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Cost-benefit analysis of waste management at Rawa Kucing landfill using refuse-derived fuel (RDF) method

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ABSTRACT

Background: This study addresses the complex challenges of waste management at the Rawa Kucing Landfill in Indonesia, highlighting the need for sustainable solutions such as Refuse-Derived Fuel (RDF) to reduce reliance on landfills and mitigate greenhouse gas emissions. Ineffective waste management, environmental pollution, and limited infrastructure underscore the urgency for methods that can effectively reduce waste volume and promote renewable energy. The study aims to evaluate the feasibility of RDF in waste management by assessing its economic, environmental, and health benefits. Using circular economy theory and cost-benefit analysis (CBA), RDF is evaluated for its potential in carbon reduction, renewable energy production, and sustainability. **Methods:** The study employs a cost-benefit analysis (CBA) framework to assess the economic, environmental, and health impacts of implementing RDF at the Rawa Kucing Landfill. Data collection includes waste volume, operational costs, and environmental impact metrics, while analytical methods focus on quantifying the benefits of RDF in terms of waste reduction, energy production, and emission reductions. **Findings:** The findings reveal significant benefits of RDF in reducing landfill waste, improving management efficiency, and providing an alternative energy source. Economic benefits, such as revenue from RDF sales, and environmental benefits, including reduced greenhouse gas emissions, are substantial. Additionally, RDF can mitigate health risks by reducing pollution from well-managed waste piles. RDF proves to be an effective and economically viable waste management alternative compared to conventional methods. **Conclusion:** The study concludes that RDF is a sustainable and economically beneficial solution for waste management at the Rawa Kucing Landfill. It recommends expanding RDF adoption across landfills in Indonesia and increasing public awareness of its benefits. **Novelty/Originality of this article:** This study contributes to the field by providing a comprehensive cost-benefit analysis of RDF implementation in a developing country context, offering new insights into its economic and environmental feasibility.

KEYWORDS: cost-benefit analysis; refuse-derived fuel; landfill; waste management.

1. Introduction

The issue of waste management in Indonesia has become a complex and urgent matter, considering its significant impacts on the environment and society, as well as the need for sustainable solutions. The amount of waste generated continues to increase alongside population growth, urbanization, and changing consumption patterns (Lestari & Trihadiningrum, 2019; Mustafa et al., 2022). Indonesia faces significant challenges in waste management, particularly in the context of rapidly growing urban waste, which has serious environmental and public health impacts. The total volume of waste produced has reached 64 million tons per year, yet only a small portion is effectively managed through recycling

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or processing, while the majority is transported to open landfills (Kurniawan et al., 2022; Lestari & Trihadiningrum, 2019). This has led to a worsening waste management crisis in Indonesia, especially in densely populated urban areas. Urban waste generation has reached alarming levels, driven by rapid urbanization and changing consumption patterns, ultimately increasing waste volumes. According to a 2024 report, reliance on landfills remains dominant in waste disposal strategies, resulting in methane emissions that have the potential to contribute 21 times more to global warming than CO_2 (Mustafa et al., 2022; Nurhasanah et al., 2021). Based on SIPSN data, waste generation in 2023 increased by 0.42% compared to 2022, with the composition of waste in 2023 consisting of food waste (39.82%), wood/twigs (11.77%), paper/cardboard (10.86%), plastic (19.19%), metal (3.23%), fabric (2.95%), rubber/leather (2.55%), glass (2.74%), and others (7.16%). Most of the waste in Indonesia (60-85%) is not properly processed but is instead dumped into Final Disposal Sites (TPA) or the surrounding environment (Bramantya et al., 2024). The condition of waste management in Indonesia is further complicated by various structural issues, such as a lack of public awareness, limited budgets, and inadequate waste management infrastructure. Although several community-based programs and recycling technologies have been implemented in regions like Sleman and Malang, their effectiveness remains limited due to the gap between operational costs and revenue from waste management (Budihardjo et al., 2023). This situation exacerbates Indonesia's waste management crisis, necessitating sustainable and innovative solutions to reduce its environmental and public health impacts.

In addressing these challenges, Refuse-Derived Fuel (RDF) offers an innovative solution by converting non-recyclable solid waste into alternative fuel. RDF has the potential to reduce the amount of waste sent to landfills and generate renewable energy from high-calorific waste such as plastic, paper, and textiles. This process aligns with the principles of the circular economy, which emphasizes optimal resource recovery and reduces dependence on fossil fuels (Prismantoko et al., 2024; Zubir et al., 2024). Studies show that RDF can replace fossil fuels in industries, reduce greenhouse gas emissions, and decrease reliance on limited resources (Kurniawan et al., 2024; Sari et al., 2024). Additionally, RDF has a high calorific value, making it capable of producing economical and environmentally friendly energy compared to conventional fuels (Ishaq & Dincer, 2024; Sanongraj et al., 2023).

The use of Refuse-Derived Fuel (RDF) in waste management demonstrates significant environmental benefits across various aspects. Based on Life Cycle Assessment (LCA) analysis, the use of RDF as an alternative fuel in cement production can reduce environmental burdens by up to 7.86% compared to conventional methods, particularly in terms of CO_2 and methane emissions, both of which play a major role in global warming (Liang et al., 2023). In Thailand, the use of RDF in national waste management schemes has significantly reduced environmental costs and become a primary choice for managing combustible wast. Additionally, the utilization of RDF in open landfills through open-pit mining techniques shows high resource recovery potential, reducing the need for landfill areas and lowering greenhouse gas emissions such as methane from organic waste decomposition (Boonsakul et al., 2023). In India, studies show that this method can also reduce CO_2 emissions by up to 285 kg per ton of processed waste (Pujara et al., 2023). Overall, RDF offers air pollution reduction, landfill space savings, and contributions to clean energy transitions by utilizing waste as an energy source (Jaisue et al., 2024).

However, integrating RDF into waste management is not without challenges, particularly regarding cost-effectiveness and efficiency. RDF production requires significant investment in sorting, processing, and quality control to ensure the fuel meets industrial standards and minimizes emissions during combustion (Zubir et al., 2024). Economic assessments of similar projects show that while RDF production can reduce certain environmental impacts, the initial infrastructure and operational costs are substantial. A study in Brazil indicates that although RDF provides environmental benefits, its infrastructure and operational costs are high, necessitating comprehensive cost-benefit evaluations before widespread adoption.

Based on data from the National Waste Management Information System (SIPSN) since 2021, Refuse-Derived Fuel (RDF) has been optimized in several provinces in Indonesia, ranging from large to small scales. By 2023, nine provinces in Indonesia have implemented RDF, including the Special Capital Region of Jakarta, West Java, East Java, Central Java, Banten, Bali, South Kalimantan, West Kalimantan, and North Sumatra. The Integrated Waste Processing Facility (TPST) RDF Cilacap in Central Java has been able to manage 100% of incoming waste, amounting to 29,098 tons/year, while the RDF Reduce, Reuse, and Recycle Waste Processing Facility (TPS3R) Rejo Lestari in South Kalimantan manages 0.003% of incoming waste, amounting to 1,277,500 tons/year. In Tangerang City, SIPSN data for 2023 recorded total waste generation reaching 514,478 tons annually, equivalent to 1,409 tons per day. The dominant waste composition is food waste (57.65%), plastic (19.66%), and paper/cardboard (13.18%), most of which can be processed into RDF to utilize the high calorific value of these materials (Mustafa et al., 2022; Zubir et al., 2024). With this composition, RDF not only serves as a solution to reduce landfill waste but also offers economic benefits through the conversion of waste into efficient and environmentally friendly renewable energy. This aligns with the principles of the circular economy in waste management, reducing reliance on conventional landfills and supporting greenhouse gas emission reductions (Kurniawan et al., 2024; Prismantoko et al., 2024).

The Rawa Kucing Landfill, located in Benda District, Tangerang City, Banten Province, has been operational since 1992 as a final waste processing facility for Tangerang City and its surroundings. Covering an area of approximately 34.8 hectares, the landfill receives domestic solid waste from 13 districts, including household, industrial, and commercial waste. With population growth and urbanization, the volume of waste entering the landfill has increased significantly. According to Aminullah (2023), during its 32 years of operation, the Rawa Kucing Landfill has experienced at least 10 fires, reducing the landfill area by 80% of its total land area. In addressing these issues, the utilization of Refuse-Derived Fuel (RDF) at the Rawa Kucing Landfill offers an innovative solution to reduce waste volume, generate renewable energy, and suppress greenhouse gas emissions by converting waste into fuel. Environmental impact analysis shows that RDF can be a sustainable alternative in urban waste management, supporting Indonesia's low-emission development targets (Mustafa et al., 2022), and reducing reliance on conventional landfill areas. By utilizing RDF, the Rawa Kucing Landfill is expected to reduce environmental pollution while creating additional economic value.

1.1 Literature Review

In 1987, the Brundtland Commission formulated the concept of sustainable development, which means meeting the needs of the present without compromising the ability of future generations to meet their own needs, by maintaining a balance between economic growth, social equity, and environmental protection (Kates et al., 2005). In the context of cost-benefit analysis (CBA) for waste-derived fuel (RDF) programs, the application of sustainable development principles is crucial. CBA must consider the interconnections between economic, social, and environmental goals by integrating environmental costs related to greenhouse gas (GHG) emissions and other impacts. This ensures that economic growth does not come at the expense of environmental integrity or social equity. Stakeholder engagement is also an essential element in the decision-making process, reflecting diverse values and perspectives. Long-term planning must account for sustainability and intergenerational equity. Additionally, integrating sustainable development indicators into the CBA framework can provide a clearer understanding of the benefits and trade-offs associated with RDF programs, leading to more sustainable waste management practices.

Cost-Benefit Analysis (CBA) is a systematic approach used to evaluate the economic impacts of decisions, projects, or policies by comparing the associated costs and benefits. The core of CBA is calculating and comparing expected positive outcomes (benefits) with potential losses (costs), formulated as Net Benefit (NB) where NB = Total Benefits - Total

Costs. CBA often uses the concept of Net Present Value (NPV) to account for the time value of money.

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

(Eq. 1)

In the Net Present Value (NPV) formula, Ct refers to the cash flow received at time t. The discount rate used in this calculation is r, reflecting the expected rate of return. Furthermore, n represents the total number of periods analyzed, which can be years, months, or other time units. Meanwhile, t is the time period starting from 0 to n, covering all time points in the cash flow analysis. A positive NPV indicates that benefits exceed costs after accounting for the time value of money. Additionally, CBA uses the Benefit-Cost Ratio (BCR) as a metric, where a BCR greater than 1 indicates that the investment is potentially profitable.

$$BCR = Total\,Benefits/Total\,Costs$$

$$BCR = \frac{\sum_{t=0}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}$$

(Eq. 2)

In the Benefit-Cost Ratio (BCR) formula, Bt represents the benefits obtained at time t. On the other hand, Ct refers to the costs incurred at the same time, t. By comparing total benefits with total costs at each period, BCR provides an overview of the economic feasibility of a project or investment. This method is crucial in assessing public policies and investments because it provides a structured evaluation framework for considering social impacts. In environmental projects, such as waste-to-energy (WTE) initiatives and the use of Refuse-Derived Fuel (RDF), CBA is often complemented by Life Cycle Assessment (LCA) to provide a comprehensive assessment by integrating environmental impacts alongside economic outcomes. This is evident in the study by Li et al. (2024), which uses CBA and LCA to evaluate RDF production options from plastic waste, considering costs such as raw materials, operations, labor, and energy, as well as revenue from outputs like electricity, oil, and recycled materials.

Refuse-Derived Fuel (RDF), a fuel produced from municipal solid waste (MSW) through carbonization, is increasingly recognized for its potential in industrial applications. According to Han et al. (2021), RDF can replace traditional fuels like coke breeze in processes such as iron ore sintering due to its similar calorific value and composition. RDF-500, produced by pyrolyzing MSW at 500°C, contains high volatile matter and lower fixed carbon, making it an effective partial substitute for coke breeze in steel production. Other studies explore RDF in integrated WTE facilities. For example, Armoo et al. (2024) propose a hybrid WTE facility for Ghana that combines solar PV, anaerobic digestion, and pyrolysis to convert MSW into electricity, hydrogen, bio-CNG, compost, and RDF. The facility is projected to process 1.6 million tons of MSW annually, demonstrating strong financial viability (NPV EUR 397–1,030 million and IRR 14–22%) and significant environmental benefits through reduced landfill waste and GHG emissions, aligning with sustainable urban development goals.

Further research by Rahothan et al. (2023) focuses on RDF production from landfill waste in Nonthaburi, Thailand, addressing waste accumulation and energy demand. The study highlights the staged RDF production process, which effectively removes non-combustible materials to produce high-quality RDF with a high calorific value (18.08–29.41 MJ/kg), suitable for WTE applications. The high content of plastic, rubber, and textiles in RDF ensures significant energy output, contributing to the circular economy by reducing landfill volume, extending landfill lifespan, and lowering GHG emissions. Additionally, the economic and industrial relevance of RDF is emphasized as it serves as an alternative fuel in sectors like cement production and power generation, reducing dependence on fossil fuels. Overall, these studies illustrate the feasibility of RDF as a sustainable fuel source within the WTE framework, supported by CBA and LCA methodologies that validate its economic and environmental benefits.

In accounting for the benefits and costs of RDF processes, externalities must also be considered. Several studies have applied externality theory in cost-benefit analysis (CBA) to better address the environmental and social impacts of waste management and resource use. Egger and Keuschnigg (2024), in their work titled "Resource dependence, recycling, and trade," discuss how recycling can reduce economic dependence on raw materials and mitigate environmental degradation by internalizing positive and negative externalities related to waste disposal. They propose policies such as waste taxes and recycling subsidies to internalize these costs and benefits, thereby encouraging recycling behavior aligned with social welfare. This theory highlights that without corrective policies, free markets will generate excessive waste and insufficient investment in recycling. The application of financial incentives helps correct market distortions, promoting sustainability through optimal resource allocation.

Similarly, Chen et al. (2023) use externality theory to understand the environmental impacts of construction and demolition waste (CDW). Their study emphasizes that negative externalities arise when CDW disposal causes pollution and ecological damage, while positive externalities are created through environmentally friendly practices that enhance ecosystem services. They advocate for ecological compensation to internalize these externalities, where governments promoting environmentally friendly practices receive compensation for the ecosystem services provided, thereby encouraging cross-regional collaborative CDW management.

Additionally, Nik Ab Rahim et al. (2021) investigate the feasibility of sanitary landfill projects in Malaysia by integrating non-market environmental values into CBA. Highlighting the negative externalities of traditional landfills, such as pollution from leachate and health risks, they show that sanitary landfills create positive externalities by providing environmental benefits. Their study proposes non-market valuation to quantify these benefits and demonstrates that incorporating environmental values into CBA enhances the feasibility of sanitary landfills. Overall, these studies illustrate the importance of externality theory in internalizing environmental costs, supporting more sustainable and socially responsible waste management practices.

The literature on circular economy theory emphasizes its role in addressing environmental and economic impacts across various industries, including construction and plastics, which can be applied in RDF processes. Wouterszoon Jansen et al. (2020) introduce the Circular Economy Life Cycle Costing (CE-LCC) model, specifically designed to assess building components within a circular economy framework. This model aims to reduce the environmental footprint of the construction industry by integrating circular economy principles such as extended product lifespan, recycling, and waste reduction. Unlike traditional Life Cycle Costing (LCC), the CE-LCC model views products as composites of parts with different lifespans and incorporates post-use processes like repair, reuse, and recycling. The model also ensures that information is accessible to all stakeholders and aligns with Life Cycle Assessment (LCA) constraints to maintain consistency. To test the model's validity, a case study was conducted on the "Circular Kitchen" (CIK), comparing three CIK variants with different sustainability levels to a traditional kitchen model over 75 years. The results show that the most flexible CIK variant achieves the lowest life cycle costs, demonstrating its economic viability for long-term sustainability. Although further testing is needed, the CE-LCC model is proposed as an effective tool to support sustainable decision-making in the construction industry.

This paper asserts that circular economy theory promotes the adoption of regenerative systems to minimize resource use, waste production, emissions, and energy leakage by "slowing, closing, and narrowing material and energy flows." This approach reduces environmental impacts through improved resource efficiency and product life cycle sustainability. Key principles highlighted include material flows that extend product lifespan (slowing flows), recycling materials (closing flows), and achieving resource efficiency (narrowing flows). Sustainability in the built environment is highly relevant to the construction industry, given its high resource consumption and waste production. Circular economy theory aims to make construction practices more sustainable by reconsidering product life cycles and supply chains. Value Retention Processes (VRP)—such as reuse, repair, refurbishment, remanufacturing, and recycling—are crucial in the circular economy. These processes enable products and materials to retain their value through multiple use cycles. The transition to a circular economy also requires systemic changes in design, supply chains, and business models, including product designs that allow for disassembly, repair, and upgrades, enabling materials to be reintegrated rather than discarded. The CE-LCC model provides a practical assessment tool to guide stakeholders in evaluating the long-term costs and benefits of circular designs for building components, supporting a more sustainable approach in the construction industry.

In a related study, Klemeš et al. (2021) explore circular economy principles in the context of plastic use. They introduce a new concept, the Plastic Waste Footprint (PWF), to assess the net environmental impact of plastics by evaluating recycling, emissions, energy consumption, and disposal. The authors emphasize that circular economy principles—waste reduction, resource efficiency, and life cycle sustainability—are crucial for plastics. In the context of plastics, the circular economy involves reduction (designing products with fewer materials, promoting alternatives, and encouraging reusable goods to reduce single-use demand), reuse and repair (extending the lifespan of plastic products through reuse, repair, and refurbishment), recycling and recovery (improving recycling processes to efficiently recover materials), and preventing environmental leakage (ensuring plastics do not leak into oceans and ecosystems, as plastic waste, especially microplastics, harms marine and terrestrial environments). By adopting these principles, the environmental footprint of plastics can be minimized.

The Plastic Waste Footprint is recommended as a tool to assess and compare the environmental impacts of various plastic alternatives within a circular economy framework. This tool provides insights into optimal approaches for plastic reduction and recycling. Overall, Klemeš et al. advocate for the circular economy as a comprehensive strategy for managing plastic waste and its associated environmental burdens, supporting economic benefits through sustainable management practices. They emphasize the importance of policies and consumer awareness to increase recycling rates and reduce waste. Regulations promoting sustainable manufacturing practices and consumer education are seen as critical steps to transform plastics from "enemies" to "friends." The authors conclude that plastics can be environmentally sustainable if integrated into a well-managed circular economy, emphasizing proper disposal, recycling, and reducing single-use applications.

Life Cycle Assessment (LCA) is a comprehensive methodology used to assess the environmental impacts of a product, process, or service throughout its life cycle—from raw material extraction, production, use, to final disposal. LCA is also highly useful when adapted into the cost-benefit analysis (CBA) framework, particularly in evaluating Refuse-Derived Fuel (RDF) systems that convert waste materials into usable energy. In the context of RDF, LCA helps calculate the environmental benefits and costs of diverting waste from landfills, including savings from reduced emissions and the value of energy recovery.

The literature on Life Cycle Assessment (LCA) theory and frameworks highlights its critical role in evaluating the environmental impacts of various end-of-life (EOL) treatments and materials. Chen et al. (2019) explore the application of LCA in assessing the environmental impacts of EOL treatments for plastic waste in China, focusing on mechanical recycling, incineration, and landfilling. LCA proves to be an effective methodology for comprehensively analyzing the environmental costs and benefits of these methods, from resource use to emissions and final disposal impacts. The study finds that mechanical recycling offers the greatest environmental benefits by replacing virgin plastic needs, while landfilling generally has negative environmental effects across all indicators. To improve waste management, the study uses LCA to model various scenarios, such as increasing recycling rates, energy conservation, and emission control strategies.

In a related study, Stančin et al. (2023) use LCA to assess the environmental impacts of pyrolysis oil production through co-pyrolysis of biomass and plastic waste. By comparing co-pyrolysis with other EOL treatments like incineration and landfilling, the study finds that co-pyrolysis significantly reduces emissions. However, electricity consumption, particularly during the pyrolysis stage, emerges as a major contributor to environmental impacts, suggesting that integrating renewable energy can reduce the overall environmental footprint. By modeling various waste management scenarios, the study demonstrates that the benefits of co-pyrolysis vary across countries and practices. Additionally, LCA provides credits for the use of byproducts like syngas and char when they replace fossil fuels, enhancing the environmental profile of the co-pyrolysis process.

Finally, Sommerhuber et al. (2017) apply LCA to evaluate wood-plastic composites (WPC) made from virgin and recycled materials, assessing the environmental impacts throughout the product's life cycle, from raw material extraction to final disposal. Following ISO standards, the study examines metrics such as global warming potential (GWP), acidification, and eutrophication. The findings show that recycling WPC is the most environmentally friendly option as it reduces the need for virgin materials. The study integrates LCA at the product level, focusing on production impacts, and LCA at the system level, covering waste management pathways, providing a complete environmental profile from production to disposal. The study emphasizes the importance of LCA in understanding the sustainability of WPC, recommending recycling as the preferred EOL method and advocating for policies to strengthen recycling infrastructure.

In the context of renewable energy, it is important to analyze various energy sources and their conversion processes, including RDF. We can view RDF from the perspective of Energy Return on Investment (EROI), which provides insights into the efficiency and sustainability of these energy systems. The concept of EROI is crucial in evaluating the sustainability and economic feasibility of energy systems. In a study by Oliveira Neto & Correia (2019), the importance of economic metrics such as Return on Investment (ROI) and Internal Rate of Return (IRR) is emphasized, although EROI is not specifically discussed. ROI is defined as the return generated by an investment relative to the profitability of a company's assets, calculated using the formula:

$$ROI = \frac{LYP}{TI} \times 100$$

(Eq. 3)

where LYP is the net annual profit and TI is the total investment. Similarly, IRR measures profitability based on projected cash flows and is expressed as:

$$IRR = \left(\frac{LYP}{TI}\right) - r$$

(Eq. 4)

where rr is the discount rate. In contrast, Nam et al. (2020) provide a detailed analysis of EROI in the context of a hybrid biomass-fusion system integrated with solid oxide fuel cells (SOFC) and gas turbines. EROI is defined as the energy output over the life cycle divided by the energy input over the life cycle, expressed as:

$$EROI = \frac{E_g}{E_c + E_o + E_d}$$

(Eq. 5)

where Eg represents gross energy output, Ec is the energy input required for construction, EoEo is operational energy input, and EdEd is the energy required for decommissioning. The study finds that the EROI for the proposed system is 3.9, indicating that for every unit of energy invested, 3.9 units of energy are produced. This value is lower compared to conventional energy sources, highlighting the current limitations of hybrid systems. Additionally, EROI can vary significantly based on the costs associated with biomass feedstock, with sensitivity analysis showing a range between 2.6 and 5.9. Such variability reflects the impact of socio-economic factors on energy intensity and overall system efficiency. This analysis underscores the importance of EROI in assessing new energy technologies and emphasizes the need for further advancements to improve feasibility and sustainability.

The Polluter Pays Principle (PPP) is an important concept in environmental economics that emphasizes that those responsible for pollution should bear the costs of its management. In waste management, PPP serves as a framework for allocating environmental costs and responsibilities. Martínez-López et al. (2020) emphasize the importance of PPP in maritime waste management, particularly through Directive (EU) 2019/883, which regulates the management of sewage waste from ships. They argue that under the Cost Recovery System (CRS), fees for waste management services should reflect the costs incurred, ensuring that polluters are financially accountable.

However, the implementation of PPP faces challenges, as revealed by Gachenga (2022) in an analysis of textile and second-hand clothing (SHC) waste. He shows that current linear waste policies are inadequate, and waste management responsibilities are often shifted from consumer countries in the Global North to importing countries in the Global South, creating a "recycling fallacy." Gachenga criticizes existing waste management laws for failing to address the complexities of global supply chains.

Both papers advocate for a transition to a circular economy (CE) framework that emphasizes the entire product life cycle and propose integrating Extended Producer Responsibility (EPR) policies into PPP to enhance producer accountability. The link between PPP and Cost-Benefit Analysis (CBA) for RDF becomes clear, where CBA can evaluate the economic feasibility and environmental impacts of RDF production by incorporating environmental damage costs and potential social benefits. Additionally, the findings from both authors highlight the need for legal reforms to address the limitations of current PPP implementation. By adopting a life cycle approach within the circular economy framework, PPP can be applied more effectively, leading to better environmental outcomes and a fairer distribution of responsibilities among stakeholders.

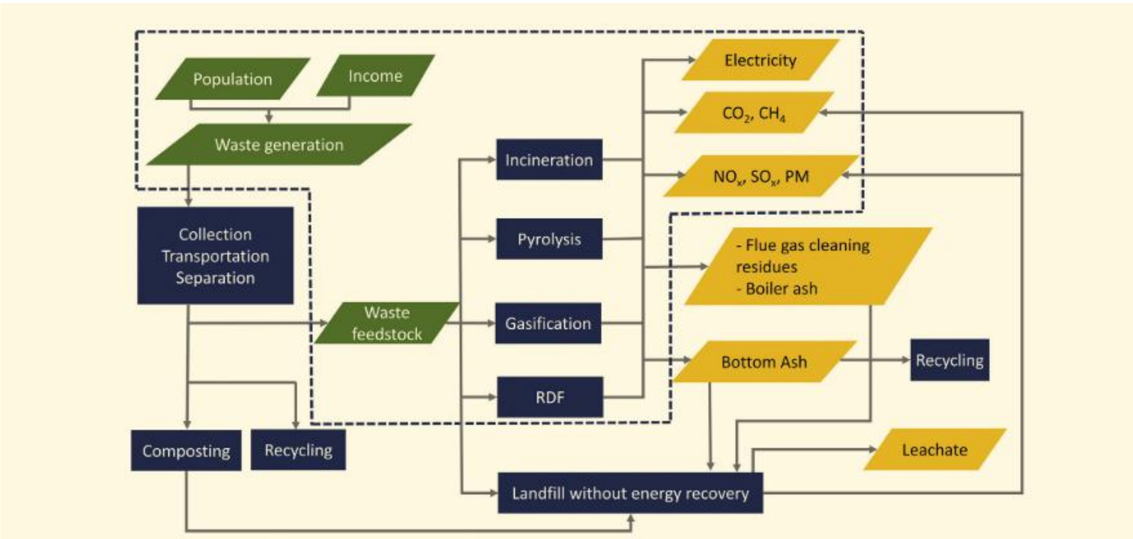

Fig. 1. The Waste to Energy Recovery Assessment (WERA) framework uses population, income, per capita waste generation, and demographic data as inputs and computes estimated electricity generation, emissions, and direct costs. The dotted lines depict the system boundary and encloses elements included in this study. Green parallelograms, blue boxes, and orange parallelograms represent input, technology (system equations), and output parameters respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig 1. WERA Framework
(Haraguchi et al., 2019)

Overall, PPP is an important framework for guiding waste management practices, particularly in the context of RDF research. Aligning PPP principles with CBA enables policymakers to better evaluate the economic implications of waste management strategies, ensuring that all costs and benefits are accounted for in promoting sustainable practices. The transition to a circular economy, supported by effective legal frameworks and EPR policies, can enhance the effectiveness of PPP and facilitate responsible waste management.

The social cost of carbon (SCC) is a crucial component in evaluating the economic feasibility of various waste management strategies, particularly in the context of waste-to-energy (WtE) systems and alternative organic waste management. In a paper by Haraguchi et al. (2019), the authors introduce the Waste to Energy Recovery Assessment (WERA) framework, which integrates SCC into cost-benefit analysis to assess the financial implications of WtE systems. This inclusion allows for a comprehensive evaluation by monetizing the environmental benefits associated with greenhouse gas (GHG) emission reductions, showing that GHG emission reductions, showing that GHG emission reductions from WtE facilities can be calculated and translated into monetary benefits, thereby enhancing their overall value. As seen in Figure 2, Haraguchi et al. develop a model to calculate the NPV of waste management technologies, with the NPV value formulated as follows.

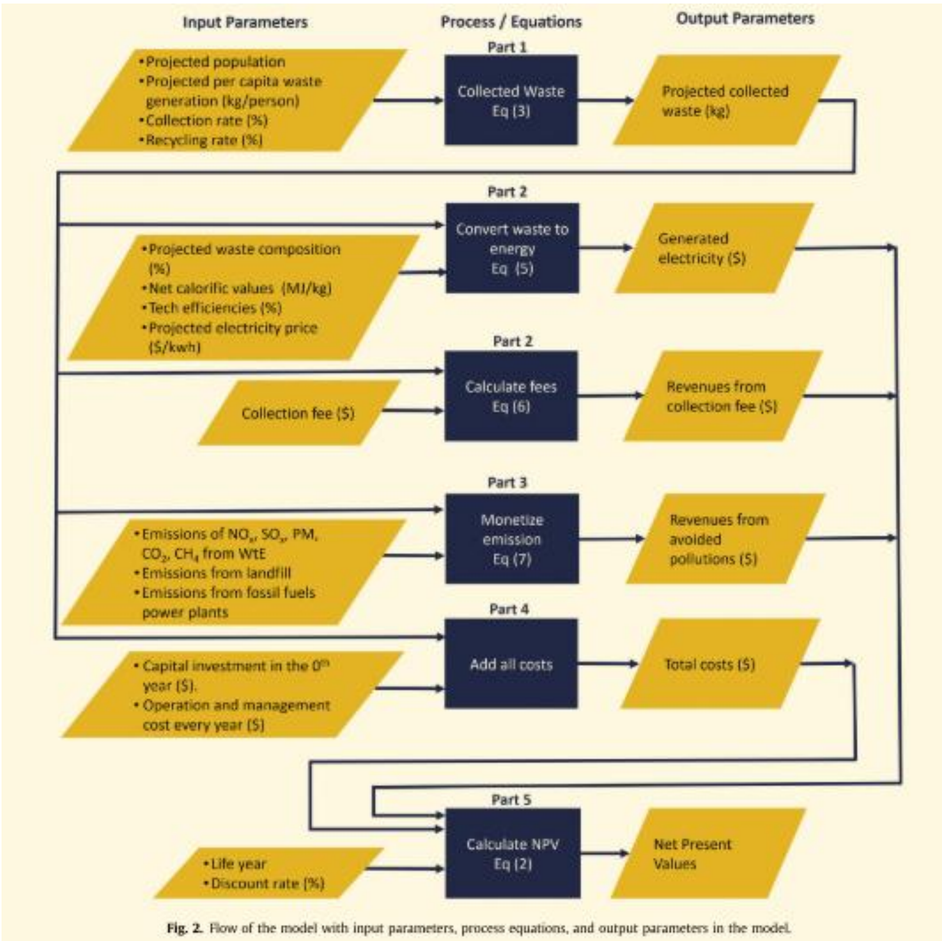

Fig. 2. Flow of the model with input parameters, process equations, and output parameters in the model.

Fig 2. NPV Calculation Flow Model

In contrast, the work by Nordahl et al. (2020) examines various organic waste management methods—such as landfilling, composting, and anaerobic digestion—and assesses their life cycle GHG emissions and associated human health impacts. The analysis finds that while composting can significantly reduce GHG emissions, it can also produce harmful air pollutants like ammonia (NH3), contributing to social costs related to health risks. By integrating SCC into their assessment, both studies emphasize the need for a holistic approach that evaluates the trade-offs between GHG emissions and health impacts, ultimately providing clearer insights into the true costs and benefits of various waste management strategies. Effective municipal solid waste (MSW) management is crucial for protecting public health, safeguarding the environment, and conserving natural resources. A study by Yang et al. (2024) explores the application of system dynamics (SD) modeling as a tool for predicting and managing MSW generation.

$$NPV_{tech} = \sum_{t=0}^{n} \frac{Benefit_{t,tech}}{(1+i)^t} - Capex_{tech} - \sum_{t=0}^{n} \frac{Opex_{t,tech}}{(1+i)^t}$$
(Eq. 6)

The study emphasizes the importance of developing accurate forecasting models that consider various influencing factors, including population growth, economic development, and waste management practices. Using VENSIM software, the researchers built a system dynamics model that integrates historical data to project future MSW generation from 2010 to 2030. The model predicts that MSW generation in Kaohsiung City will increase significantly, reaching approximately 3.04 million tons by 2030.

2. Methods

This study employs a comprehensive literature review combined with a cost-benefit analysis (CBA) framework to evaluate the feasibility of implementing Refuse-Derived Fuel (RDF) technology at the Rawa Kucing Landfill. The methodology is designed to systematically assess the economic, environmental, and social impacts of RDF adoption, drawing on existing research, case studies, and empirical data. The approach aligns with the principles of sustainable development and circular economy theory, ensuring a holistic evaluation of RDF's potential benefits and challenges.

The literature review component involves a systematic collection and analysis of peer-reviewed articles, government reports, and technical documents related to RDF technology, waste management practices, and their applications in developing countries, particularly Indonesia. Key databases such as Scopus, Web of Science, and Google Scholar were utilized to identify relevant studies published between 2019 and 2024. The selection criteria focused on articles addressing RDF production, environmental impacts, economic viability, and case studies of RDF implementation in landfill settings. This review provides the theoretical foundation for the CBA, highlighting gaps and opportunities in current waste management strategies.

For the cost-benefit analysis, quantitative data were collected from secondary sources, including the Ministry of National Development Planning (Bappenas) and the German Cooperation (GIZ), to estimate investment costs (CAPEX), operational expenses (OPEX), and projected revenues from RDF sales. Environmental benefits, such as reductions in CO_2 emissions and landfill land use, were quantified using standardized metrics, while health benefits were derived from epidemiological data and treatment cost estimates. The analysis employed financial indicators such as Net Present Value (NPV), Economic Internal Rate of Return (EIRR), and Benefit-Cost Ratio (BCR) to evaluate the project's feasibility. Sensitivity analyses were conducted to account for uncertainties in cost and benefit projections, ensuring robust conclusions. Together, these methods provide a rigorous assessment of RDF's potential to transform waste management at the Rawa Kucing Landfill.

3. Results and Discussion

3.1 Existing Conditions of Waste Processing Facilities

The Rawa Kucing Landfill, located in Tangerang City, Banten Province, is one of the largest final waste processing facilities in Indonesia, covering an area of approximately 38 hectares. The landfill receives over 1,500 tons of waste daily from various sources, including household, commercial, and industrial waste. The high accumulation of waste, with piles reaching up to 25 meters in some areas, has worsened the landfill's physical condition and increased the risk of environmental pollution (Maulidah et al., 2023). Currently, waste management at the Rawa Kucing Landfill is still dominated by the landfill system, which causes air pollution, groundwater contamination, and disrupts the landscape's aesthetics. Frequent fires caused by methane gas accumulation from organic waste not only endanger the local ecosystem but also negatively impact the health of surrounding communities, particularly through increased air pollution (Aminullah, 2023). Another major issue at the Rawa Kucing Landfill is the drainage and leachate management system. During the rainy season, leachate from waste piles often overflows and contaminates nearby rivers and water bodies. Efforts to improve the leachate treatment system have been made, but pollution persists due to the large volume of waste and suboptimal management capacity. This leachate pollution has serious impacts on groundwater quality and the health of nearby communities (Bramantya et al., 2024). This situation highlights the need for sustainable solutions that not only reduce the volume of waste entering the landfill but also mitigate its negative environmental impacts.

The Rawa Kucing Landfill was initially built to accommodate waste from Tangerang City and its surroundings. However, over time, the volume of waste received by the landfill has increased significantly. Data from Maulidah et al. (2023) shows that the volume of waste entering the landfill in 2020 reached 474,846 tons, increased to 514,571 tons in 2021, and slightly rose to 514,582 tons in 2022. This increase aligns with population growth and economic activity in the region, causing the Rawa Kucing Landfill to exceed its capacity. Without effective solutions, this condition could accelerate the landfill's overcapacity and lead to worse environmental impacts in the future (Mustafa et al., 2022).

In an effort to manage the increasing volume of waste, the Tangerang City Government has divided waste transportation to the Rawa Kucing Landfill into two zones: the western and eastern regions, with a total transportation of approximately 1,350 tons of residue per day. Waste arriving at the Rawa Kucing Landfill is processed using sanitary landfill and open dumping methods. In some areas, waste is leveled and compacted using heavy equipment, then covered with soil and geomembranes to reduce odor and inhibit fly breeding. A leachate management system and methane gas management facilities have also been built to reduce negative environmental impacts. However, most areas still use the open dumping method, which is prone to environmental pollution, indicating the need for a full transition to the safer and more environmentally friendly sanitary landfill method (Aminullah, 2023; Bramantya et al., 2024).

As part of initiatives to reduce the amount of waste entering the landfill, the Tangerang City Government has initiated a Waste-to-Energy Power Plant (PLTSa) project. This project aims to process up to 2,000 tons of waste per day with a power generation capacity of 13.5 MW, which is expected to support more efficient waste management and contribute to the transition to renewable energy (SIPSN, 2023). In addition to the PLTSa, the government is also developing community-based waste management initiatives through the Reduce, Reuse, and Recycle Waste Processing Facility (TPS3R) program, which aims to sort and process waste at the community level before sending it to the landfill. However, infrastructure and funding limitations remain the main challenges in implementing this program (Budihardjo et al., 2023). The use of Refuse-Derived Fuel (RDF) at the Rawa Kucing Landfill provides a sustainable approach to waste management while reducing GHG emissions. RDF technology allows the conversion of non-recyclable solid waste, such as plastics and textiles, into high-calorific alternative fuels that can replace fossil fuels. This technology aligns with the principles of the circular economy, which aims to minimize waste and maximize resource utilization (Zubir et al., 2024).

The PLTSa project being developed at the Rawa Kucing Landfill, combined with the use of RDF, is expected to optimize the use of waste as a renewable energy source. The implementation of RDF will not only reduce the volume of waste entering the landfill but also make a significant contribution to reducing carbon emissions and environmental pollution, while generating electricity for local needs. By leveraging the potential of RDF, the Rawa Kucing Landfill can become a model for sustainable waste management in Indonesia, addressing both waste overcapacity and providing alternative energy that supports lowcarbon emission targets (Maulidah et al., 2023; Prismantoko et al., 2024). The use of RDF at the Rawa Kucing Landfill can reduce reliance on high-risk open dumping methods and improve waste management efficiency through renewable energy utilization. Therefore, RDF plays a crucial role in transforming waste management systems in Indonesia, particularly at the Rawa Kucing Landfill, from conventional final disposal models to circular economy models focused on waste reduction and energy resource conservation.

3.2 Cost and Benefit Analysis of Refuse-Derived Fuel

3.2.1 Investment Costs (Capital Expenditure)

The initial investment costs required to build Refuse-Derived Fuel (RDF) facilities in several planned regions, based on the 2023 RDF Potential Analysis Study prepared by GIZ (German Cooperation) and the Ministry of National Development Planning (Bappenas), are as follows (GIZ & Bappenas, 2023):

Table 1. RDF development plan by the Ministry of Public Works and Housing

No	RDF Plant	RDF Product (Tons/Day)	Investment Cost (IDR)	Operation & Maintenance (IDR/Ton Waste)
1	Tuban Regency	50	110,000,000,000	125,000
2	Cirebon City	80	208,000,000,000	173,000
3	Bogor Regency	54	157,000,000,000	167,000
4	Bandung City (Cicabe)	30	16,306,247,500	162,758
5	Bandung City (Cicukang)	18	9,852,416,500	201,523
6	Karawang Regency	30	17,944,927,500	162,758
7	Purwakarta Regency	30	14,214,736,500	162,758

Thus, for an RDF product of 600 tons per day from a total waste generation of 1,500 tons per day, the planned investment cost (CAPEX) for building the RDF facility at the Rawa Kucing Landfill is IDR 1,095,859,578,082, or approximately IDR 1.1 trillion. This cost is an assumption of the total investment cost for equipment, installation, and training, covering the basic needs for building and operating the RDF facility at the Rawa Kucing Landfill.

Based on Table 1, for an RDF product of 600 tons per day from a total waste generation of 1,500 tons per day, the annual operational cost (OPEX) for the RDF facility at the Rawa Kucing Landfill is IDR 36,128,649,000, or approximately IDR 36 billion. This cost covers the overall operational costs of machinery, labor, maintenance, and upkeep, which are essential to ensure the RDF facility operates optimally and efficiently at the Rawa Kucing Landfill.

3.2.2 Benefits and health benefits

The economic benefits of processing waste into RDF at the Rawa Kucing Landfill come from potential revenue through the sale of RDF as an alternative fuel for industries. Based on Table 1, the RDF facility at the Rawa Kucing Landfill is capable of producing 40% of the total waste generated, amounting to 600 tons of RDF per year, and has the potential to generate revenue for Tangerang City of IDR 50,000,000,000 per year (GIZ & Bappenas, 2023). This not only provides direct revenue for the landfill management but also reduces dependence on fossil fuels, supporting the transition to clean energy for industries that adopt it.

Waste management through RDF has positive health impacts for surrounding communities. Reducing the volume of waste dumped decreases methane emissions, a greenhouse gas and harmful pollutant, and prevents open burning, which often produces toxic pollutants such as carbon monoxide (CO), sulfur dioxide (SO_2), and volatile organic compounds (VOCs). This can reduce the potential for respiratory diseases (ARI) and gastrointestinal infections caused by groundwater or surface water contamination from leachate at the landfill site. Based on data from the Central Statistics Agency, the population of Tangerang City in Neglasari District in 2023 was 124,907, with an estimated 10-30% of the population at risk of direct exposure to respiratory and digestive diseases. Additionally, the estimated cost of treatment for gastrointestinal diseases such as diarrhea is IDR 1,562,950 per person per year (Gunawan et al., 2022). Furthermore, the cost of treatment for respiratory diseases (ARI) is IDR 2,693,417 per person per year (Wardhani et al., 2024). The following table shows the health benefits of RDF as follows.

Table 2. Health benefits of RDF

No	Description	Unit	Amount
1	Population of Neglasari District (2023)	People	124,907
2	Potential risk of respiratory and digestive diseases (15% of population)	People	18,736
3	Estimated treatment cost for gastrointestinal diseases (Diarrhea)	IDR/Person/Year	1,562,950
4	Estimated treatment cost for respiratory diseases (ARI)	IDR/Person/Year	2,693,417
5	Average treatment cost for gastrointestinal and respiratory diseases	IDR/Person/Year	2,128,184
6	Total treatment cost for gastrointestinal and respiratory diseases	IDR	39,873,752,465

Thus, the overall health benefits of using RDF at the Rawa Kucing Landfill amount to IDR 39,873,752,465, or approximately IDR 40 billion annually.

3.2.3 Environmental benefits

The use of Refuse-Derived Fuel (RDF) as a waste management solution in Indonesia, such as at the Bantargebang Integrated Waste Processing Facility (TPST), provides significant environmental benefits, particularly in terms of carbon emission reduction. Based on research, RDF used in co-firing processes in the cement industry has the potential to reduce carbon dioxide (CO_2) emissions by 1.75 tons of CO_2 per ton of RDF. In practice, this means that every time RDF replaces fossil fuels such as coal, the carbon emissions produced by the industry are substantially reduced. This process not only supports national emission reduction targets but also provides a more environmentally friendly energy alternative and reduces dependence on fossil fuels (GIZ & Bappenas, 2023). The following table shows the environmental benefits of reducing CO_2 emissions, with an estimated social cost of carbon (SCC) of USD 50/ton CO_2.

Table 3. Environmental benefits of CO_2 emission reduction

No	Description	Unit	Amount
1	RDF Product Produced	Tons	600
2	CO_2 Emissions Eliminated	Tons CO_2/Ton RDF	1.75
3	Annual CO_2 Calculation	Tons CO_2/Year	1,050
4	Environmental Benefit Calculation	IDR	287,437,500,000

In addition to emission reduction benefits, the implementation of RDF also contributes to land use efficiency, which is a major challenge in landfill management. By processing waste into RDF, the Bantargebang TPST has successfully reduced the volume of waste sent to landfills by up to 40%, directly extending the landfill's lifespan and reducing the need for new land. This RDF is then used as a substitute for coal in the cement industry, reducing waste accumulation and associated environmental impacts such as groundwater and air pollution. Reducing landfill land use is particularly important for cities with limited land availability, making RDF an effective solution for maintaining sustainable waste management in Indonesia (GIZ & Bappenas, 2023; Jakita, 2023). The following table shows the environmental benefits of land use savings.

Table 4. Environmental benefits of land use savings

No	Description	Unit	Amount
1	Area of Rawa Kucing Landfill	Hectares	38
2	Potential Land Reduction (50%)	Hectares	19
3	Land Use Savings	IDR	258,400,000,000

Thus, the overall environmental benefits of using RDF at the Rawa Kucing Landfill amount to IDR 545,837,500,000, or approximately IDR 550 billion annually.

Cost-Benefit Analysis (CBA) is used to assess the feasibility and economic and environmental impacts of implementing RDF at the Rawa Kucing Landfill. This analysis includes detailed calculations of costs, such as initial investment, operational, and maintenance costs, as well as benefits, including RDF revenue, carbon emission reductions, reduced landfill land requirements, and health benefits for the surrounding community. This approach provides an overview of the long-term effectiveness of RDF, helping stakeholders understand the potential returns and environmental contributions of the project, and supporting sustainable decision-making.

3.3 Net present value (NPV)

The Net Present Value (NPV) of IDR 4,068,853,161,934, or approximately IDR 4.1 trillion, from the use of RDF indicates that the investment in the RDF facility at the Rawa Kucing Landfill shows that the financial and economic benefits of the RDF project significantly outweigh the costs incurred. This very high NPV indicates that the RDF facility is not only financially profitable but also presents significant opportunities for efficiency in waste management, which has long been a heavy burden for major cities in Indonesia. Through significant savings in waste management costs, the RDF facility can reduce the operational expenditure typically spent on waste transportation and management at conventional landfills. Additionally, RDF can extend the landfill's lifespan by reducing the amount of waste that needs to be transported and processed conventionally, reducing pressure on the need for new land, which often disrupts the environment and causes conflicts with surrounding communities.

The reduction in landfill land use is an important aspect of this RDF investment, especially considering the increasing scarcity of land in urban areas and the high economic value of land savings. On the other hand, the substitution of RDF as an alternative fuel in industries adds significant economic value, as RDF can replace coal and other fossil fuels, which have high costs and significant environmental impacts. Investing in the RDF facility not only helps reduce dependence on fossil fuels but also contributes to Indonesia's targets in reducing carbon emissions through the reduction of greenhouse gases using alternative energy sources. The success of this project's NPV also indicates that RDF technology at the Rawa Kucing Landfill can become a sustainable and economically viable waste management model for application in other locations, providing long-term economic benefits for communities, governments, and industries.

3.3.1 Economic internal rate of return (EIRR)

The Economic Internal Rate of Return (EIRR) of 45%, which is higher than the Social Discount Rate (SDR) of 9%, indicates a very high potential return on investment. A high EIRR suggests that the RDF project is not only economically feasible but also has strong resilience to market fluctuations and potential cost increases during its operational period. The advantage of such a high EIRR indicates that the economic benefits of the RDF project will remain high even if there are changes in operational costs, such as energy prices, facility maintenance, or variations in revenue from the sale of RDF as an alternative fuel. This makes the RDF project at the Rawa Kucing Landfill more adaptable and resilient to external economic risks, such as increases in raw material prices or decreases in demand for fossil fuels.

With positive cash flow projections over 20 years, the RDF project at the Rawa Kucing Landfill provides high investment security and the potential for quick returns. This effort not only advances more efficient and sustainable waste management but also creates a stable long-term revenue source that can fund landfill operations and support various environmental programs in the future. Additionally, the high EIRR reflects the positive impact of RDF on environmental and economic aspects through improved waste management efficiency, reduced greenhouse gas emissions, and contributions to the provision of alternative fuels.

3.3.2 Benefit-cost ratio (BCR)

The Benefit-Cost Ratio (BCR) of 4.43 for the RDF project at the Rawa Kucing Landfill indicates that the economic benefits generated by the project exceed the costs incurred, demonstrating very high economic efficiency. This BCR figure means that for every IDR 1 invested in the RDF facility, there is an economic benefit of IDR 4.43, showing the attractiveness of RDF investment as a highly profitable approach. With such a high BCR, the RDF project at the Rawa Kucing Landfill has proven to provide significant positive impacts, not only economically but also in terms of more responsible environmental management. The shift from a conventional landfill system to Refuse-Derived Fuel (RDF) also brings significant changes in waste management efficiency and capacity. RDF technology allows waste that was previously just buried in landfills to be processed into alternative fuel, which means the volume of waste entering landfills can be significantly reduced. In the context of the nearly full-capacity Rawa Kucing landfill, RDF becomes a crucial solution to extend the operational lifespan of the landfill, reducing the pressure for new land that could disrupt ecosystems and surrounding residential areas. The high BCR (Benefit-Cost Ratio) and EIRR (Economic Internal Rate of Return) achieved indicate that this change is not merely a new approach but a fundamental transformation in more effective, efficient, and sustainable waste management.

From a community perspective, the benefits of RDF are increasingly evident with the reduction in environmental impacts from conventional landfill methods, which risk causing soil, water, and air pollution. The significant reduction in waste volume at landfills means a decrease in the risk of groundwater contamination by harmful leachate and a reduction in air pollution due to methane emissions from decomposing organic waste in landfills. Thus, RDF not only generates high economic benefits for the government through a high BCR but also provides tangible health benefits for communities around landfills. The implementation of RDF also reduces reliance on open dumping methods that require vast land, thereby providing space for more productive development or other needs in increasingly dense urban areas. Overall, the high BCR and EIRR of this project demonstrate that RDF is a sustainable investment, offering a long-term solution to the increasingly urgent waste management problem in Indonesia.

4. Conclusions

The implementation of Refuse-Derived Fuel (RDF) technology at the Rawa Kucing Landfill has demonstrated significant economic, environmental, and social benefits. With a Benefit-Cost Ratio (BCR) of 4.43 and an Economic Internal Rate of Return (EIRR) of 45%, which exceeds the Social Discount Rate (SDR) of 9%, the RDF project showcases economic advantages that outweigh the investment costs. It also offers a more efficient waste management solution compared to conventional landfill methods. RDF technology significantly reduces waste volume, conserves landfill space, and lowers carbon emissions by substituting fossil fuels with more environmentally friendly RDF. This transition from landfill to RDF not only extends the operational lifespan of the landfill but also improves environmental quality and public health by reducing the risks of soil, water, and air pollution.

Therefore, the government is advised to expand the adoption of RDF technology to other landfills across Indonesia, supported by strong policies and regulations to encourage investment and accelerate the transition from landfill to RDF. Education and awareness campaigns about the benefits of RDF for the public and industrial sectors are also crucial to increase understanding of the importance of sustainable waste management. Furthermore, continuous monitoring and evaluation of the RDF project's impacts are necessary to ensure that environmental and economic benefits remain optimal in the long term, establishing RDF as a sustainable national model for waste management.

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Author Contribution
PHS, as the first author, contributed to determining the title and study location, composing the background of the scientific article, describing the existing conditions of the study area, and conducting the cost-benefit analysis related to the use of RDF tools. Additionally, the author performed the final review and overall finalization of the article. NF, as the second author, contributed to the preparation of the literature review and participated in the final review and overall finalization of this scientific article.

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