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Life Cycle Analysis of Coal and RDF Utilization as Energy Sources for Industry: A Comparative Study of Environmental Impacts

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Abstract

This study utilized an LCA approach to comparatively analyze the environmental impact of using coal and RDF as industrial energy sources. Coal, which constitutes the foundation of Indonesia's economy and its primary energy source, has resulted in substantial emissions. In response to this challenge, RDF has emerged as a promising alternative fuel made from municipal waste with a calorific value equivalent to coal. The findings of this research consistently demonstrate that RDF exhibits a considerably diminished environmental impact profile in comparison to coal, across a wide range of evaluated impact categories. For instance, RDF contributes a mere 2% to terrestrial and freshwater aquatic ecotoxicity, whereas coal contributes 98%. RDF exhibits a minimal contribution to acidification potential, eutrophication, ozone depletion, and human toxicity. The novelty of this research lies in its in-depth comparative analysis of the environmental impacts of coal and RDF using LCA with gate-to-gate boundaries, as well as the identification of key impact points (hotspots) in each energy production process. These findings serve to reinforce the argument that RDF is a more sustainable and environmentally friendly energy option for Indonesia's industrial sector.

Keywords: Life cycle assessment; coal; refuse derived fuel; environmental impact; alternative energy

1. Introduction

The main energy source in Indonesia is coal, especially for electricity production. Despite the availability of a wide range of renewable energy sources, coal still contributes to most of Indonesia's energy mix because of its accessibility, desirability from an economic perspective, and firmly established infrastructure (Pambudi et al., 2023). To support highly energy-intensive companies, the government intends to increase captive coal production by up to 180% over the next few decades, further strengthening this dependence. According to data from the International Energy Agency ((IEA), 2022), coal-fired power plants provide more than 60% of Indonesia's electricity, making it one of the world's biggest coal consumers, according to data from the ((IEA), 2022). However, this significant dependency on coal has placed a significant financial burden on the country's power provider, PLN, as the increase in coal generation has complicated efforts to expand clean energy sources and contributed to an excess of power. In line with the Paris Agreement's global climate liabilities, this significant dependence on coal leads to problems with carbon emissions and environmental pollution (Ministry of Energy and Mineral Resources, 2023). In response, Indonesia has initiated a strategic energy transition plan that aims to increase the proportion of renewable energy and gradually reduce its reliance on coal through Indonesia's National Energy Policy (KEN), which aims to achieve 23% of the primary energy mix from renewable sources by 2025 and 31% by 2050, serves as a roadmap for the transition (Yudiartono et al., 2023). Policies, investments, and pilot projects are being used to promote various renewable energy technologies, including solar, hydro, geothermal, and bioenergy (Halimatussadiah et al., 2024). Therefore, transitional technologies that can be integrated with Indonesia's current coal infrastructure are essential to the country's energy decarbonization process. Ineffective waste management increases greenhouse gas emissions, public health hazards and environmental deterioration. Generating electricity from these biomass materials can reduce waste and the use of fossil fuels. This renewable energy source remains unexplored. Harnessing this enormous biomass potential for energy requires technological advancements and effective policies that balance waste management with renewable energy goals.

Refuse-Derived Fuel (RDF) is an alternative fuel derived from municipal solid waste and serves as a substitute for conventional fossil fuels (Zaman et al., 2024). Through RDF technology, waste is converted into renewable and environmentally friendly fuel (Widyarsana and Saraswati, 2022), contributing to both waste reduction and clean energy production. RDF can be used in various industrial sectors, particularly in the cement industry, where its net calorific value is considered sufficient for fuel applications. The net calorific value of the RDF sample is nearly equivalent to coal and is deemed suitable as an alternative fuel (Yasar et al., 2019, Reza et al., 2013), especially as RDF's calorific value in dry phase approaches that of coal (Zaman et al., 2024, Yasar et al., 2019, Reza et al., 2013). Emission tests in European-scale industrial operations have confirmed that flue gas emissions remain below the regulatory thresholds (Kara, 2012). Moreover, RDF has the potential to reduce greenhouse gas (GHG) emissions, acidification, and landfill-related costs (Yasar et al., 2019) compared to the direct combustion of coal (Hapsari et al., 2023). Additionally, RDF production yields various environmental and economic benefits (Reza et al., 2013), offering fuel cost savings while contributing to resource conservation by decreasing the dependency on non-renewable fossil energy (Kara, 2012). From a sustainability perspective, RDF has significant potential to replace coal in energy generation. However, the application of RDF in Indonesia remains limited (Sari et al., 2024). Local processing facilities are still deemed inadequate for producing high-quality RDF suitable for substituting coal-based fuels (Al Qadar et al., 2023). Local processing facilities are still deemed inadequate for producing high-quality RDF suitable for substituting coal-based fuels (Al Qadar et al., 2023).

This study focuses on comparing the environmental impacts of coal versus RDF as fuel alternatives. Life Cycle Assessment (LCA) is widely applied to evaluate and compare environmental impacts, making it particularly suitable for providing integrated and systematic assessments across a product's or process's life cycle (Dubsok et al., 2024). LCA has also been applied specifically to waste processing technologies such as RDF (Laurent et al.), with findings indicating that landfill-based waste management systems produce the most adverse environmental impacts compared to other management techniques. An LCA study conducted around a cement industry in Cirebon demonstrated that converting municipal solid waste into RDF is more environmentally sound than direct coal combustion (Anasstasia et al., 2020). Environmental impact indicators assessed through LCA show that RDF results in 0.84 kg CO_2-eq greenhouse gas emissions, lower than coal, which typically releases 0.9–1.0 kg CO_2-eq per equivalent energy output. RDF also exhibits lower potential for acidification, eutrophication, ozone depletion, and human toxicity compared to coal (Wagland et al.). Similarly, a study conducted in Greece by Liang, Dang (Liang et al., 2023) analyzing seven LCA scenarios for alternative fuel use in cement kilns revealed that RDF-based scenarios had the lowest environmental impact compared to options such as biological sludge or scrap tires. In Egypt, research by SS Siwal, Zhang (Siwal et al., 2021) demonstrated that co-combusting RDF and biomass with coal in clinker production could reduce CO_2 emissions by up to 15% compared to using coal alone. In this study, LCA is used to quantify and compare the total environmental impacts of a product, process, or system throughout its life cycle, from defining objectives and scope, compiling inventory data, assessing impacts, and interpreting results (Seto et al.), offering a comprehensive view of environmental consequences (Salaripoor et al., 2025). This method allows for more accurate comparisons by assessing various factors that might be missed in a simpler analysis. In addition, LCA methods can be standardized, making it easier to compare study results between regions. LCA provides decision-makers with insights into the full spectrum of environmental consequences associated with RDF and coal impacts on the cement industry. In the context of this study, it can be developed by choosing a wiser and more sustainable energy policy. Material Flow Analysis (MFA) complements LCA by identifying and quantifying the flow of material inputs, transformation processes, and outputs in a predefined system, such as the conversion of waste to RDF in cement plants.

2. Method

2.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a method used to evaluate the environmental impacts of a product or system throughout its life cycle (Wahyono et al., 2022). This study provides a comparative analysis of energy supply from two different sources: coal mining processes and energy production from Refuse-Derived Fuel (RDF) derived from waste. This approach was used to assess the substitution of fossil fuels with alternative fuels in the form of RDF. Therefore, the analysis in this study was based on a life cycle perspective of the two processes, aiming to comprehensively evaluate their environmental impacts.

2.1.1. Goal and Scope Definition

Each RDF production process can generate energy that, in some cases, contributes to reducing emissions compared to those of fossil fuels (Sari et al., 2024). However, these processes require resource inputs and often produce pollutants. The same applies to fossil fuel-based energy sources, where mining activities are known to emit significant amounts of pollutants at each stage (Reza et al., 2013). Therefore, it is essential to examine both fossil fuel and RDF production processes. A key objective of this study was to compare and interpret the overall environmental impacts of both processes. This system adopts a cradle-to-gate approach, wherein the system boundary is limited to the processes from raw material acquisition to the point at which the fuel is ready for industrial use. The functional unit used in this study was the daily output of fuel in tons, with system boundaries established based on the relevant literature. The main focus of both systems is raw material acquisition, processing, and the resulting product that is intended to serve as an energy source, primarily for use in industrial applications such as the cement industry.

2.1.2. Life Cycle Inventory

In Life Cycle Assessment (LCA), it is essential to define the system boundaries in the production process of a product (Christensen et al., 2020). The boundaries outlined earlier are intended to prevent the scope of the study from becoming too broad and to determine which stages will be considered in the impact assessment (Ekvall and Weidema, 2004). The Life Cycle Inventory (LCI) is conducted to quantify raw material and energy inputs, environmental emissions, and waste outputs within the defined system boundaries

(Edwards et al., 2017). The LCI plays a crucial role in quantifying material and energy inputs, environmental emissions, and outputs that occur within the specified boundaries. To inventory the material flows within the boundaries of this study, the OpenLCA software was used, utilizing the ELCD database. This database provides various types of mass flows, both input and output, and allows for the assessment of the contribution of each process (Arba and Thamrin, 2022). The inventory stages according to the defined system boundaries are shown in Table 1 and Table 2.

Table 1 and Table 2 present the inventory of raw materials and each process in the coal industry and RDF production. The ELCD database is necessary to identify the providers of inputs to determine the characterization of emissions generated in each process. The inventory process, whether it be coal mining or RDF, is based on relevant literature. The coal process, with a gate-to-gate study, has four main processes, namely coal getting, coal hauling, coal crushing, and conveyor to stockpile (Darpawanto et al., 2022).. The mass flow includes raw materials, solar energy, water, diesel, and majun. Meanwhile, in the RDF process, the main processes involved in mass flow include sorting, screening, biodrying, and shredding (Salaripoor et al., 2025). As shown in Table 1, the gate-to-gate inventory for coal includes four main processes: coal acquisition, coal hauling, coal crushing, and coal conveying to the stockpile. As shown in Table 2, the RDF production process comprises four main stages: sorting, shredding, biodrying, and screening. Each process in both systems is analyzed based on a functional unit of 1 ton, to ensure equivalency when interpreting and comparing the environmental impacts generated by each system. The mass flows in the inventory consist of raw material flows, such as raw coal in the coal supply chain. The raw material used in the RDF system is dry inorganic domestic waste. In addition to raw materials, energy flows—primarily electricity and diesel fuel—are also considered. Electricity, particularly in the RDF process, is used to operate machinery such as shredding machines, conveyor belts for waste separation, and bio-drying systems. Meanwhile, diesel fuel in the coal mining process is used primarily for transportation in raw coal extraction, as well as for powering conveying and crushing equipment to produce coal in the market-required size.

Table 1. Coal mining industry inventory with gate-to-gate system boundary

Name	Amount	Units	FU	Database
Coal Getting				
Input				
Coal	3,687,229	ton	1.0000	Coal/hard/resource/unspesific
Solar	650,488	L	0.1764	Energy Carries and Technology/Crude Oil based to fuels
Ouput				
Coal for Hauling	3,687,229	ton	1.0000	
Coal Hauling				
Input				
Coal	3,687,229	ton	1.0000	
Solar	1,534,629	L	0.4162	Energy Carries and Technology/Crude Oil based to fuels
Ouput				
Coal for Crushing	3,687,229	ton	1.0000	

Name	Amount	Units	FU	Database
Coal Crushing				
Input				
Coal	3,687,229	ton	1.0000	
Solar	3,966,686	L	1.0758	Energy Carries and Technology/Crude Oil based to fuels
Ouput				
Coal for Conveying	3,687,229	ton	1.0000	
Coal conveying to Stickpile				
Input				
Coal	3,687,229	ton	1.0000	
Oli	9	ton	0.0000	Heavy Fuel Oil/ Energy Consumption
Majun	14	ton	0.0000	System/ Packaging
Solar	1,923,082	L	0.5216	Energy Carries and Technology/Crude Oil based to fuels
Biodiesel	240	L	0.0001	
Air	81	m3	2.19E-05	Material Production/Water
Ouput				
Stockiple	3,687,229	ton	1.0000	

Table 2. RDF industry inventory with gate-to-gate system boundary

Name	Amount	Units	FU	Database
Sorting				
Input				
Waste	512	ton	1.05	Waste/Inorganic/Waste/Unspecific
Electricity	10,249	kWh	21.05	Energy Carries and Technology/Electricity
Output				
Sorted Waste	512	Ton	1.05	
Shreeding				
Input				
Electricity	10,249	kWh	21.05	Energy Carries and Technology/Electricity
Shredeed Waste	512	ton	1.05	

Name	Amount	Units	FU	Database
Output				
Shredeed Waste	512	ton	1.05	
Biodrying				
Input				
Electricity	128,115	kWh	263.16	Energy Carries and Technology/Electricity
Shredeed Waste	512	ton	1.05	
Output				
Biodrying RDF	512	ton	1.05	
Screening				
Input				
Electricity	15,374	kWh	31.58	Energy Carries and Technology/Electricity
Waste	512	ton	1.05	
Product				
RDF Ready for Use	487	ton	1.00	

2.2. Material Flow Analysis

Material Flow Analysis (MFA) is a tool used to quantify the flows and stocks of materials within complex systems. It has been widely applied to material systems to provide valuable insights into resource-use patterns and material losses in the environment (Budihardjo et al., 2023).

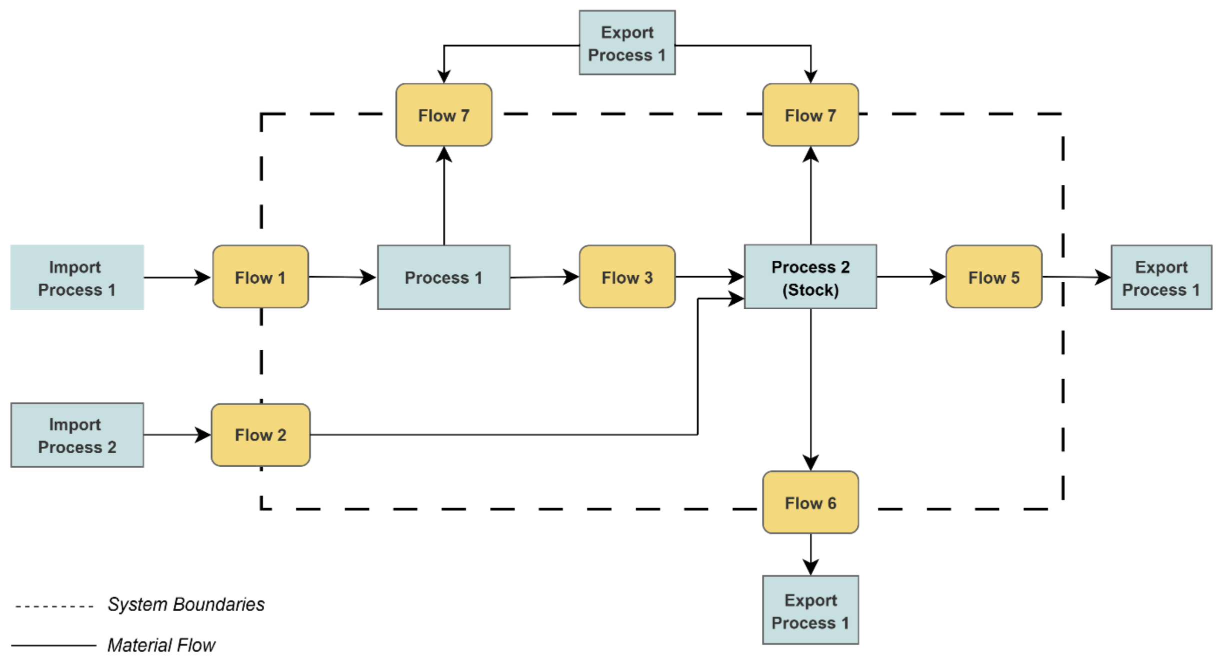

Figure 1. Elements of Material Flow Analysis (MFA) model

This study introduces an innovative approach to inorganic waste management, particularly plastic waste, by integrating Refuse Derived Fuel (RDF) technology with the Material Flow Analysis (MFA) method to enhance urban waste processing efficiency and assess its environmental impacts. MFA is employed to comprehensively map the quantity, type, and distribution of waste from its sources to the final treatment processes (Sharma et al., 2025). Traditionally, Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are distinct tools used to support environmental decision-making. These methods fundamentally differ in terms of system boundary definitions and the specific subjects of investigation. However, overlaps between the two approaches have been identified (Rochat et al., 2013). This indicates that MFA and LCA can complement each other, thereby enhancing the quality of research in both domains. Consequently, the integration of these tools offers the potential for more consistent and reliable decision support in environmental and resource management.

2.2. Impact Assessment

Impact assessment is a critical stage in Life Cycle Assessment (LCA) because it enables the identification of environmental impact hotspots and can be used to inform improvement recommendations. The impact characterization in this study was based on the characterization factors specific to each impact category. These factors quantify the contribution of mass flows, both inputs and outputs, to specific environmental impacts. In this study, the selection of impact categories refers to the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number 1 of 2021 concerning the Corporate Performance Rating Program in Environmental Management (PROPER). Four main impact categories were assessed: Global Warming Potential (GWP), Acidification Potential, Eutrophication Potential, and Ozone Layer Depletion. The selected impact categories were based on their relevance and significance within the regulatory context of environmental impact indicators in Indonesia. The units of measurement for each impact category are presented in Table 3.

Table 3. Impact category and units for LCA analyse

Impact Category	Units (CML IA Baseline)
Global Warming Potential	Kg CO_2eq
Acidification	Kg SO_2eq
Eutrophication	Kg PO_4eq
Ozone Layer Depletion	Kg CFC-11 eq

In the impact interpretation stage, the method used in this study was the CML-IA Baseline, which is commonly applied in LCA studies, particularly to evaluate and compare the environmental impacts of various process scenarios, especially those involving waste generation. In this study, the CML-IA Baseline method was applied to two different scenarios: coal production at mining sites and RDF production utilizing domestically sourced waste. Each process scenario requires energy inputs, which negatively contribute to climate change, environmental quality, and ecotoxicity. The selection of the CML-IA Baseline method for impact interpretation was based on its relevance and frequent application in studies conducted in Indonesia. Impact categories such as Global Warming Potential (GWP) and Ozone Layer Depletion are prioritized because of their high sensitivity to direct emissions that influence global temperature rise and ozone depletion. The Acidification Potential and Eutrophication Potential were considered based on their influence on terrestrial and aquatic ecotoxicity. The resulting impact characterizations were normalized using the World 2000 normalization method available within the OpenLCA software.

3. Result and Discussion

3.1. Coal Production

In this study, four stages of coal core production must be undertaken to produce coal that is ready for use. The process starts with Coal Getting and ends with Coal Conveying to Stockpile. Input and output materials are essential in every process, as shown in Figure 2. The environmental impact is also greatly influenced by the materials used as inputs and outputs.

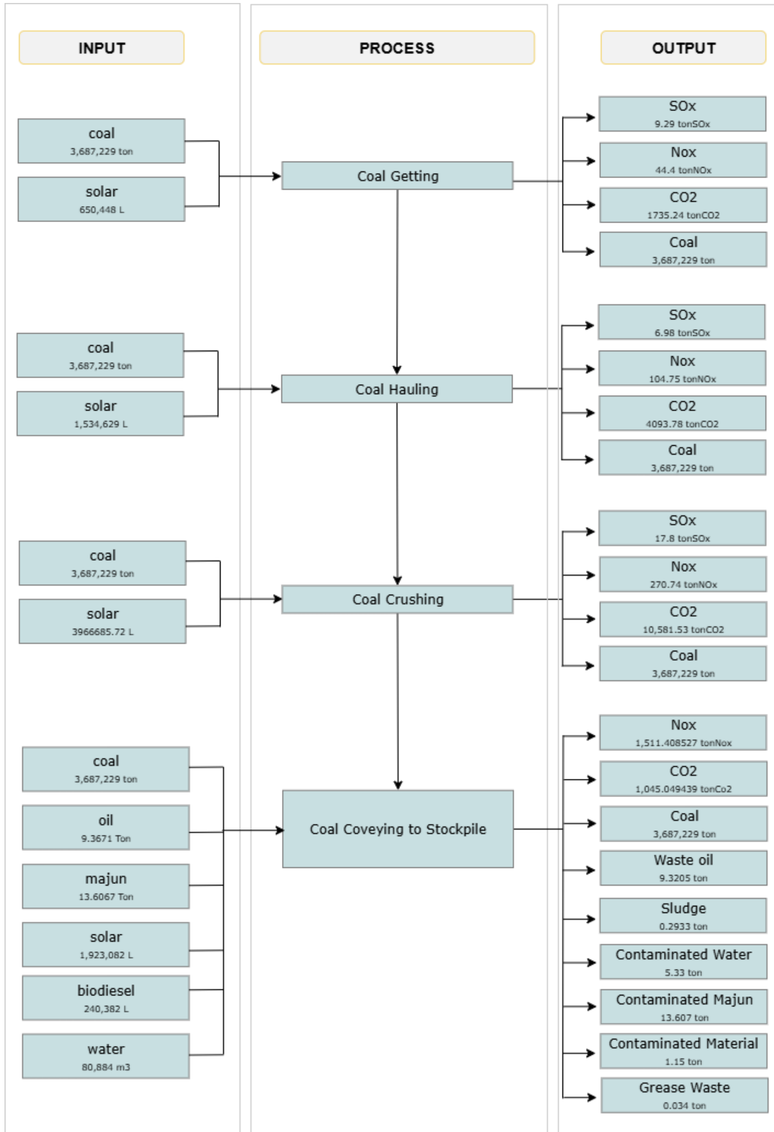

Figure 2. Flow diagram of core coal production process

The first stage of RDF processing is Coal Getting, which is the process of excavating or extracting coal from the mine site using heavy equipment that utilizes energy from liquid fuel, mainly diesel. This process is the beginning of the entire chain of activities and is one of the initial contributors to gas emissions such as sulfur oxide (SOx), nitrogen oxide (NOx), and carbon dioxide (CO_2) due to fuel combustion. This stage requires 650,448 tons of diesel fuel and the extraction of 3,687,229 tons of coal. 2.92 tons of sulfur oxides (SOx), 44.40 tons of nitrogen oxides (NOx), and 1,735.24 tons of carbon dioxide (CO_2) are released into the atmosphere as a result of this process. This stage focuses on the extraction of raw materials without any further processing of the coal itself. Once the coal has been successfully extracted, the material is then transported in the Coal Hauling process (Fan, 2017). The Coal Hauling process typically uses heavy transport fleets to transport coal to the next processing unit. The hauling process is energy-intensive and produces greater emissions than the previous stage due to the greater distance and volume of material transported, as well as the high frequency of transport. This stage continues to process 3,687.229 tons of coal but increases solar usage to 1,534,629 liters. Emissions from this phase are higher, releasing 4,093.78 tons of CO2, 6.98 tons of SOx, and 104.75 tons of NOx into the atmosphere (Liu et al., 2015).

The next stage is Coal crushing, which uses 3,966,685.72 liters of diesel and processes 3,687,229 tons of coal, is the third phase. Coal is crushed in this operation to produce smaller, more consistent pieces that can be used in other procedures. This procedure is crucial for preparing coal for the final preservation phase. At this point, energy consumption increases dramatically, particularly when crushers are operated, which produce a significant amount of exhaust pollutants. Crushing operations generate 17.80 tons of SOx, 270.74 tons of NOx, and a significantly higher emission of 10,581.53 tons of CO_2 owing to the increased energy input (Liu et al., 2015). Finally, the crushed coal is sent through the Coal Conveying to Stockpile process. At this point, energy consumption becomes more challenging because, in addition to diesel and biodiesel fuel, this process also involves lubricants and other media that support the movement and maintenance of the conveyor system. This process uses the 3,687.229 tons of coal as its primary input along with 9,367.1 tons of oli, 13.6067 tons of majun (rags), 1,923.082 L of solar, 240.385 L of biodiesel, and 80.884 m^3 of air. It also results in substantial environmental emissions and waste generation, including 1,511.41 tons of NOx, 1,045.05 tons of CO_2, and several categories of hazardous waste such as used oil 9.3205 tons, contaminated sludge 0.9233 tons, contaminated water 5.53 tons, contaminated rags 13.607 tons, other contaminated materials 1.15 tons, and used grease 0.034 tons. This process demonstrates that energy and waste management are critical to coal system operations if we are to effectively minimize environmental impacts (Ogunkunle and Ahmed, 2021).

3.2. RDF Production for Industry

In the subsequent study, the waste processing system is analyzed starting from the generation of urban waste, which is then sorted by type. Hazardous waste (B3) is separated for special handling at the Hazardous Temporary Disposal Site (TPS B3). Organic waste, such as food scraps and leaves, is directed to composting facilities (TPST Composting) to be processed into fertilizer. Meanwhile, metals and glass that still have economic value are sent to the 3R Temporary Disposal Site (TPST 3R) or landfill for recycling or disposal if they cannot be utilized. Waste such as paper, plastic, and fabric undergo mechanical processes like drying and shredding, involving pre-treatment before being sent to the RDF Plant to be processed into alternative fuel. Paper, plastic, and fabric waste entering the RDF Plant go through several processing stages. It begins with shredding to reduce size, followed by biodrying, which lowers moisture content through biological heat, thereby increasing the calorific value. Afterward, the material is screened to separate fractions suitable for RDF production (the product), heavy inorganic materials (inert), and unusable residue (reject). The RDF product fraction is directed to off takers, namely end-user industries such as cement factories, to be used as an alternative fuel replacing coal. Meanwhile, the inert and reject fractions are disposed of in landfills because they have no energy value or recycling potential.

RDF functions as an innovative solution which helps industries keep production running while reducing their dependence on traditional fossil fuel sources. The cement industry can utilize RDF as a fuel source which provides energy recovery and minimizes their dependence on conventional fuels. The assessment of greenhouse gas emissions from RDF combustion must be performed alongside direct comparisons to emissions from conventional fossil fuel burning. Research demonstrates that burning RDF generates more environmental impact than the mechanical processing steps which create it. The carbon dioxide emissions from RDF refining operations represent 0.18% of the total emissions produced during fuel combustion (Reza et al., 2013). The production of RDF through mechanical processes involves several stages that need a lot of energy and produce emissions. The operation of conveyors crushers coolers and dryers demands electricity usage which leads to atmospheric pollution when the power comes from certain fuel types (Tun and Juchelková, 2019).

The RDF production scheme, represented in the system boundary diagram (see in Figure 3), embodies an integrated waste management framework in which municipal solid waste (MSW) is carefully sorted to recover resources and lessen environmental impact. The scheme commences with an overall weight of 9361,385 tons of MSW, which is disaggregated into 7,117 tons of hazardous waste, 171,925 tons of organic material, 97,272 tons of metals and glass, and 512,460 tons of combustible residues, principally plastics, paper, and textiles. These inputs are directed to an initial sorting process, whereby recyclable and compostable materials are redirected to respective facilities: hazardous waste to TPS B3, organic waste to composting facilities (TPST), and recyclables to 3R processing centers. Residuals from this step, particularly the combustible fractions, are directed to the RDF plant, supported by auxiliary energy inputs—200 kWh/ton for shredding, 250 kWh/ton for biodrying, and 200 kWh/ton for screening operations. The RDF plant outputs consist of 486.63 tons of RDF product, alongside 20.49 tons of inert material and 5.14 tons of reject. By transforming waste into alternative fuels, this arrangement curbs reliance on landfilling and advances circular economy objectives. Utilisation of RDF in industrial thermal systems has yielded marked declines in greenhouse gas emissions and diminished fossil fuel use compared to coal. These benefits concur with life cycle assessments in the literature Arena (2012), Chyang et al. (2010), Consonni and Viganò (2012) that highlight RDF's viability as an environmentally sound substitute in processes requiring sustained high temperatures.

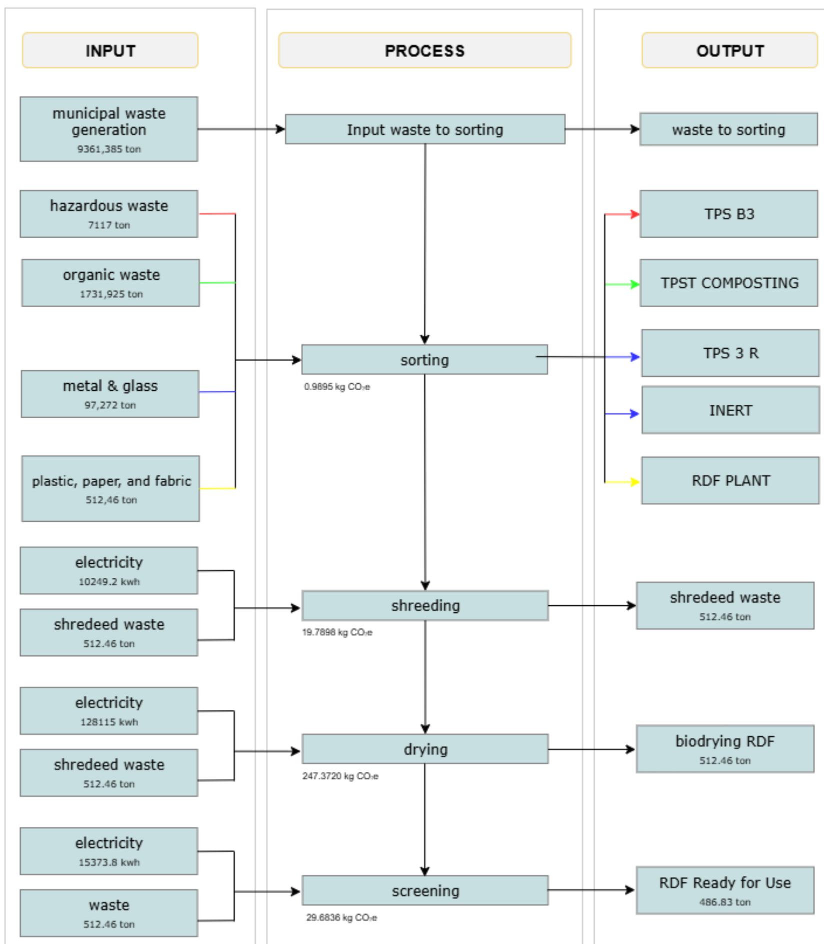

Figure 3. RDF production core process flowchart

3.3. Normalization and Weighting

The normalization step aims to provide context to the magnitude of characterized impacts by comparing them to reference values, such as the average per capita contribution within a specific region or on a global scale. Through this process, various impact categories with different units and scales can be converted into dimensionless values that are directly comparable. As shown in Figure 4, the normalization results indicate that RDF contributes significantly less to environmental impacts compared to coal across nearly all categories (Dubsok et al., 2024). For example, RDF contributes only 2% to terrestrial ecotoxicity and freshwater aquatic ecotoxicity, while coal accounts for 98%. In the global warming category (GWP100a), RDF contributes 7%, whereas coal contributes 93%. A similar pattern is observed in the acidification category (6% RDF vs. 94% coal), eutrophication (5% RDF vs. 95% coal), and ozone layer depletion (10% RDF vs. 90% coal).

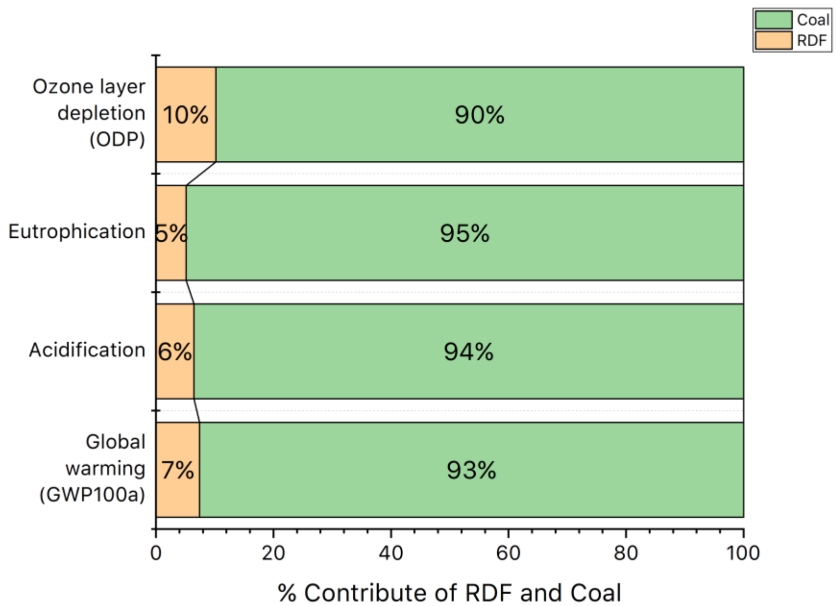

Figure 4. Normalization and weighting

The weighting stage involves assigning relative importance to each normalized impact category, based on scientific, social, and environmental considerations. This weighting allows for the aggregation of various impact indicators into a single total score or prioritization of categories that have the most significant implications for policy and decision-making (Khoo, 2009). In the context of current environmental policy, which emphasizes climate change mitigation and human health protection, categories such as Global Warming Potential (GWP), Human Toxicity, and Acidification are typically assigned higher weights. In this regard, the substantially lower contributions of RDF to these categories indicate that, overall, RDF has a lighter environmental burden compared to coal (Armoo et al., 2025). Most notably, RDF shows zero percent (0%) contribution in both the Human Toxicity and Marine Aquatic Ecotoxicity categories, while coal accounts for 100% in both. When weighting factors are applied, this contrast becomes even more significant, further reinforcing the position of RDF as a more sustainable alternative to conventional fossil fuels (Kumawat et al., 2024).

3.4. Interpretation

Table 4 presents the results of the life cycle impact assessment across four environmental impact categories, evaluated in accordance with the Regulation of the Minister of Environment and Forestry Number 1 of 2021, using the CML-IA Baseline method for impact interpretation. Based on the impact analysis results shown in Table 4, the normalized values for each category revealed a significant difference, with the impact values associated with coal generally being considerably higher than those of the RDF process across all assessed categories.

Table 4. Total impact of each scenario process after normalization

Impact Category	Total Impact of RDF	Total Impact of Coal Production
Global warming (GWP100a)	5.70E-15 kgCO2eq	7.10E-14 kgCO2eq
Acidification	4.88E-15 kgSO2eq	7.08E-14 kgSO2eq
Eutrophication	4.83E-16 kgPO4eq	8.92E-15 kgPO4eq
Ozone layer depletion (ODP)	6.85E-17 kgCFC-11 eq	6.04E-16 kgCFC-11eq

3.4.1. Global Warming Potential (GWP)

Figure 5 illustrates the interpretation of impacts for each process within the Global Warming Potential (GWP) category, using the CML-IA Baseline method. The figure identifies the hotspot in the coal mining process as the coal crushing stage, whereas in the RDF process, the hotspot lies in the biodrying stage. In the coal crushing process, energy consumption is dominated by diesel fuel, with a total daily usage reaching 3,966,686 liters. This high fuel consumption directly contributes to the increase in greenhouse gas emissions, particularly GWP. According to Zhou et al. (2024), fossil fuel consumption in mining activities significantly contributes to the growth of greenhouse gas emissions, with each liter of diesel combusted emitting approximately 2.68 kg of CO_2. Therefore, it is estimated that the coal crushing process alone generates approximately 10.62 tons of CO_2 emissions per day. In the RDF process, biodrying emerges as the primary hotspot, indicating a high contribution to impact due to the substantial thermal and electrical energy requirements during the drying of organic materials. Velis et al. (2012) state that while RDF is generally considered a more environmentally friendly fuel compared to coal, its processing can still result in a significant carbon footprint—especially if the energy used in RDF production is derived from non-renewable sources. Emissions from the biodrying process are primarily due to the partial degradation of organic matter, which releases methane (CH_4) and carbon dioxide (CO_2), both of which are potent greenhouse gases.

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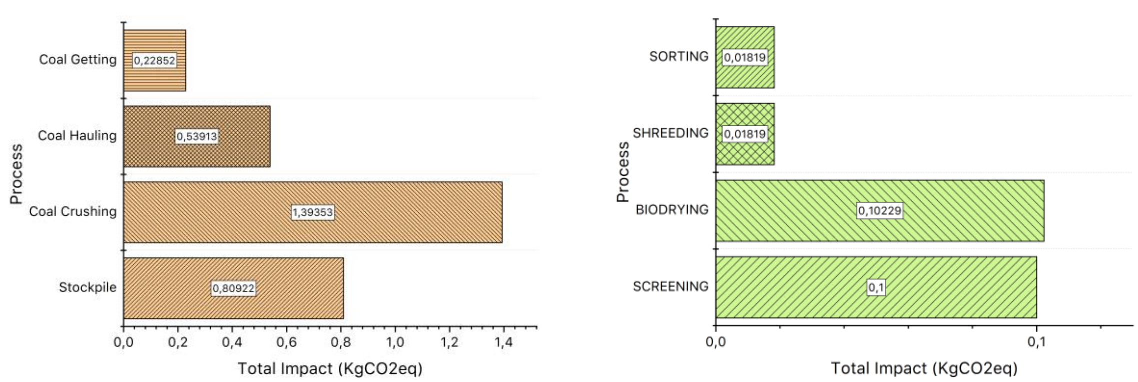


(a) (b)

Figure 5. Hotspot interpretation of global warming potential impact: (a) coal mining process (b) RDF production process

Between the two processes, the cumulative Global Warming Potential (GWP) impact is highest in the coal mining process compared to RDF production. This is primarily due to the larger energy input required for mining operations than for RDF processing. Coal mining involves the use of diesel fuel, machinery, biodiesel, and water consumption—all of which contribute to higher greenhouse gas emissions than those generated during RDF production. Therefore, RDF presents potential as an alternative in the transition to renewable and low-emission energy sources. However, it is important to note that the RDF process still produces emissions, particularly during the maturation and curing phases. Therefore, further evaluation of energy substitution strategies in RDF processing is necessary to minimize the emissions that contribute to global warming.

3.4.2. Acidification

Acidification potential is one of the parameters assessed in this analysis. Figure 6 identifies the hotspot in each process, with coal crushing contributing the highest acidification potential in the coal mining process at 0.0793 kg SO_2 eq, and biodrying identified as the hotspot in RDF production with an impact of 0.0013 kg SO_2 eq. Acidification refers to the contribution of compounds such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3), which can react with atmospheric water vapor to form acids. Acidification impacts may result in decreased pH levels in soil and water, vegetation damage, and infrastructure corrosion (Gade et al., 2021). The high acidification value for coal crushing shown in Figure 5 is primarily attributed to the intensive use of diesel fuel as the main energy source for operating heavy equipment and coal-crushing machinery. The combustion of diesel releases significant amounts of SO_2 and NO_x, which are key precursors to acid rain formation (Jaramillo et al., 2009). In contrast, emissions from the biodrying process are relatively low compared to those from mining activities, as biodrying generally relies on heat generated from the biological decomposition of organic material and electricity consumption. Although there are still emissions due to energy use, they are considerably lower than those from fossil-based fuels such as diesel. However, it is important to note that the electricity used in biodrying often comes from fossil-based energy sources, which can still contribute to acidification potential (Papageorgiou et al., 2023)

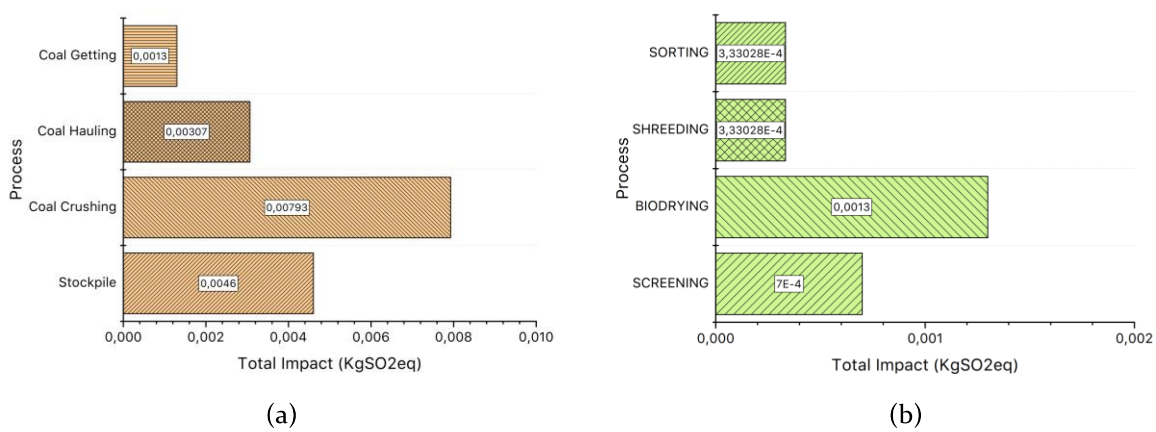


Figure 6. Hotspot interpretation of acidification: (a) coal mining process (b) RDF production process

The difference in impact magnitude indicates that the coal crushing process in coal mining is a hotspot in the acidification impact category. Considering that RDF production results in relatively lower environmental impacts compared to coal, it can be recommended as a potential alternative to fossil fuels as a nonrenewable energy source. However, it is important to note that electricity consumption in the RDF process, particularly during biodrying, still relies on fossil-based energy sources, especially coal. Therefore, we recommend substituting these energy sources with renewable alternatives to reduce the growth rate of emissions, particularly those producing SO_2 and NO_x, which contribute significantly to acidification-related pollution.

3.4.3. Eutrophication

Figure 7 presents an interpretation of the hotspot impacts related to the eutrophication potential of both coal mining and RDF processes. In the coal mining process, the identified hotspot was coal crushing, with an impact value of 6.62 × 10^{-4} kg PO_4 eq. Meanwhile, in the RDF process, the hotspot occurred during biodrying, with an impact value of 3.2 × 10^{-4} kg PO_4 eq. Eutrophication potential refers to the increase in nutrient concentrations, particularly nitrogen and phosphorus compounds, in aquatic or terrestrial ecosystems, which can trigger excessive algae growth (algal blooms), a decrease in dissolved oxygen levels, and disruption of aquatic ecosystems (Paerl et al., 2001). Based on the hotspot interpretation results in Figure 6, the eutrophication impact value for the coal mining process, particularly in coal crushing, was significantly higher than that of the RDF process. The elevated impact of coal mining is primarily due to the potential release of wastewater and particles containing nitrogen and phosphorus compounds into the environment through runoff or improper waste discharge (Huijbregts and Seppälä, 2001). Moreover, coal mining and crushing activities disturb soil structures and increase the likelihood of nutrient leaching and heavy metal contamination in water bodies, thereby exacerbating eutrophication pollution. According to Gorman (2019), mining activities that lack adequate wastewater management systems are a major contributor to nutrient loading in aquatic ecosystems.

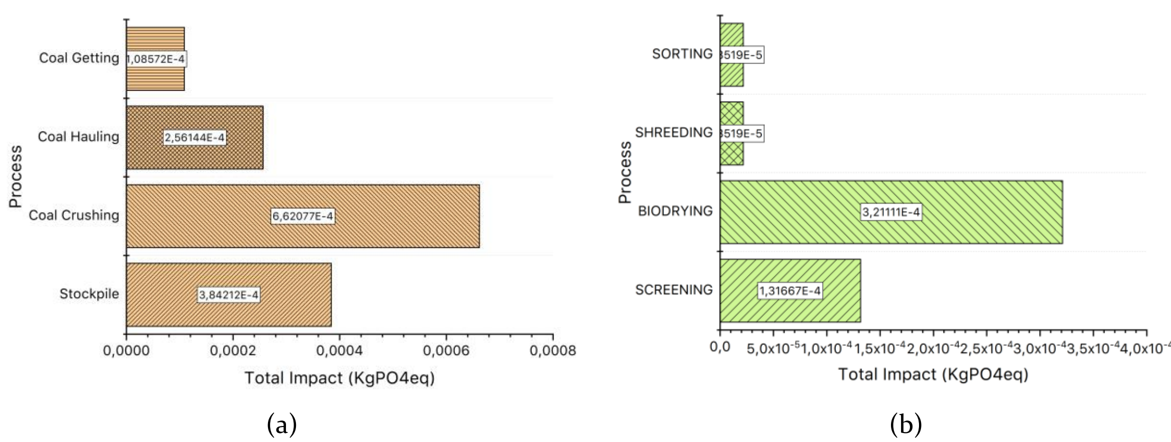
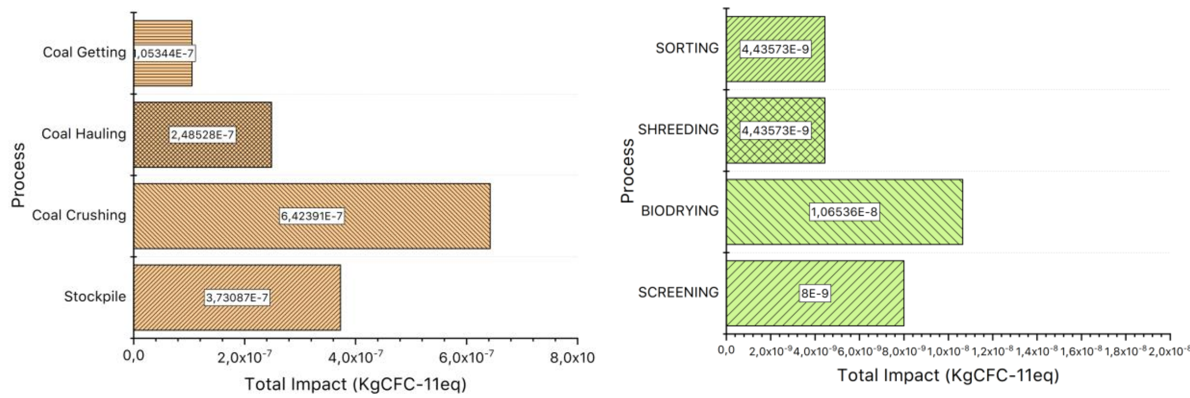


Figure 7. Hotspot Interpretation of eutrophication: (a) coal mining process (b) RDF production process

On the other hand, the eutrophication impact from the RDF process, particularly during biodrying, is relatively lower because of the limited involvement of water and the use of closed-system operations, which potentially reduce the release of eutrophication-related substances into the environment. However, if leachate treatment in RDF facilities is not carried out optimally, the potential impact can increase significantly (Di Gianfilippo et al., 2016). From the eutrophication impact interpretation analysis, the accumulated impact value of RDF was considerably lower than that of coal mining. Therefore, RDF has the potential to be applied in various regions as an alternative fuel source with relatively lower environmental impact than coal.

3.4.4. Ozone Layer Depletion

Figure 8 presents the interpretation of hotspot impacts related to ozone layer depletion in the coal mining and RDF processing scenarios. The highest impact in the coal mining process was observed in the coal crushing stage, with a value of 6.4 × 10^{-7} kg CFC-11 eq. Meanwhile, the hotspot in the RDF process was found in the biodrying stage, with a significantly lower impact value of 1.06 × 10^{-8} kg CFC-11 eq. Ozone layer depletion refers to the reduction in ozone concentration in the stratosphere due to the release of ozone-depleting substances (ODS), such as chlorofluorocarbons (CFCs), halons, and other chlorine- and bromine-containing compounds (Heijungs et al., 1992). The significant difference in impact values between the two scenarios indicates that coal mining activities, particularly coal crushing, contribute more substantially to the release of ozone-depleting substances. This process requires a large amount of diesel fuel to operate heavy machinery, which often utilizes cooling systems or lubricants containing chlorine-based compounds such as CFCs or HCFCs—especially in older equipment lacking adequate emission control systems (Jeswani et al., 2015)



(a) (b)

Figure 8. Hotspot interpretation of ozone layer depletion: (a) coal mining process (b) RDF production process

In addition, indirect emissions from the production and distribution of fossil fuels also contribute to the release of ozone-depleting substances (Sharma and Gupta, 2020).In contrast, the biodrying process in RDF production showed a relatively lower impact in the ozone depletion category than coal mining. This is due to the limited use of fossil fuels, which helps minimize emissions from refrigerant-based cooling systems containing CFCs. Biodrying primarily relies on biological heat and aeration to reduce waste moisture content, thereby generating minimal ozone-depleting emissions. However, it is important to note that electricity use in the RDF biodrying process contributes to indirect emissions, depending on the energy mix of the electricity generation system.

4. Conclusion

Life Cycle Assessment (LCA) analysis demonstrates that the utilization of coal as the primary energy source in industrial contexts, particularly in Indonesia, contributes substantially to adverse environmental consequences. The extraction of coal and the subsequent combustion of this fossil fuel result in elevated levels of greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NOx). These emissions contribute to several environmental issues, including global warming (Global Warming Potential), acidification (Acidification Potential), eutrophication, ozone depletion (Ozone Depletion Potential), and toxicity to humans and ecosystems. The coal production process is also highly intensive in terms of energy and resource use. This underscores the substantial environmental implications of Indonesia's heavy reliance on coal, a pivotal economic sector that contributes over 60% of the nation's electricity.

This study proposes a more sustainable alternative, demonstrating that Refuse Derived Fuel (RDF) exhibits a significantly reduced environmental impact profile in nearly all impact categories evaluated when compared to coal. From the interpretation of the impacts, the total GWP potential of the coal process has a total accumulated global warming impact of 2.97 kgCO2eq, which is significantly greater than the RDF process, which is 0.2 kgCO2eq. Additionally, in terms of acidification impacts, coal mining has an impact of 0.01 kgSO2eq, which is greater than the RDF process's impact of 0.002 kgSO2eq. This also applies to eutrophication and ozone layer depletion impacts, where coal mining contributes emissions of of 0.0014 kgPO4eq for eutrophication and 1.3 X 10^{-6} kgCFC-11 eq, indicating a greater impact compared to the RDF process, which is 0.0008 kgPO4eq and 2.7 x 10^{-8} kgCFC-11 eq. RDF, a byproduct of municipal waste processing with a calorific value equivalent to that of coal, has been shown to significantly reduce greenhouse gas emissions and dependence on fossil fuels. For instance, in the present study, RDF contributed only 2% to the terrestrial and freshwater aquatic ecotoxicity categories, whereas coal contributed 98%. Furthermore, RDF exhibited a negligible contribution to the human toxicity and marine aquatic ecotoxicity categories, in contrast to the 100% contribution of coal. Notwithstanding the energy consumption and emission generation inherent to the RDF production process, particularly during the biodrying stage, its overall contribution to greenhouse gas (GHG) emissions, toxicity potential, and eutrophication is considerably less than that of coal. Consequently, the transition to RDF utilization in the industrial sector constitutes a strategic initiative to support decarbonization efforts and sustainable waste management in Indonesia.

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