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Community empowerment model in the refuse-derived fuel waste management program in Indonesia

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ABSTRACT

This study develops an integrative community empowerment model specifically designed for refuse-derived fuel (RDF)-based waste management systems in developing countries, using a case study in rural Indonesia. Despite the increasing attention on RDF as a sustainable waste-to-energy solution, previous studies have predominantly focused on technical and environmental aspects, leaving a critical research gap in understanding how socially embedded empowerment models can support RDF implementation. While RDF offers promising waste-to-energy solutions, its success is constrained by low community participation, limited technical skills, and fragmented institutional support. Employing a qualitative case study approach, data were collected through in-depth interviews, focus group discussions, participant observation, and document analysis in three partner villages. The findings reveal that effective RDF implementation requires a multi-level empowerment strategy that combines technical capacity building, decentralized waste management infrastructure, and participatory governance involving corporate, governmental, and community actors. The proposed model uniquely integrates circular economy principles with community development theories, emphasizing feedback loops, inclusive decision-making, and economic incentives to sustain participation. This study contributes a novel and transferable framework that enhances local agency and system resilience in waste-to-energy transitions, bridging circular economy and social inclusion—an area largely overlooked in existing RDF research.

1. Introduction

Rapid population growth and urbanization in developing countries have intensified the challenges of municipal solid waste management. In Indonesia alone, over 190,000 tons of waste are generated daily, with a significant portion ending up unmanaged in landfills or illegal dump sites (Tempo, 2024). One emerging solution to this issue is the adoption of refuse-derived fuel (RDF), which transforms combustible waste into an alternative industrial fuel. However, the success of RDF programs is highly dependent on the quality of waste sorting at the community level—an area that remains a major bottleneck due to limited public awareness, inadequate infrastructure, and fragmented stakeholder coordination.

Community participation plays a crucial role in the successful implementation of RDF programs. Unlike conventional waste management approaches, RDF requires consistent input quality that can only be achieved through behavioral changes at the household level and strong institutional support. Despite its growing adoption, few studies have systematically explored how communities can be empowered to meet these requirements. Most existing RDF research focuses on technical and environmental aspects (Hutabarat et al., 2018; Chaerul and Wardhani, 2020), with limited attention given to the human and social dimensions of implementation.

This research gap is particularly relevant given recent findings from other developing country contexts. For instance, Islam et al. (2025) highlight the complexity of adopting circular economy (CE) principles in Bangladesh's e-waste sector, where regulatory gaps and low public awareness hinder effective implementation. While Mishra et al. (2025) show that industrial sectors in India are gradually transitioning toward CE, albeit slowly, due to systemic and cultural challenges. Collectively, these studies underscore the need for localized, socially embedded approaches that extend beyond purely technical fixes.

In line with this, Valencia et al. (2023) emphasize that circular economy transitions must deliver not only environmental and economic outcomes but also social contributions such as equity, collaboration, and governance maturity. Their findings underscore that overlooking these social dimensions may undermine the long-term viability of CE initiatives, particularly in diverse community settings. The present study

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addresses this research gap by developing an empowerment model specifically tailored to RDF-based waste management.

The model integrates community development theory with circular economy principles, aiming to create a structured yet flexible pathway for active and sustainable community involvement. Although the model is tested in a rural Indonesian context, its design offers insights that are applicable to other developing countries facing similar waste-to-energy challenges. Accordingly, this study seeks to formulate a community empowerment model that enables inclusive, context-sensitive, and sustainable implementation of RDF waste-to-energy programs in developing contexts.

This study addresses a critical gap in existing RDF research, which has rarely examined how participatory and empowerment-oriented strategies can be systematically integrated into RDF governance frameworks. To pursue this objective, a qualitative case study was conducted using interviews, observations, and document analysis in selected rural areas involved in RDF initiatives. Community empowerment has been widely discussed across various sectors, including agriculture (Tesafa et al., 2025), tourism (Ataöv et al., 2022), and healthcare (Eccher et al., 2020).

Existing studies have predominantly emphasized the significance of participatory governance, the utilization of local knowledge, and capacity building. However, there remains a notable gap in the literature regarding how community empowerment is operationalized within technologically intensive environmental programs—particularly those involving refuse-derived fuel, a technology that converts combustible waste into alternative energy sources. To ensure alignment with recent advancements in the field, this study draws upon a selection of contemporary scholarly works that focus on circular economy principles, stakeholder engagement, and waste governance models within developing country contexts (e.g., Al-Raqeb et al., 2023; Valencia et al., 2023; Zhang et al., 2025).

In the field of waste management, Maulana et al. (2021) underscore the critical importance of integrating technological interventions with active community participation. This alignment is particularly relevant in the implementation of biodrying and RDF systems, whose effectiveness is largely contingent upon consistent and efficient upstream waste segregation. Such segregation, in turn, necessitates sustained engagement from local communities. Nevertheless, much of the existing literature tends to overlook the institutional and behavioral dynamics that underpin long-term participatory practices, particularly in decentralized or rural waste management settings.

Advancements in technical modeling further illuminate this gap. Fakhrzad and Verma (2025) introduced a mixed-integer linear programming (MILP) model to optimize medical waste transportation, while Arantes et al. (2020) developed a georeferenced multi-criteria decision-making approach for the siting of municipal solid waste treatment facilities—highlighting the growing reliance on algorithmic tools in spatial and operational decision-making. These innovations underscore the increasing role of digital and systems-based tools in waste management logistics. However, such approaches often fall short in addressing the human and community dimensions of waste governance.

In contrast, a study in Shanghai illustrates how collaborative governance—particularly partnerships between local governments and NGOs—can effectively address urban waste challenges by integrating social participation and local knowledge into waste management processes. This underscores the importance of coupling technical innovation with socially embedded and participatory approaches.

From a governance and social development perspective, Al-Raqeb et al. (2023) highlighted institutional bottlenecks in implementing reduce-reuse-recycle-recover (4 R) strategies in Kuwait's construction waste sector. Studies specifically focused on RDF in Indonesia, such as those by Widowati (2023) and Rania et al. (2019), confirm the technical feasibility of RDF adoption. However, these studies fall short in addressing how communities can be systematically empowered to support such programs.

In this context, the study by Picavet et al. (2023) offers a compelling illustration of how Transnational Municipal Networks (TMNs) can serve as catalysts for the emergence of collaborative governance regimes at the local level. Focusing on waste management in Gangtok, India, the authors demonstrate how TMNs contributed to building capacity for joint action—by enhancing institutional structures, leadership dynamics, knowledge exchange mechanisms, and resource mobilization. Notably, the initiative enabled local actors not only to implement composting programs effectively, but also to act as knowledge providers within wider transnational networks.

Similarly, Harfadli et al. (2025) proposed a roadmap for emission reduction in Balikpapan through household-level waste separation; however, their approach lacks integration with institutional support and scalable empowerment strategies. The concept of a community empowerment model is essential in bridging this gap. As Ritonga (2022) explains, it serves as a reference pattern and a structured effort to enhance capabilities and independence, enabling individuals or institutions to optimally develop their potential.

According to Yefni (2018), empowerment models can be implemented through three main approaches: centralization, participation, and community development—each serving as a framework for program planning that drives transformational change. Herlon et al. (2023) further assert that the ideal empowerment model emphasizes community potential, collective awareness, and the capacity to manage resources and capabilities independently. This perspective aligns with Ife's view (Dina et al., 2023), which holds that empowerment is fundamentally oriented toward addressing issues of power and inequality, encouraging communities to take control over decisions that affect their lives.

Likewise, Calves (Sany, 2019) underscores that community empowerment extends beyond social and political concerns and encompasses economic dimensions, particularly poverty alleviation. In this context, the RDF waste management program can serve as a catalyst for local economic improvement while reinforcing participatory, people-centered, and sustainable development practices (Habib, 2021). In the broader environmental governance literature, dos Santos et al. (2024) criticized the disconnect between circular economy principles and social inclusion efforts.

To fill this gap, the present study proposes a hybrid empowerment model that integrates RDF technology with participatory development practices, grounded in CE principles. This study uniquely addresses the lack of integrative frameworks that link circular economy implementation with grassroots empowerment mechanisms in the context of RDF programs—offering both theoretical and operational contributions. The model emphasizes feedback loops, stakeholder coordination, and community-based behavior change as core components.

Unlike previous studies that focus solely on technical tools or policy frameworks, this research contributes a systems-based and context-sensitive model for inclusive waste-to-energy (WtE) solutions in developing countries—providing a more comprehensive foundation for sustainable RDF implementation.

2. Methods

This study employs a qualitative case study design to examine how community empowerment can be embedded in refuse-derived fuel waste management programs in developing-country contexts. The case study approach enables an in-depth contextual investigation of the social, institutional, and technological dynamics that influence RDF program outcomes.

This methodology is particularly well-suited to capture the complex interplay among community participation, stakeholder roles, and environmental innovation. The research was conducted in three rural villages (Fig. 1) in Cirebon, West Java—Palimanan Barat, Kedungbunder, and Cupang—where RDF programs have been initiated in collaboration with Indocement Tunggal Prakarsa, a cement company implementing

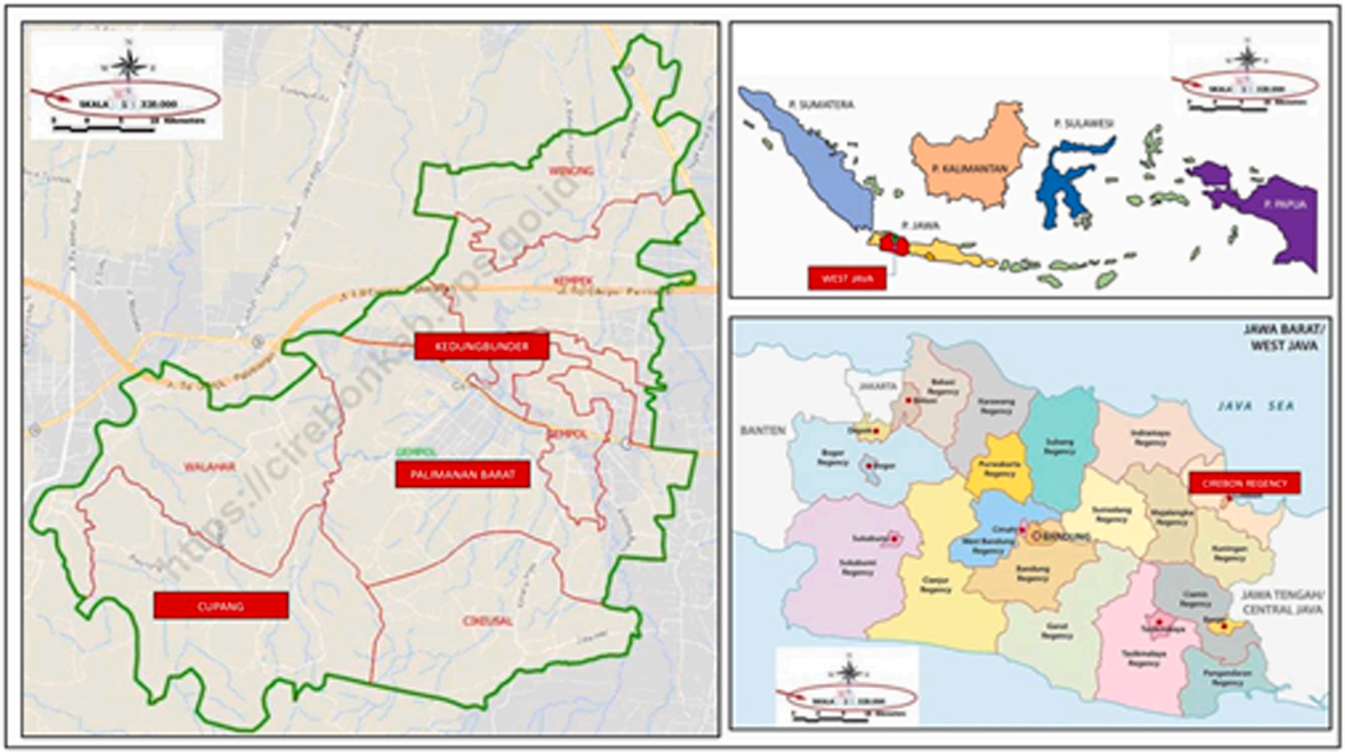

Fig. 1. Geographical locations of the study areas.

corporate social responsibility-based environmental initiatives. The sites were purposively selected based on their active involvement in RDF waste sorting, decentralized waste processing, and community-led environmental awareness campaigns.

Data collection relied on triangulated qualitative techniques to ensure robustness and credibility:

a. In-depth interviews using semi-structured interview guides were conducted with 22 informants, including community leaders, RDF waste bank managers, local government officials, and CSR program facilitators from Indocement.
b. Participant observation was carried out at local waste treatment units (TPS3R and RDF sorting centers) over a three-month period to observe actual practices and social interactions.
c. Document analysis involved the review of sustainability reports, program evaluation documents, regional waste management regulations, and technical training manuals provided to community members.

All interviews were audio-recorded and transcribed verbatim. The data were analyzed using the interactive model by Miles and Huberman (1994), which consists of data condensation, data display, and conclusion drawing/verification. To ensure research validity and trustworthiness, several strategies were implemented: methodological triangulation to confirm consistency across data sources, member checking with selected informants to validate interpretations, peer debriefing with academic colleagues to ensure analytic rigor, and thick description to support transferability. An audit trail was maintained throughout the research process, enabling transparency and confirmability.

These combined techniques enhance the credibility and dependability of the findings. Open coding was conducted initially, followed by axial coding to identify emergent patterns and relationships across themes such as empowerment mechanisms, adaptation to RDF technologies, stakeholder collaboration, and institutional support structures. To ensure research validity and trustworthiness, several strategies were implemented:

a. Methodological triangulation was employed to ensure the convergence of findings from different data sources.
b. Member checking was conducted with selected participants to verify the accuracy of the interpretations.
c. Peer debriefing with academic colleagues was used to help refine categories and minimize researcher bias.
d. Thick description was employed to enhance the transferability of the findings.
e. An audit trail was maintained throughout the research process to support dependability and confirmability.

This methodological framework provides a systematic and context-sensitive lens to uncover how local communities in rural Indonesia experience, adapt to, and influence the success of RDF-based waste management systems. It also highlights the conditions under which technological innovation aligns with inclusive environmental governance, offering insights that can be applied to other developing-country contexts facing similar challenges.

3. Results and discussion

3.1. Human capacity building and technical training

Field observations during the case study revealed a consistent challenge across the three village sites: local community members demonstrated limited technical competence in operating refuse-derived fuel processing equipment. This limitation created operational bottlenecks in maintaining consistent RDF quality, particularly with respect to input segregation and moisture control—both of which are critical to ensuring fuel efficacy.

These empirical findings align with a growing body of literature that emphasizes the importance of structured system design in waste management (Fakhrzad and Verma, 2025). Similarly, Arantes et al. (2020) employed a georeferenced multi-criteria approach to optimize the spatial allocation of waste treatment facilities, underscoring the need for technically sound and spatially intelligent planning. Complementing

this, Zhang et al. (2025) argue that improvements in eco-efficiency can serve as catalysts for citizen co-production, particularly when institutional capacity exceeds a certain threshold.

In the context of complex waste logistics, advanced modeling approaches—such as the two-stage stochastic MILP model applied in medical waste systems—further reveal that the reliability of high-tech waste infrastructure is highly contingent upon human capacity. This observation is echoed in the work of Picavet et al. (2023), who demonstrate that Transnational Municipal Networks (TMNs) can play a pivotal role in strengthening local institutional frameworks, leadership dynamics, learning mechanisms, and resource mobilization, thereby enabling communities to co-manage waste systems through collaborative governance regimes.

Translating these insights into the RDF initiative led by Indocement, the company has implemented a series of targeted technical training programs for local residents involved in the waste value chain. These trainings focus on practical competencies such as heavy equipment operation, routine maintenance, and proper waste segregation techniques aligned with RDF specifications—particularly ensuring that input materials maintain a moisture content below 5 %. By equipping community members with these operational skills, the program aims to reduce dependence on external technicians while fostering local autonomy in managing waste-to-energy systems.

This strategy reflects the principles of Rappaport's empowerment framework (Rappaport, 1987), which identifies knowledge acquisition, participatory control, and self-efficacy as core dimensions of psychological and structural empowerment. The incorporation of certified training—often delivered by instructors accredited by the National Professional Certification Board—serves as both a technical intervention and a social empowerment mechanism. It transforms community members from passive beneficiaries into active contributors capable of sustaining decentralized waste infrastructures.

This approach further reflects the capability approach articulated by Sen (1999), which emphasizes that true empowerment is not merely about transferring technical skills but about expanding individuals' substantive freedoms and real opportunities to shape their own development trajectories.

In the RDF program context, equipping community members with certified technical skills and operational know-how empowers them to participate not only as labor but as decision-makers and co-designers of waste management strategies. This transformation shifts their role from passive recipients of CSR activities into active agents who can negotiate, adapt, and sustain environmental innovations in line with local realities.

Moreover, integrating participatory governance into capacity-building initiatives addresses a critical gap often found in top-down technological interventions. By fostering inclusive decision-making structures, such programs ensure that training efforts are responsive to local needs and cultural contexts, thereby enhancing a sense of ownership and encouraging long-term engagement.

In the context of rural waste management, this approach supports behavioral transformation by aligning technical competencies with socially embedded practices. When circular economy principles are incorporated into empowerment strategies, community agency is further strengthened—linking practical skills with economic incentives and environmental responsibility. This integrated model allows the RDF program in Cirebon to not only enhance its waste-to-energy performance but also lay the groundwork for an adaptive and inclusive governance framework rooted in local participation.

Furthermore, this approach resonates with emerging trends in environmental governance, where technical capacity is increasingly recognized not just as a support mechanism, but as a foundational element of inclusive and resilient development. Particularly in Global South contexts, where formal infrastructure may be lacking, community-based training can serve as a critical enabler of system reliability and sustainability.

Therefore, the integration of human resource development in RDF systems—through hands-on training, certification, and localized knowledge transfer—represents both a practical necessity and a theoretical advancement. It operationalizes the empowerment concept within a circular economy framework, ensuring that technological innovation is not detached from social inclusion. This constitutes one of the novel contributions of this study: demonstrating how structured capacity building enables community-driven sustainability in waste-to-energy systems.

Based on these findings, the community empowerment model for the RDF waste management program can be conceptualized as follows:

Based on Fig. 2, the community empowerment model in the RDF waste management program is designed to support the implementation of the company's policy, which aims to utilize waste as an alternative fuel to replace fossil fuels such as coal. This model emphasizes the importance of synergy among corporate policies, effective communication, community empowerment, stakeholder collaboration, and a continuous feedback process. Below is a detailed explanation of each component in this model:

1) The company has established a policy that supports the use of waste as refuse-derived fuel, which serves as an alternative energy source. This policy not only aims to reduce dependence on coal but also represents a step toward addressing environmental issues by converting waste into a more environmentally friendly energy source.
2) Communication acts as a liaison between the company and its stakeholders. In this model, communication ensures a clear and transparent flow of information regarding policies, strategies, and program implementation.
3) The empowerment strategy focuses on increasing community capacity and developing waste processing units. One of the strategic steps taken is providing training on waste sorting based on the principles of the circular economy. Through this training, the community is equipped with the skills needed to sort waste according to RDF requirements, enabling them to actively participate in the program.
4) The success of this program is highly dependent on the strength of collaboration among various stakeholders, including companies, local governments, communities, academics, media, and other related parties. This collaboration enables stronger support in terms of policies, resources, and technical implementation on the ground.
5) The feedback process is a key element of this model. Through periodic evaluations, the company and stakeholders can assess the effectiveness of the program and identify areas for improvement. This process ensures that the program remains relevant, adaptive, and capable of achieving its set goals.

The integration of community participation in refuse-derived fuel programs is not a symbolic gesture—it constitutes a direct and functional alignment with local economic systems. Findings from this study indicate that RDF-related livelihoods in the Cirebon villages operate under two principal income schemes: (1) volume-based remuneration, where workers are paid approximately IDR 200 per kilogram of processed waste; and (2) daily wages, which follow regional minimum wage standards. These income arrangements are not only structured but also scalable, serving as practical incentives for sustained community engagement.

Beyond the formal employment track, RDF initiatives have stimulated broader economic activity through micro-incentive mechanisms. For instance, waste banks offer financial rewards for segregated household waste, while community groups reinvest collective earnings into tools, infrastructure, or shared welfare funds.

These incentive structures create what Sen (1999) would call a "capability-expanding environment"—where individuals gain real, tangible options for improving their material and environmental conditions. Such environments are particularly vital in contexts where structural limitations restrict formal access to sustainability solutions. In

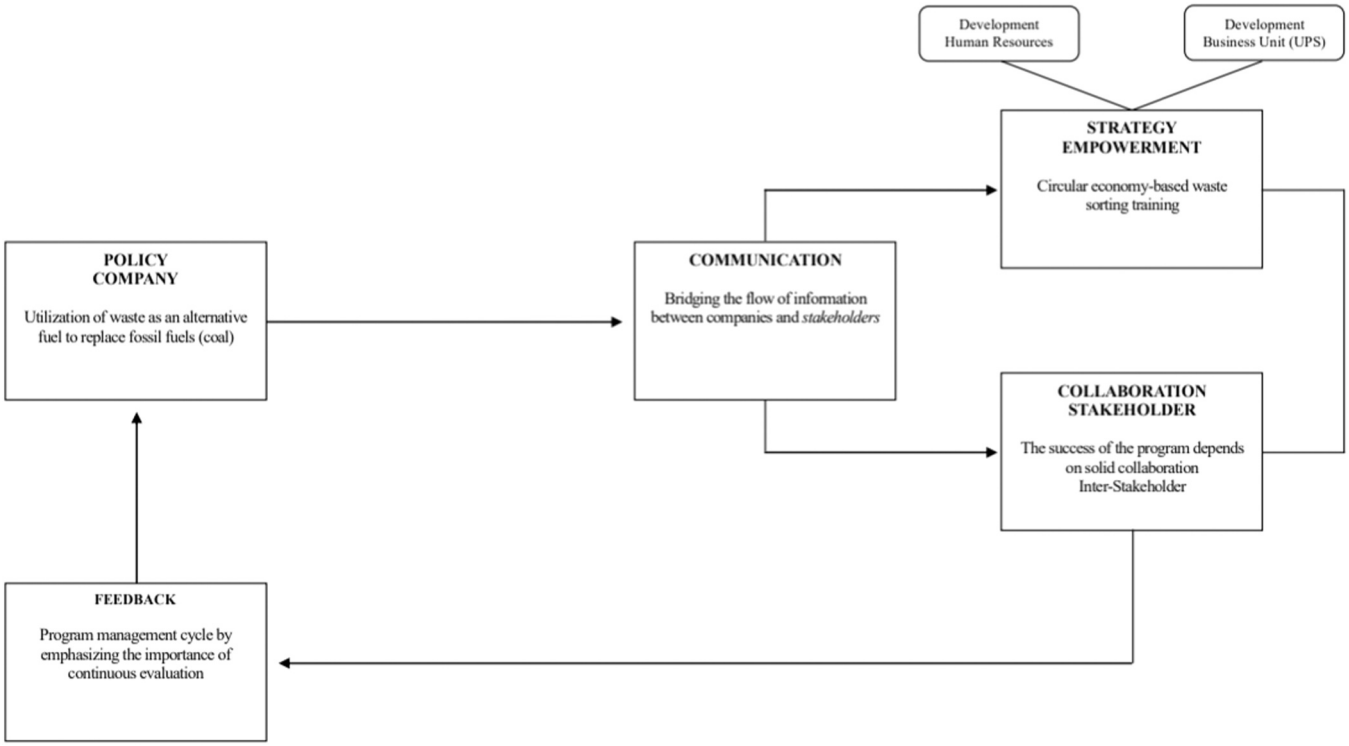

Fig. 2. Community empowerment model in the RDF waste management program.

line with this, Harfadli et al. (2025) highlight how multi-criteria integration—encompassing environmental, social, and economic considerations—serves as a key success factor in the governance of RDF initiatives in Indonesia, enabling more inclusive and durable community engagement.

This dynamic aligns with broader global insights indicating that economic empowerment plays a pivotal role in enabling sustainable waste practices. In many rural settings, community behavior around waste is not solely driven by financial incentives but is also shaped by shared ethical norms, trust-based interactions, and participatory engagement. These social capital elements appear to reinforce material outcomes, as observed in Cupang and Kedungbunder, where households engaged in early-stage waste sorting reported higher returns and more effective waste bank operations.

In many developing regions, community-led responses to environmental challenges increasingly take the form of grassroots economic innovation. This pattern resonates with the RDF model, where villagers have adopted entrepreneurial roles as waste collectors, sorters, and waste bank coordinators. These roles not only generate household income but also contribute to environmental value creation, positioning the RDF initiative as a platform for integrated socio-economic transformation.

In Indonesia, Harfadli et al. (2025) used an Analytic Hierarchy Process (AHP) to evaluate municipal solid waste management strategies in Balikpapan. Their study shows that the most effective strategies are those that balance environmental, social, and economic criteria—an insight that underscores the multidimensional benefits of RDF systems. In the villages studied here, RDF not only contributes to emission reduction and landfill diversion but also functions as an informal economic engine for marginalized populations.

At the organizational level, behavioral transformation in waste management is often shaped by institutional support mechanisms and cultural context. Interviews with waste bank leaders in this study confirmed that community participation is most effective when supported by sustained awareness-building efforts and ongoing technical training. These activities are frequently accompanied by financial incentives, creating a synergistic model that combines behavioral economics with environmental education.

From a systems engineering perspective, Fakhrzad and Verma (2025) argue that economic feasibility in waste-to-energy systems is maximized when waste streams are optimized and value extraction is prioritized. The RDF model under Indocement operationalizes this insight through differentiated pricing for sorted versus unsorted materials. Such differentiation reinforces sorting behavior at the source and converts waste into a monetizable resource—a key tenet of circular economy thinking.

Even in settings where digital infrastructure is limited, sustainable community practices can still be reinforced through localized feedback mechanisms. In the case of the RDF program, informal reward systems—such as public recognition, reduced waste transport costs, and group savings—serve as effective incentives that promote consistent participation and reinforce pro-environmental behavior over time.

Taken together, these findings demonstrate that RDF programs do not merely represent environmental interventions but act as integrated platforms for community empowerment and economic development. The model outlined in this study reveals how economic incentives—grounded in local knowledge, participatory governance, and decentralized systems—can activate inclusive transitions toward circularity.

In sum, the RDF initiative in Cirebon showcases a locally grounded application of circular economy principles, wherein economic opportunity, environmental sustainability, and social inclusion converge. This serves as a replicable model for other low- and middle-income regions seeking to implement waste-based livelihoods without relying entirely on state or corporate subsidies.

Fig. 3 shows that, in an effort to preserve the environment while increasing operational efficiency, the company has implemented an optimal waste management strategy through various reuse methods. For waste classified as B3 (hazardous and toxic materials), the company has successfully reused 62.5 % of the total B3 waste internally. This approach not only reduces dependence on external parties but also ensures that hazardous waste is managed safely within the company's facilities, thereby minimizing adverse environmental impacts.

On the other hand, the company also utilizes some waste as a

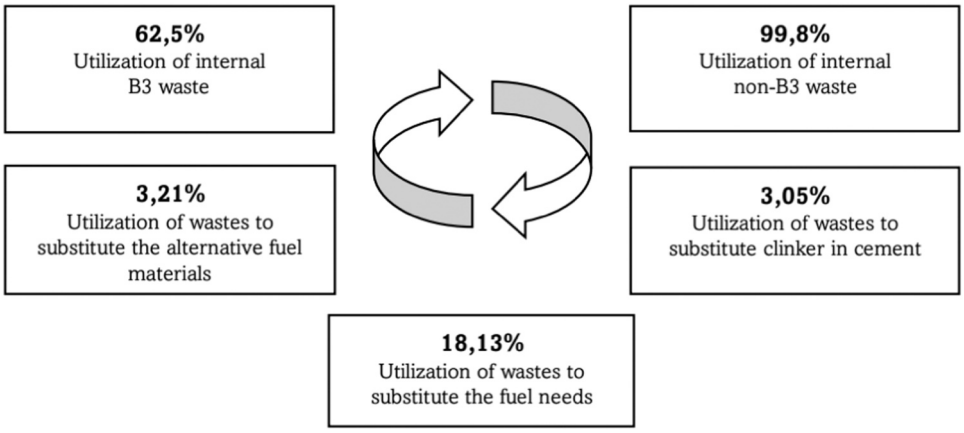

Fig. 3. Circular economy business model.
(Source: Indocement sustainability report 2023)

substitute material to meet its energy needs. About 3.21 % of the total waste has been reused as alternative fuel, helping to reduce reliance on conventional energy sources, which typically have a higher carbon footprint. Additionally, around 18.13 % of the waste is used as a substitute for the company's primary fuel needs. This strategy not only contributes to cost savings but also reduces energy consumption from less environmentally friendly sources.

The company has also established a highly efficient non-B3 waste utilization system, successfully reusing 99.8 % of the non-B3 waste generated from its operational activities. This remarkable achievement underscores the company's strong commitment to recycling by ensuring that non-hazardous waste is reintegrated into the production chain rather than being sent to disposal. Notably, a portion of this waste is used as a substitute for clinker in the cement manufacturing process, resulting in a utilization rate of 3.05 %. Since clinker is a key ingredient in cement and has a significant carbon footprint, using waste as a substitute for some of this clinker not only reduces carbon emissions but also decreases dependence on mineral resources.

The sustainability of RDF initiatives is strongly tied to institutional support. Community-based organizations (e.g., BUMDes, waste banks) function as intermediaries between corporations and households. For instance, in Palimanan Barat, collaboration with BUMDes facilitates the collection and sorting of household waste into RDF feedstock. Community forums and village-level waste banks (e.g., Alkarimah and Indah Makmur) serve as training hubs and distribution centers.

According to local managers, these institutions play a key role in socializing the importance of waste separation and fostering a culture of accountability. Over time, the number of active waste banks grew from 20 to 50 between 2020 and 2023, demonstrating increased community participation. This aligns with Ife's (2016) view that empowerment must be rooted in local institutions that ensure equitable access to information, participation, and decision-making. These platforms enable a form of participatory governance that anchors RDF implementation in community-led structures.

3.2. Technical challenges in RDF processing

Despite notable improvements in community engagement and social readiness, the implementation of RDF technology continues to face persistent technical and infrastructural challenges. Field observations and stakeholder interviews indicate that RDF feedstock frequently contains undesirable elements such as chlorinated plastics, heavy metals, and high-moisture organic waste, which compromise the calorific value and combustion quality. In cement production, particularly during the clinkerization process, such contaminants can cause technical disruptions, emission spikes, and equipment degradation.

The calorific value of RDF sourced from the villages studied—estimated between 2500 and 3500 kcal/kg—remains significantly below that of conventional fuels such as coal (~6000 kcal/kg). This necessitates blending RDF with biomass or industrial by-products to ensure sufficient thermal energy for kiln operations, a practice observed at Indocement's Cirebon plant. However, such blending increases logistical complexity and introduces variability in fuel consistency, which in turn demands tighter quality control and technical oversight.

These technical challenges also illustrate the importance of adaptive governance and iterative system design in RDF implementation. Rather than perceiving technical bottlenecks purely as engineering problems, they should be viewed as dynamic points of learning that require continuous community feedback and responsive management. This perspective aligns with open systems theory, which posits that organizations and programs must continuously adapt to external and internal changes to maintain effectiveness and sustainability. By integrating feedback loops from community experiences—such as sorting errors, equipment failures, and quality inconsistencies—the RDF program can recalibrate its operational strategies and training protocols in real time.

Furthermore, these operational challenges underscore the importance of adapting RDF technologies to local conditions rather than applying one-size-fits-all solutions. Ignoring variations in waste characteristics, socio-cultural norms, and local expertise often results in system inefficiencies or outright failure (Rania et al., 2019).

The Cirebon RDF program's partial success in revitalizing processing units and improving daily capacity showcases the critical role of localized innovation supported by participatory governance structures. By acknowledging technical uncertainties as inherent components of system evolution, the program strengthens its resilience and fosters a culture of joint problem-solving between corporate actors and community stakeholders. This hybrid approach not only addresses immediate operational gaps but also builds a foundation for more robust, community-driven waste-to-energy transitions in developing country contexts.

At the operational level, the waste processing unit in Palimanan Barat has undergone partial revitalization, increasing processing capacity from 2 tons/day to 10 tons/day. This upgrade includes the installation of crushers, shredders, RDF-specific conveyors, and aerobic composting modules. Nonetheless, the long-term goal of scaling up to 30 tons/day remains constrained by limited machinery, high maintenance costs, and gaps in operator expertise. Such limitations reflect a broader theme identified in RDF projects globally: technological viability is not synonymous with operational resilience.

The effectiveness of RDF as an alternative fuel largely hinges on the quality and consistency of waste inputs. Insufficient segregation or contamination with incompatible materials may lead to combustion

inefficiencies, increased emissions, and potential damage to thermal infrastructure. In line with this, Rania et al. (2019) underscore how RDF initiatives in Morocco were hampered by technological mismatches and underperforming equipment, especially when foreign machinery failed to accommodate local waste profiles and environmental conditions.

These cases parallel the Indonesian context, where equipment compatibility, technical skill gaps, and inconsistent waste inputs remain significant hurdles. In Palimanan Barat, for instance, stakeholders noted that manual sorting methods are still predominant, increasing labor intensity and the margin for error. While certified technical training (as discussed earlier) is helping to mitigate these issues, the absence of predictive maintenance systems, real-time monitoring, and automated quality assurance continues to expose the RDF chain to inefficiencies and operational risk.

From a systems perspective, this illustrates the fragility of RDF infrastructure in developing contexts, where local innovation must compensate for the absence of industrial-scale robustness. Technological solutions must therefore be coupled with institutional governance, adaptive maintenance regimes, and cross-sectoral investment. Experience from the field further suggests that the sustainability of such systems depends not solely on hardware or technical design, but on the alignment of stakeholders across community, regulatory, and operational domains.

Moreover, while RDF is often framed as an environmentally superior alternative to landfilling or incineration, the benefits can only materialize if fuel standards—such as moisture content, particle size, and chlorine thresholds—are consistently met. Current operations in the Cirebon region demonstrate a promising trajectory, but without structural improvements in equipment standardization, waste segregation protocols, and data-driven monitoring, the RDF process risks becoming a technological patch rather than a transformative solution.

In summary, the findings suggest that technical challenges in RDF processing are not isolated mechanical issues but systemic barriers that demand integrated responses. The Indonesian case adds to a growing body of global evidence that local adaptation, continuous capacity building, and public–private coordination are indispensable for RDF systems to evolve from pilot stages into resilient, scalable, and sustainable energy infrastructures.

The RDF waste processing process, as shown in Fig. 4, begins with waste received from the community. The waste is first fed into crusher machine 1. Next, it is transferred to BC 2 and then processed further in the composting machine, where it is sorted to separate materials suitable for composting. Large plastic waste is directly transferred to BC 3 and then fed into crusher machine 2, which breaks the waste into pieces approximately 3 cm in size. After the shredding process, the resulting material, known as municipal solid waste (MSW), is used as raw material for the production of RDF.

Before being used as an alternative fuel, the MSW is mixed with rice husks. The final product is then transported by motor to Indocement for further processing and use as an alternative fuel in cement production. Based on the researcher's observations, the waste processing unit in Palimanan Barat is equipped with two shredders, four crushers, two compost screeners, and one presser.

The visualization in Fig. 5 shows how the system works in practice. MSW mixed with rice husks can be directly used as fuel or further processed into RDF. This approach reduces coal dependency by using waste as a renewable energy source. RDF is produced from non-hazardous household and industrial waste through stages such as shredding, drying, and metal separation. Its raw materials include biomass (like rice husks and sawdust) and industrial waste (such as tires and shoes). This diversification supports RDF as a sustainable energy solution. So far, Indocement has replaced about 20 % of its total fuel use with these alternatives, making RDF a key part of its long-term energy strategy.

As shown in Table 1, RDF has a lower combustion potential than coal. Consequently, cement plants need to use more RDF to achieve the same energy output as coal. Alternatively, RDF can be mixed with other fuels that have a higher calorific value, such as biomass or industrial waste. This is crucial for planning energy requirements and improving operational efficiency in RDF combustion. Harmful compounds in RDF

Fig. 5. Processed MSW with husk, ready for combustion or RDF production.

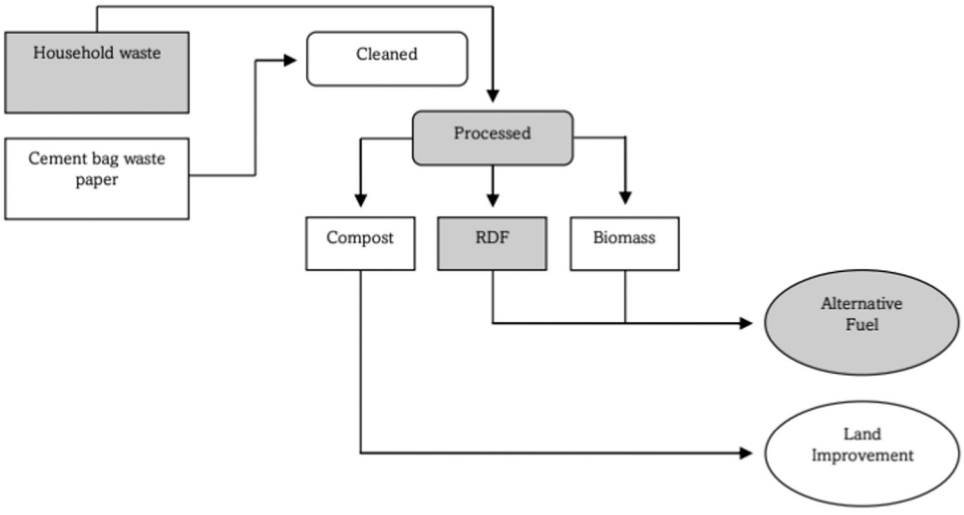

Fig. 4. RDF waste processing process flow at UPS Palimanan Barat.

Table 1
Analysis of heating values, proxies, and RDF elements for cement plants.

Aspects	Data	Information
Heating Value (Heat)	RDF calorific value: 2500 to 3500 kcal/kg	The heating value of RDF is lower than that of coal (4500 to 5000 kcal/kg). This has implications for the need to increase the amount of RDF burned or mix with other fuels that have higher calorific values, such as biomass or other industrial wastes.
Proximate Analysis	Levels of undesirable compounds: phosphates, chlorine, heavy metals	RDF proximate analysis reveals the presence of harmful compounds such as phosphates, chlorine, and heavy metals. Therefore, RDF quality control is essential to minimize contamination of hazardous compounds before they are burned in cement kilns.
Elemental Analysis	Harmful compound content: phosphates, chlorine, heavy metals	The phosphate, chlorine, and heavy metal content contained in RDF has the potential to interfere with the chemical process in the cement kiln and affect the quality of the clinker. Therefore, elemental analysis needs to be carried out to identify content that has the potential to interfere with the production process.
Effect on Clinker Quality	Effect of harmful compounds on clinker quality and kiln parts	The harmful compounds contained in RDF, such as chlorine and heavy metals, can cause corrosion in kiln equipment, affect the quality of clinker, and damage the exploitation process. Therefore, the quality of RDF should be strictly monitored to ensure it does not affect the final product.
Changes to the Cement Kiln Process	Equipment design modification and kiln operating conditions	The process of burning RDF as a coal replacement fuel requires adjustments to kiln design and operating parameters to ensure efficient burning. This change also allows increased control over the composition and quality of RDF before it is put into the kiln.

can disrupt the stability of the kiln combustion process, as they may settle and cause corrosion in cement plant equipment.

For example, chlorine can react with other compounds in the kiln to form corrosive substances, damaging equipment and increasing maintenance costs. Heavy metals can also contaminate clinker products, compromising the quality of the final cement. Therefore, closely monitoring RDF quality and refining it before use in cement kilns are essential to minimize these harmful compounds.

The phosphate and heavy metal content in RDF, such as cadmium and lead, can interfere with the clinkerization process in the kiln. These heavy metals may accumulate in the clinker, compromising the quality of the cement. Thus, elemental analysis is vital to ensure that the RDF composition meets the quality standards required for deep combustion in the kiln. Procedures to separate or reduce harmful compounds in RDF are necessary to make it safe for use in cement production.

The clinkerization process is a critical stage in cement production, where raw materials are heated in a kiln to form clinker. The quality of the clinker is highly dependent on the stability of the combustion process. The presence of harmful compounds, such as chlorine and heavy metals, in RDF can disrupt temperature stability and chemical reactions in the kiln, which can negatively affect clinker quality. This, in turn, impacts both the quality of the cement produced and the energy efficiency of the plant.

Using RDF as a substitute for coal requires adjustments to kiln equipment design and operational conditions. Cement kilns originally designed for coal may need modifications to ensure that RDF burns efficiently and to mitigate the impact of harmful compounds. These adjustments may include optimizing temperature and heating times in the kiln, as well as improving control over the composition of RDF to minimize potential disruptions in the clinkerization process. Such modifications aim to ensure that the combustion process remains efficient and that the clinker yield meets quality standards.

The development trajectory of RDF production capacity at Indocement, as summarized in Table 2, illustrates a significant and continuous increase from its initial establishment in 2008 until the projected target in 2030. Starting with a modest capacity of only 0.5 tons per day, the facility has steadily expanded through successive revitalization stages, reaching 10 tons per day in 2023 and aiming for 30 tons per day by 2030. This progressive enhancement not only reflects technological and operational improvements but also signifies the company's commitment to scaling up its waste-to-energy initiatives in response to both local and global environmental challenges.

The refuse-derived fuel waste management program implemented by Indocement in Cirebon represents more than an isolated environmental intervention; it constitutes a holistic model of integrated empowerment and policy alignment. Anchored within the broader corporate sustainability roadmap of Heidelberg Materials, the initiative strategically links local participatory action with global environmental targets, such as emission reduction, circular economy practices, and inclusive development.

This multidimensional framework resonates with the idea that organizations function not as closed entities but as adaptive systems continuously shaped by feedback from their external environment. In this case, community actors—including waste sorters, bank managers, and informal workers—act not only as beneficiaries but also as co-constructors of system evolution. The RDF model demonstrates dynamic interaction among corporate policy, participatory communication, stakeholder collaboration, and recursive feedback mechanisms, reinforcing adaptability and shared ownership.

Field data indicate that empowerment manifests across multiple, interconnected levels. At the individual level, the development of skills in sorting, weighing, and managing waste materials translates into concrete livelihood opportunities. At the institutional level, waste banks function as micro-hubs for capacity building and economic redistribution, channeling profits from sorted waste to support operational sustainability and provide community-based incentives.

These practices are consistent with Sen's (1999) capability approach, which conceptualizes empowerment not merely as access to resources, but as the expansion of real freedoms and practical opportunities that enable individuals and groups to attain well-being and exercise agency.

The program's dual payment mechanism—combining weight-based compensation with daily wages aligned to regional labor standards—enhances economic inclusion, particularly among informal and vulnerable labor segments. In the villages of Cupang and Kedungbunder, waste bank coordinators reported that well-sorted waste consistently yields higher market value, with resulting profits reinvested into

Table 2
RDF daily production capacity development at UPS Palimanan Barat.

Year	Production Capacity (Ton)	Information
2008	0.5	RDF production capacity at the beginning of establishment
2021	5	Average capacity before revitalization
2022	7	Average capacity after revitalization
2023	10	Daily capacity to date
2030	30	The expected future target has been achieved in 2030

community welfare initiatives, environmental education, and equipment maintenance. These mechanisms contribute to the institutionalization of empowerment, transforming it from sporadic training interventions into embedded operational norms.

These findings underscore the pivotal role of institutional trust and shared social norms in sustaining behavioral change in waste management. Community-based infrastructures, such as waste banks, often function as social anchors—encouraging collective responsibility and reinforcing long-term habit transformation. Likewise, Fakhrzad and Verma (2025) highlight the importance of cooperative economic systems and structured incentive models in transitioning informal waste practices into resilient value chains—an attribute clearly observable in the RDF Indocement case.

Furthermore, the program's governance model is distinguished by multi-level participatory structures, including Forum Bilikom, community meetings, and direct consultations with village leaders. These platforms enable multi-directional communication, supporting continuous dialogue and enhancing the system's adaptability to changing local conditions. By incorporating bottom-up feedback into top-down strategic planning, the RDF program exemplifies responsive governance, as opposed to rigid policy enforcement.

These economic and institutional arrangements underscore the program's novelty in integrating livelihood creation with environmental governance. By embedding dual payment mechanisms and participatory financial models, the RDF initiative not only incentivizes waste sorting but also builds economic resilience among marginalized communities. This dual approach aligns with Sen's (1999) capability framework and complements circular economy principles by turning waste management into an inclusive economic opportunity rather than a purely environmental obligation.

Furthermore, the incorporation of local governance platforms, such as waste banks and community forums, illustrates a practical application of co-governance models, enabling communities to actively influence program design and benefit distribution. In such settings, the combination of economic incentives and social trust has proven effective in sustaining long-term behavioral change and enhancing institutional resilience—particularly when participation is embedded within culturally familiar mechanisms of collaboration and accountability.

The Cirebon case thus advances a hybrid model that bridges global ESG imperatives with localized empowerment strategies, offering valuable insights for future policy design in other developing countries. From a sustainability science perspective, the RDF program exemplifies the integration of environmental, social, and governance (ESG) principles, as advocated by Harfadli et al. (2025), who emphasize the need for synergistic models that do not isolate environmental responsibility from broader social and economic imperatives.

Indocement's RDF initiative advances this vision by aligning corporate climate action strategies—such as reducing fossil fuel dependency—with community development priorities, including livelihood creation, waste literacy, and infrastructure support. Importantly, this approach is not without precedent; however, it adds value by illustrating how global ESG imperatives can be translated into community-driven solutions through locally embedded governance structures. In doing so, the RDF model contributes to ongoing debates on inclusive sustainability transitions, particularly in contexts marked by informal labor systems, limited institutional capacity, and pronounced resource asymmetries.

4. Conclusion

This study has examined the dynamics of community empowerment within the refuse-derived fuel waste management program implemented by Indocement in Cirebon, Indonesia. The findings suggest that the program represents more than a technical response to waste; it constitutes a hybrid governance model that integrates environmental stewardship, corporate social responsibility, and local community engagement into a cohesive and adaptive system.

The model operates across multiple levels: individual empowerment through skills development and dual-payment mechanisms; institutional strengthening through waste banks and community-based roles; and systemic feedback via participatory forums and policy responsiveness. Collectively, these mechanisms illustrate a transition from linear, top-down CSR interventions toward a co-evolutionary system of shared governance and continuous learning.

The implications of this model suggest its applicability beyond the immediate Indonesian context, particularly in other Global South regions where informal labor structures and limited infrastructure present similar challenges. Future research could examine the scalability of this model through cross-site comparative studies and mixed-method evaluations that assess long-term behavioral and environmental impacts.

Theoretically, this study contributes to the application of open systems theory by demonstrating how recursive feedback between corporate structures and local actors enhances adaptability and institutional resilience. It further operationalizes the capability approach within the context of the circular economy, wherein empowerment is conceptualized as the expansion of real freedoms to act, choose, and participate meaningfully in sustainable practices.

Comparatively, the Indocement model distinguishes itself from many global RDF initiatives by prioritizing social architecture and participatory governance over purely technical optimization. Within the Indonesian context, it addresses the limitations of technocratic waste management strategies that often overlook informal labor dynamics and community inclusion.

Recommendation

Based on the research findings, the following recommendations are proposed:

For policymakers

Adopt integrated waste governance frameworks that align environmental objectives with principles of social inclusion. Future RDF and waste management policies should embed empowerment components and ensure institutional sustainability beyond the pilot phase.

For corporations/CSR practitioners

Reframe corporate social responsibility not as philanthropy, but as a co-governance mechanism. Corporations are encouraged to institutionalize feedback loops, co-develop programs with local stakeholders, and invest in long-term empowerment infrastructure, such as waste banks and community-based forums.

For community organizations

Strengthen local organizational capacity by formalizing operational roles, enhancing skills development initiatives, and promoting peer-to-peer learning among waste bank managers. Establishing institutional networks at the village level can amplify community voices and increase legitimacy in policy dialogues.

For future research

Conduct comparative studies to assess the scalability and adaptability of this empowerment model across regions with diverse socio-economic and cultural conditions. Mixed-method approaches are also recommended to complement qualitative insights with quantitative evaluations of environmental and economic impact.

Limitations of the study

This study is limited by its single-case focus on the RDF program in Cirebon, which may constrain the generalizability of the findings to contexts lacking corporate-driven CSR frameworks. Data were collected within a specific timeframe, restricting insights into long-term institutional adaptation. The analysis is primarily qualitative, without quantitative validation of environmental or economic impacts. In addition, perspectives from certain stakeholders—such as regional policymakers and private waste operators—were not fully represented. While the study engages with circular economy principles through the lens of RDF and community empowerment, broader upstream and systemic dimensions fall outside its analytical scope.

These limitations highlight important avenues for future research to deepen understanding and support the replication of the model. Specifically, the study's single-case design and qualitative nature limit the generalizability of findings. Future studies should employ comparative and longitudinal methods, integrate quantitative measures of RDF performance and empowerment outcomes, and incorporate perspectives from a broader range of stakeholders.

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CRediT authorship contribution statement

Mahendra Wijaya: Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Dikhorir Afnan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Agung Wibowo:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Drajat Tri Kartono:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

Generative AI and AI-assisted technologies were utilized during the writing process to enhance the readability and linguistic quality of the manuscript. These technologies were implemented under strict human oversight and control. The authors thoroughly reviewed and carefully edited all AI-generated content to avoid authoritative-sounding text that could potentially be incorrect, incomplete, or biased. The authors bear full responsibility for the final content of this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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