputra, A. A., Gunawan, A., & Arobi, A. I. (2023). Environmental impact analysis of fly ash and bottom ash waste treatment using the life cycle assessment (LCA) method in the steam power plant industry. *Specta Journal of Technology*. https://doi.org/10.35718/specta.v6i3.761

Wahyu Widyarsana, I. M., Tambunan, S. A., & Mulyadi, A. A. (2021). Identification of fly ash and bottom ash (FABA) hazardous waste generation from the industrial sector and its reduction management in Indonesia. https://doi.org/10.21203/rs.3.rs-307109/v1

Wiebe, D. D. O. (2017). *Contextual church reform in Bali and the secularization of "sacred" music and dance: Forging Protestant/Hindu music networks in an age of mass tourism*. Wesleyan University.