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Circular Economy Pathways in Coal Combustion Residue Management: An Industrial Symbiosis and SWOT Approach

Nurliah Jafar[1], Ahmad Padhil[2*], Muhammad Hardin Wakila[1], Muh. Ilham Anggamulia[3]

[1] Department of Mining Engineering, Universitas Muslim Indonesia, Makassar 90231, Indonesia
[2] Department of Industrial Engineering, Universitas Muslim Indonesia, Makassar 90231, Indonesia
[3] Department of Environmental Engineering, Universitas Muslim Indonesia, Makassar 90231, Indonesia

Corresponding Author Email: ahmad.padhil@umi.ac.id

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ABSTRACT

Coal combustion residues (CCRs), including fly ash and bottom ash (FABA), represent one of the largest industrial by-products with significant environmental impacts if disposed of untreated. Despite their potential applications in construction, small and medium-sized enterprises (SMEs), and agriculture, utilization rates in Indonesia remain below 10%, far behind countries such as Japan and South Korea. This study explores the development of an industrial symbiosis model for CCR management in Bone Regency, Indonesia, by integrating material flow analysis (MFA) and Strengths, Weaknesses, Opportunities, Threats (SWOT) assessment. Secondary data were collected from power plant reports, government statistics, and scientific literature, while industrial mapping identified key demand sectors. The results show that moderate utilization, with 25% fly ash substitution in construction, could replace approximately 50,000 tons of cement annually, reduce CO_2 emissions by 15%, and lower construction costs by 10%. Under an optimistic scenario, CCR utilization could substitute 100,000 tons of cement and 15,000 tons of aggregates, achieving emission reductions of up to 25% and lowering SME production costs by 18%. SWOT analysis indicates strong opportunities driven by supportive regulations and circular economy momentum but highlights persistent weaknesses in SME technical capacity and the absence of CCR product standards. The conceptual model developed in this study demonstrates how multi-stakeholder collaboration can transform CCR from waste into a valuable resource, delivering both environmental and socio-economic benefits. By situating CCR utilization within an industrial symbiosis framework, this research provides a replicable strategy for advancing circular economy practices in developing countries.

1. INTRODUCTION

Coal mining and combustion industries remain among the most critical sectors in the global energy landscape, ensuring continuous supply of energy and strategic materials. However, these activities generate vast amounts of coal combustion residues (CCRs), including fly ash and bottom ash (FABA), which pose severe environmental risks if not properly managed [1, 2]. These residues contain chemical compounds that may threaten ecosystems, while simultaneously representing untapped resources with potential industrial applications [3].

Industrial symbiosis, which emphasizes cross-sectoral collaboration to transform waste into valuable resources, has been increasingly recognized as a key enabler of circular economy transitions [4, 5]. The circular economy promotes resource efficiency through the principles of reduce, reuse, and recycle, aiming to minimize waste and extend material lifecycles [6]. While industrial symbiosis practices have been widely applied in manufacturing and energy sectors, their application in coal-related industries remains limited [7]. Yet, CCRs present significant opportunities, such as using fly ash as a partial substitute for cement and bottom ash as lightweight aggregate or filler material, thereby supporting sustainability in construction and related sectors [8, 9].

Tools such as Life Cycle Assessment (LCA) are frequently used to evaluate the environmental impacts of waste utilization pathways [10]. However, beyond environmental evaluation, industrial symbiosis frameworks offer a strategic model to both reduce waste and create added value through inter-industry collaboration [11]. In Indonesia, where CCRs exceed millions of tons annually, adopting industrial symbiosis could mitigate carbon emissions, improve material efficiency, and support national green economy agendas [12, 13].

Despite these opportunities, prior studies tend to focus on single aspects, such as the use of fly ash in concrete mixtures [14] or small-scale waste management practices [15]. Comprehensive studies that integrate material flow, Strengths, Weaknesses, Opportunities, Threats (SWOT) - based strategic analysis, and circular economy perspectives in the context of

CCRs remain scarce [16]. Addressing this gap, the present study aims to explore and conceptualize an industrial symbiosis model for optimizing coal combustion waste utilization, incorporating material flow analysis (MFA) and SWOT assessment to evaluate strengths, weaknesses, opportunities, and threats in its implementation [17]. This approach is expected to contribute both theoretically and practically by establishing a holistic framework for coal waste management within circular economy transitions. Furthermore, it provides policymakers, industries, and local stakeholders with actionable strategies to transform coal residues from environmental burdens into valuable resources, thereby advancing sustainability and supporting broader green economy goals [18, 19].

Based on the reviewed literature, existing studies on CCR utilization have predominantly focused on single utilization pathways, such as cement substitution, landfill reduction, or isolated recycling applications. While MFA has been widely applied to quantify CCR generation and utilization potentials, and SWOT analysis has been used to identify strategic factors, these approaches are often applied independently and at a generalized or national scale. Limited attention has been given to integrated regional-scale frameworks that combine MFA with strategic analysis to support industrial symbiosis among multiple local stakeholders. Consequently, there remains a research gap in developing a comprehensive model that integrates material flow quantification and strategic evaluation to support CCR utilization through regional industrial symbiosis, particularly in emerging industrial regions. To address this gap, this study proposes an integrated framework combining MFA, SWOT analysis, and industrial mapping to evaluate CCR utilization scenarios at the regional level, using Steam Power Plant (PLTU) Punagaya and its surrounding industrial ecosystem as a case study.

2. METHODOLOGY

This study adopted an exploratory and analytical design to conceptualize an industrial symbiosis model for CCR management within circular economy transitions. The research was conducted in Bone Regency, South Sulawesi, Indonesia, focusing on CCR generated from the Punagaya coal-fired power plant, which produces an estimated 200–300 thousand tons of FABA annually. The methodology consisted of five systematic stages.

2.1 Data collection

Secondary data were collected from a range of official and scientific sources to provide baseline information on CCR generation, utilization, and regulatory context. The collected data included:

•CCR production and composition: obtained from the operational reports of PLTU Punagaya and published statistics on coal-fired power plants in Indonesia (Ministry of Energy and Mineral Resources, ESDM).

•National-level CCR data: sourced from the Central Agency (BP) Statistical Review of World Energy and government energy balance reports, which provided estimates of annual CCR generation exceeding 10 million tons nationally.

•Regulatory framework: derived from policy documents of the Ministry of Environment and Forestry (KLHK) and ESDM, particularly regulations classifying FABA as non-hazardous waste.

•Case studies and prior applications: taken from peer-reviewed journals and technical reports, such as small-scale uses of fly ash in construction and road projects.

•Local development data: reports from the Bone Regency Government and infrastructure project documentation, highlighting material demand in construction, housing, and reclamation sectors.

Secondary data are widely applied in exploratory studies to establish a contextual foundation where primary data are not yet available [20].

2.2 Industrial mapping

Industrial mapping was conducted to identify sectors with potential to utilize CCR. These included:

•Construction industry (cement and concrete substitution),

•Building material Small and Medium Enterprises (SMEs) (paving blocks, bricks, and lightweight materials),

•Agriculture and land reclamation (soil stabilization and amelioration),

•Experimental energy applications (co-firing and alternative fuels).

Each sector was analyzed in terms of demand for substitute materials, compatibility with CCR properties, and potential barriers. Industrial mapping is a recognized method for exploring resource efficiency opportunities across industries [21].

Industrial mapping was conducted using a purposive and sector-based approach to identify industries with the highest potential for CCR utilization. The mapping focused on construction-related enterprises, building material SMEs (paving blocks and bricks), agricultural and land reclamation activities, and experimental energy applications within Bone Regency. Sector identification was based on regional development reports, infrastructure project records, and prior studies on CCR utilization. Rather than aiming for statistical generalization, the mapping emphasizes sectoral relevance and material compatibility, consistent with the exploratory nature of the study.

2.3 Material flow analysis

The MFA was conducted using a regional and scenario-based approach. The spatial boundary of the MFA is defined as Bone Regency, South Sulawesi, Indonesia, with CCR originating exclusively from PLTU Punagaya. The system boundary includes CCR generation (FABA), temporary storage, transportation, material substitution in local industries, and final utilization. The MFA does not include upstream coal extraction or downstream product end-of-life phases. The analyzed scenarios are indicative and exploratory, designed to estimate substitution potential and environmental benefits rather than to provide predictive forecasts.

MFA was applied to model the flow of CCR from PLTU Punagaya to potential industrial users. Three utilization scenarios were compared:

•Scenario A (Business-as-Usual): complete disposal,

•Scenario B (Moderate Utilization): 25% fly ash applied in local construction,

•Scenario C (Optimistic Utilization): 50% fly ash and 30% bottom ash distributed across multiple sectors.

MFA has been widely used to quantify material substitution potential and environmental impacts [22].

2.4 Strengths, Weaknesses, Opportunities, Threats analysis

A SWOT framework was used to assess feasibility by analyzing internal and external factors influencing CCR utilization. Strengths and weaknesses were identified in terms of resource supply, technology readiness, and SME capacity, while opportunities and threats were analyzed in terms of policy, market acceptance, and logistical challenges. SWOT analysis is frequently applied in strategic sustainability studies [23].

The identification of internal and external factors in the SWOT analysis was carried out through a triangulation process. Initial factors were derived from an extensive literature review on CCR utilization, industrial symbiosis, and circular economy practices. These factors were then contextualized using secondary data from government reports, power plant documentation, and regional development plans. To enhance the rationality of factor selection, informal expert consultations were conducted with academics and practitioners experienced in CCR management, construction materials, and SME development in South Sulawesi. The finalized SWOT factors represent convergent insights from literature, data sources, and expert judgment.

2.5 Conceptual model development

The insights from MFA and SWOT were integrated into a draft industrial symbiosis model. The model connects CCR suppliers (PLTU Punagaya), users (construction, SMEs, agriculture), and mediating stakeholders (local government, academia, financial institutions). Such integration of MFA and strategic assessment has been applied in waste-to-resource frameworks in emerging economies [24].

2.6 Data calculation method

The quantitative values presented in Table 1 were derived using a scenario-based calculation approach intended to estimate the potential scale of CCR utilization and its associated environmental benefits. The calculations are indicative and exploratory in nature, aiming to support comparative analysis between scenarios rather than precise prediction. The total CCR generation from PLTU Punagaya is estimated at approximately 200–300 thousand tons per year, based on secondary data from power plant operational reports. In Scenario B (Moderate Utilization), a fly ash utilization rate of 25% was assumed, resulting in an estimated CCR utilization volume of approximately 75,000 tons per year. This value represents the proportion of fly ash diverted from disposal to local utilization sectors. In Scenario C (Optimistic Utilization), higher utilization rates were assumed, leading to an estimated CCR utilization volume of approximately 150,000 tons per year.

The cement substitution volume was calculated by assuming that fly ash can replace 20–30% of cement in concrete and mortar production, as widely reported in the literature. Accordingly, the estimated fly ash utilization volumes were translated into equivalent cement substitution quantities of approximately 50,000 tons per year in Scenario B and 100,000 tons per year in Scenario C.

The CO_2 emission reduction rates were estimated using commonly reported emission factors for cement production, which range between 0.8–0.9 tons of CO_2 per ton of cement produced. By comparing the avoided cement production under each utilization scenario with the baseline (Scenario A), the relative CO_2 emission reduction rates were estimated at approximately 15% for Scenario B and up to 25% for Scenario C. These values represent proportional reductions relative to the baseline cement demand in the local construction sector.

Overall, the calculation approach is designed to provide a transparent and reproducible estimation framework that supports strategic decision-making within an industrial symbiosis and circular economy context.

3. RESULTS AND DISCUSSION

3.1 Literature review and conceptual findings

The literature review confirmed that CCRs, especially FABA, have significant potential for reuse in construction and land rehabilitation. Fly ash is rich in silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), making it suitable for partial substitution of cement up to 30% without reducing performance [20]. Bottom ash, on the other hand, has granular physical characteristics that can be applied as lightweight aggregates for paving blocks and bricks [21].

Despite these technical potentials, the application of industrial symbiosis in Indonesia's coal sector remains underdeveloped. Most existing studies focus on isolated uses of CCR, such as fly ash in concrete [22] or small-scale pilot projects [23]. The novelty of this study lies in integrating the industrial symbiosis approach with circular economy principles to propose a local case-based model for CCR utilization in Bone Regency.

Secondary data showed that Indonesia produces more than 10 million tons of CCR annually [24]. Regulatory changes, particularly the reclassification of FABA as non-hazardous waste by the Ministry of Environment and Forestry in 2021, have opened opportunities for industrial-scale reuse [25, 26].

At the local level, PLTU Punagaya generates an estimated 200–300 thousand tons of FABA per year, of which about 80% is fly ash and 20% is bottom ash. Meanwhile, demand for construction materials in Bone Regency is rapidly increasing due to infrastructure expansion (roads, bridges, housing). This creates an opportunity for local industrial symbiosis where CCR can substitute conventional materials [27].

3.2 Industrial mapping

The industrial mapping identified four main sectors in Bone Regency with potential to utilize CCRs, namely construction, building material SMEs, agriculture and land reclamation, and experimental energy applications.

•Construction: Fly ash can substitute 20–30% of cement in concrete and mortar. With infrastructure projects increasing in the region, this substitution could reduce construction costs while lowering CO_2 emissions. The primary barrier is the absence of clear national standards for fly ash-based construction materials.

•Building Material SMEs: Bottom ash has potential as lightweight aggregate in paving blocks and bricks. SMEs could achieve production cost reductions of 10–12%, but face limitations in technical expertise and access to appropriate mixing technology.

•Agriculture and Reclamation: Fly ash can serve as a soil stabilizer and ameliorant to improve marginal land productivity, particularly for post-mining reclamation. However, further laboratory testing is required to ensure safe application with respect to heavy metal content.

•Energy Applications: CCRs may be used as alternative fuel in co-firing technology. While promising, this remains experimental and would require significant technological investment for local implementation.

This mapping demonstrates a strong alignment between CCR supply from Punagaya Power Plant and material demand in local industries, especially in construction and SMEs.

3.3 Material flow analysis in the production system

To enhance the interpretability of the MFA results, a material flow diagram is presented in Figure 1 The diagram visualizes the distribution of CCRs from PLTU Punagaya Power Plant to different utilization sectors and disposal pathways under each analyzed scenario. The material flows shown in the diagram correspond directly to the quantitative values summarized in Table 1, providing an intuitive representation of CCR generation, substitution, and disposal.

Three scenarios were developed to analyze material flows and substitution potential:

•Scenario A (Business-as-Usual): all CCR is disposed, leading to high environmental burden and no economic value.

•Scenario B (Moderate Utilization): 25% fly ash is reused locally, replacing ~50,000 tons of cement annually, reducing CO_2 emissions by 15%, and lowering construction costs by ~10%.

•Scenario C (Optimistic Utilization): 50% fly ash and 30% bottom ash are reused across multiple sectors, replacing up to 100,000 tons of cement and 15,000 tons of aggregate annually, cutting emissions by 25%, and reducing SME production costs by up to 18%.

This analysis shows that even moderate utilization already yields substantial benefits, while optimistic scenarios would significantly transform CCR from waste into a resource. In order to evaluate potential material utilization pathways of CCRs, three analytical scenarios were developed. These scenarios describe alternative options for CCR recovery and integration within industrial symbiosis networks, as summarized in Table 1. The table outlines the input–output relationships, substitution potentials, and environmental implications considered for each scenario.

Table 1. Material flow analysis scenarios for coal combustion residue utilization

Indicator	Scenario A (BAU)	Scenario B (Moderate)	Scenario C (Optimistic)
CCR utilized (ton/year)	0	~75,000	~150,000
Cement substitution (ton/year)	0	~50,000	~100,000
Aggregate substitution (ton/year)	0	~5,000	~15,000
CO_2 reduction (%)	0	~15%	~25%
Cost savings (%)	0	~10%	~15–18%

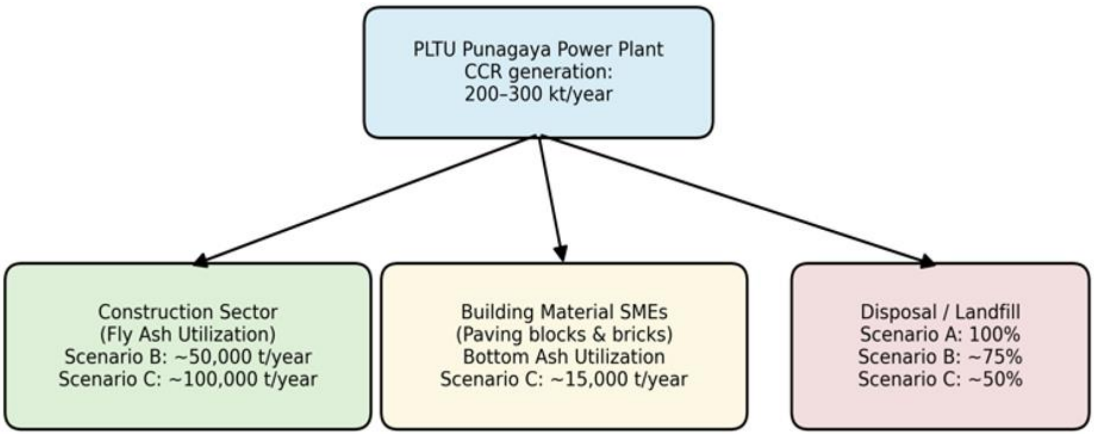

Figure 1. Material flow diagram of coal combustion residues from PLTU Punagaya Power Plant to utilization and disposal pathways under Scenario A (Business-as-Usual), Scenario B (Moderate Utilization), and Scenario C (Optimistic Utilization)

As shown in Table 1, Scenario 1 represents the baseline case without any symbiotic exchange, whereas Scenario 2 and Scenario 3 involve incremental integration of CCR reuse within cement and construction industries. These distinctions form the basis for subsequent material flow and SWOT analyses.

3.4 SWOT-based strategic analysis

The internal and external factors influencing CCR utilization were evaluated using a SWOT framework. Table 2 summarizes the key strengths, weaknesses, opportunities, and threats identified from the field data and literature review

Table 2 indicates that regulatory support and market incentives represent the major opportunities, while technological gaps remain the dominant weakness restricting CCR reuse.

Based on the SWOT findings, feasible strategic, building on the SWOT factors identified in Table 2, Table 3 presents a strategic prioritization of key factors that are most influential in supporting CCR utilization through industrial symbiosis and circular economy implementation.

The SWOT results emphasize that opportunities and strengths are significant, but weaknesses and threats need to be addressed through standardization, capacity building for SMEs, and logistical innovation. As presented in Table 3, SO strategies emphasize cross-industry collaboration and technology sharing, whereas WO strategies focus on capacity building and policy alignment.

Table 2. SWOT analysis of CCR utilization

Aspect	Details
Strengths	•Large supply of CCR from PLTU Punagaya (200–300 thousand tons/year)
	•High and growing demand for construction materials in Bone Regency (roads, housing, infrastructure)
	•Fly ash with high silica and alumina content suitable as partial cement substitute (20–30%)
	•Bottom ash with granular properties suitable as lightweight aggregate for paving and bricks
	•Availability of SMEs already engaged in building materials production
Weaknesses	•Limited technical capacity of local SMEs to process CCR into standardized products
	•Lack of awareness and technical knowledge about CCR utilization
	•Absence of clear national standards Indonesian National Standard (SNI) for CCR-based concrete and bricks
	•Dependence on secondary data, limited laboratory testing at the local level
	•Distribution channels for CCR to SMEs are not yet established
Opportunities	•Supportive national regulations classifying FABA as non-hazardous (non-B3)
	•Alignment with circular economy and green economy strategies at national and global levels
	•Potential for reducing CO_2 emissions through partial substitution of cement
	•Opportunities for job creation and SME competitiveness improvement
	•Potential to scale up utilization beyond Bone to other coal power plant regions in Indonesia
Threats	•Market resistance to waste-based products due to stigma of "low quality"
	•Additional costs of logistics and storage facilities for CCR distribution
	•Risk of environmental concern if CCR contains heavy metals beyond threshold
	•High initial investment required for SME equipment and processing technology
	•Policy uncertainty regarding future coal phase-out and CCR regulation

Table 3. Strategic priority ranking of key factors for CCR utilization through industrial symbiosis

Priority Level	Key Factor	SWOT Category	Strategic Relevance to Industrial Symbiosis
High	Supportive FABA non-hazardous regulation	Opportunity	Enables legal cross-sector exchange of CCR and reduces institutional barriers
High	High regional demand for construction materials	Strength	Provides stable demand anchor for symbiotic material flows
High	Large and continuous CCR supply from PLTU Punagaya	Strength	Ensures reliability of material input for symbiosis networks
Medium	Limited technical capacity of SMEs	Weakness	Requires capacity building to enable effective participation in symbiosis
Medium	Absence of CCR-based product standards (SNI)	Weakness	Limits market acceptance and scalability of CCR products
Medium	Logistics and distribution constraints	Threat	Affects economic feasibility of CCR exchange
Low	Market stigma toward waste-based materials	Threat	Can be mitigated through certification and awareness programs

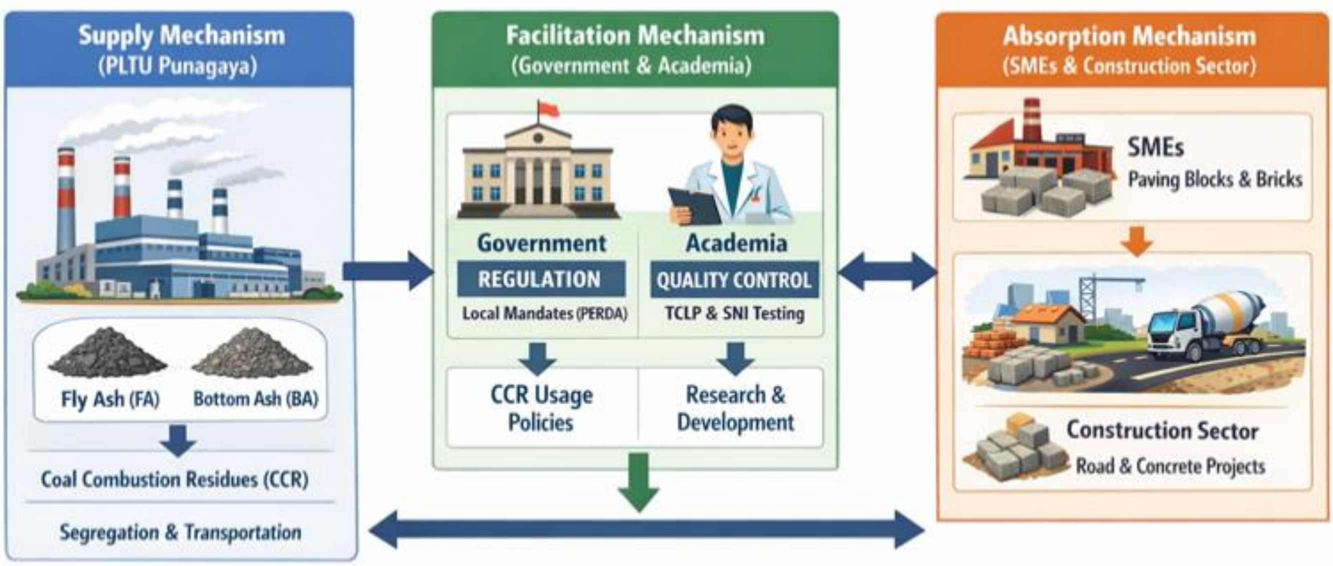

Figure 2. Conceptual framework of CCR-based industrial symbiosis integrating material flows and stakeholder collaboration

3.5 Conceptual industrial symbiosis model

Based on MFA and SWOT findings, a conceptual industrial symbiosis model was formulated. The model connects:

•Suppliers: Punagaya Power Plant as CCR producer.

•Users: construction sector, SMEs in building materials, and agriculture/reclamation projects.

•Mediators: local government (policy and regulation), academia (testing and standardization), and financial institutions (investment in logistics and processing technology).

This model reframes CCR as a secondary resource instead of waste, generating environmental, economic, and social benefits:

•Environmental: reducing landfill disposal by up to 200,000 tons/year and lowering CO_2 emissions by 15–25%.

•Economic: saving 10–18% in material costs for construction and SMEs.

•Social: creating job opportunities in CCR processing and enhancing community awareness of circular economy practices.

To clarify the proposed industrial symbiosis mechanism, a conceptual framework is developed to illustrate the interaction between material flows and institutional actors.

As illustrated in Figure 2, PLTU Punagaya functions as the primary CCR generator, supplying FABA to local utilization sectors such as the cement industry, construction materials, and small-scale enterprises. Government institutions facilitate regulatory alignment, policy support, and economic incentives to enable CCR utilization. Academia contributes through research support, technical assistance, and capacity building to improve processing performance and environmental outcomes. Enterprises play a critical role in processing, distributing, and integrating CCR-derived products into regional markets. The coordinated interaction among these actors forms an industrial symbiosis system that supports sustainable CCR management within a regional circular economy framework.

3.6 Discussion

The results of this study demonstrate that CCR, particularly FABA, hold significant potential as alternative raw materials for construction, SMEs, and land reclamation. The literature has established the technical feasibility of CCR reuse, with fly ash shown to substitute up to 30% of cement without reducing compressive strength [20, 28], and bottom ash serving as lightweight aggregates in paving blocks [29, 30]. However, Indonesia's utilization of CCR remains below 10%, far behind countries like Japan, where over 90% of fly ash is reused [31, 32]. This underscores the gap between policy recognition and practical adoption in emerging economies.

At the policy level, Indonesia's government has taken a progressive step by reclassifying FABA as non-hazardous waste (non-B3) under Government Regulation No. 22/2021. This aligns with global best practices, such as in South Korea and Japan, where CCR has long been treated as a resource rather than waste [33, 34]. Nonetheless, regulatory reform alone is insufficient. Comparable cases in India demonstrate that policy incentives without SME capacity-building resulted in limited adoption of CCR in local industries [35]. This resonates with the findings of this study, where SMEs in Bone Regency show interest in CCR utilization but lack technical capacity, quality standards, and infrastructure.

The MFA in this study reveals that even a moderate utilization scenario (25% fly ash substitution) could reduce CO_2 emissions by 15% and replace approximately 50,000 tons of cement annually. Similar MFA-based studies in China found comparable reductions when utilization reached 20% [36, 37]. Under an optimistic scenario, up to 100,000 tons of cement and 15,000 tons of aggregate could be substituted annually, leading to CO_2 reductions of 25%. These findings are consistent with European experiences where CCR reuse achieved 20–30% emission reductions [35]. The novelty of this research lies in situating MFA within a localized developing-region context, where infrastructural and institutional gaps must be bridged for large-scale adoption.

The SWOT analysis highlights both opportunities and weaknesses as dominant factors. Opportunities arise from strong regulatory backing and alignment with the circular economy and green economy agendas [38]. At the same time, weaknesses include limited SME technical capabilities, absence of CCR-based product standards (SNI), and logistical barriers. This mirrors patterns in India, where lack of training and certification frameworks limited CCR adoption [36]. By contrast, South Korea's industrial symbiosis programs demonstrate that structured government–industry partnerships can overcome such barriers, achieving greater circularity [38].

Finally, the proposed conceptual model builds upon international experiences such as the Kalundborg Symbiosis in Denmark, but adapts it to the Indonesian context. Unlike Kalundborg, which evolved organically through private-sector collaboration, the Bone Regency model depends heavily on government facilitation and academic support. This difference reflects broader contrasts between industrialized and developing economies, where government intervention plays a central role in enabling circular economy practices. Recent research further supports this perspective, emphasizing that effective policy frameworks and institutional collaboration are crucial for transitioning towards a circular economy in developing nations [39].

4. CONCLUSIONS

This study explored the potential of CCRs management through an industrial symbiosis framework in Bone Regency, Indonesia. The findings reveal that FABA can be effectively integrated into multiple sectors, including construction, SMEs, and agriculture, contributing to cost savings, CO_2 emission reductions, and waste minimization.

Three key conclusions can be drawn:

•Environmental benefit – CCR utilization under moderate and optimistic scenarios could reduce CO_2 emissions by 15–25% while diverting up to 150,000 tons of CCR annually from disposal.

•Economic and social benefit – SMEs adopting CCR as raw materials could lower production costs by 10–18% while simultaneously creating new jobs and improving local competitiveness.

•Strategic insights – The SWOT analysis emphasizes that while regulatory frameworks create strong opportunities, technological and institutional weaknesses of SMEs remain barriers to adoption.

The proposed conceptual model demonstrates how cross-sector collaboration—facilitated by government, academia, and industry—can transform CCR from an environmental liability into a regional development driver. This research thus extends the literature by situating industrial symbiosis within a developing-country context and providing a replicable framework for sustainable CCR management.

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