

Original Research Article

## Environmental Impact of Energy Diversification Using Refuse-Derived Fuel in Cement Industry

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### Abstract

Processing municipal solid waste into refuse-derived fuel (RDF) is an alternative solution to the waste problem. This study determined the potential environmental impact of Sleman RDF as an energy diversification agent in the cement industry using life cycle assessment (LCA). The boundary system of this study is gate-to-grave, with a functional unit of co-firing energy requirements for the production of 1 metric ton of clinker. Two clinker co-firing scenarios were developed, involving a combination of coal and alternative fuels. The results showed that the production of 1 metric ton of clinker requires a large amount of resources and contributes significantly to climate change, ecosystem toxicity, and human toxicity. Co-firing clinker in the alternative scenario successfully reduced the potential environmental impact by 14% with a thermal substitution rate of 20%. The findings of this study indicate that RDF is effective in reducing dependence on fossil fuels and lowering emissions and the potential environmental impact.

**Keywords:** Clinker; LCA; refuse-derived fuel

### 1. Introduction

Scientists and environmentalists state that environmental degradation in the last decade has become a global problem that affects the sustainability of nature (Arora et al., 2018). This is triggered by economic activities that are more than 80% driven by fossil energy (Abas et al., 2015). Nearly 73% of the coal is utilized to generate electricity, while over 25% is used for industry, such as the cement sector (MEMR, 2021). The high demand for coal in the country has resulted in an energy crisis, as coal reserves

are dwindling. Several countries, including Indonesia, have begun to pursue diversification of alternative energy sources as a solution to the energy crisis and environmental degradation (Setyono and Kiono, 2021). Concrete steps have been taken by the Indonesian government through Government Regulation No. 79/2014 on National Energy Policy that regulates energy transition and targets the composition of Indonesia's energy use by 2025. Under the plan, fossil fuels should be less than 20%, while the renewable energy mix is expected to reach 23% of the total energy used (MEMR, 2014).

Alternative energy that is currently being developed is Refuse-Derived Fuel (RDF) from municipal solid waste (MSW) (Shumal et al., 2020). Waste is a challenge in environmental management, especially in large, densely populated cities. According to the Ministry of Environment and Forestry, in Indonesia, the amount of waste generated increased by 35% from 2019 to 2023. In contrast, the capacity of landfills in Indonesia is almost at its limit because approximately 500 landfills still use an open dumping system (Gabriel et al., 2015). This encourages sustainable waste management efforts. By creating integrated waste treatment facilities that convert waste into RDF, the government is attempting to manage waste. RDF is derived from MSW, which includes organic materials other than chlorinated ones, paper, plastic, textiles, and rubber (Martignon, 2020). RDF is an effort to reduce the volume and utilization of waste into energy. Research by Tihin et al. (2023) states that RDF processing technology can be divided into mechanical treatment (MT) and mechanical biological treatment (MBT). The cement industry uses RDF products as alternative fuels. In the pre-calciner phase of the clinkering process, alternative fuels are utilized. RDF effectively meets 3 %–6% of the cement industry's annual energy requirements (Sagala et al., 2018). This can reduce greenhouse gas emissions resulting from industrial operations (Kemala et al., 2023). On the other hand, the Indonesian cement industry has a target of using alternative fuels and raw materials (AFR) with a thermal substitution rate (TSR) of 20% by 2030 (SIG, 2022).

RDF derived from waste can be a solution to the problem of the energy crisis and environmental damage. The planned innovation is not expected to cause problem shifting, namely, the displacement of new environmental problems that may arise because of the technology applied, elsewhere or in the future. To avoid this, the process of utilizing urban waste to produce RDF as an alternative energy source must be studied thoroughly from each production stage. In contrast to previous studies that examined the efficiency, performance, economic feasibility, and quality of RDF produced using various methods (Widyarsana and Saraswati, 2022; Anastasia et al., 2018; Maulana et al., 2021). In this study, an environmental impact evaluation was conducted using the life cycle assessment (LCA) approach for the waste conversion process to RDF as an alternative energy source. LCA methods can be standardized, making it easier to compare study results between regions. LCA analysis is expected to provide information related to the estimated impacts generated in this activity as a reference focus for stakeholders to make sustainable improvements.

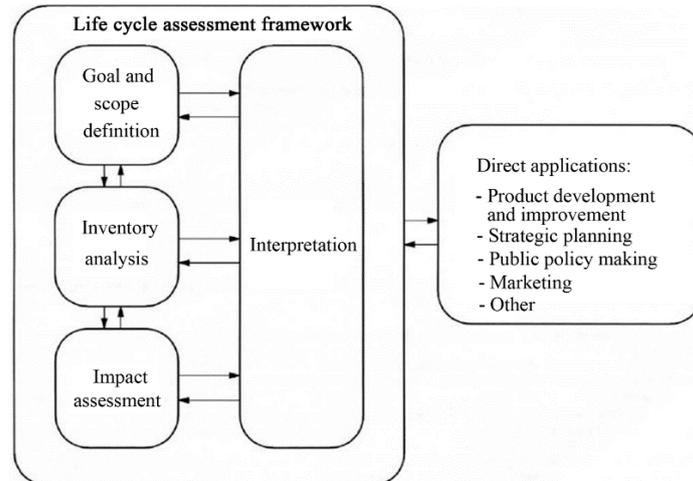
## **2. Methods**

### **2.1 Study Area**

This study was conducted at a waste management site in Sleman Regency, Central Java, which is the location of RDF production, and at a cement industry in Cilacap Regency, Central Java, which is the location of RDF utilization as an alternative energy source. The research period was from September 2024 to January 2025. The research location was chosen because it is integrated, allowing it to describe the RDF production process from municipal solid waste to the use of RDF on an industrial scale.

### **2.2 Life Cycle Assessment**

LCA is a structured approach for analyzing the environmental performance of a product. According to the ISO 14040:2006 standard, the LCA framework consists of goal and scope definitions, inventory compilation, impact evaluation, and result interpretation, as shown in **Figure 1**.



**Figure 1.** Stage of life cycle assessment  
 Resources: *International standard ISO 14040, 2006*

**2.2.1 Goal and Scope Definition**

The RDF production stage has the potential to generate energy that, under certain conditions, can reduce emissions compared to the use of fossil fuels (Hossain et al., 2017). However, this process still requires resource inputs and can result in pollutant emissions. The scope of this study is " gate-to-grave," where the life cycle analysis starts from the waste source, RDF production process, and RDF conversion as an energy source in cement clinker production. The purpose of this LCA study is to quantitatively assess the impact of the RDF production and utilization processes in cement kiln co-firing. In this study, there are two scenarios of co-firing in clinker production: (1) co-firing baseline and (2) co-firing with a thermal substitution rate of 20%. The functional unit in this analysis is the energy requirement for the production of one metric ton of clinker. The system boundaries of this study are illustrated in **Figure 2**.

Scenarios 1 and 2 compare the periods before and after energy diversification with simultaneous clinker combustion. In scenario 2, the use of alternative fuels is projected to substitute coal by 20% because it refers to the Indonesian Cement Industry target regarding the use of AFR with a TSR of 20% in 2030 (SIG, 2022).

**2.2.2 Life Cycle Inventory**

The inventory stage evaluates material flows and energy use, covering the inputs and outputs for producing one metric ton of RDF and the energy required for clinker manufacturing. The inventoried data include the consumption of raw materials, chemicals, fuel, electricity, waste, and emissions generated.

The methodology for estimating emission factors follows the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The IPCC calculation uses Tier 1, referring to the availability of data, and the basic method for estimating emissions using **Equation (1)**.

$$GHG = Activity\ Data \times Emission\ Factor \dots\dots\dots(1)$$

Data collection and field studies in LCA are essential to ensure that the data used in the analysis is an accurate representation of the life cycle of the product being evaluated. Primary data mining was obtained based on the condition of RDF production at the Integrated Waste Management Site (IWMS), Sleman, and RDF utilization at the cement industry in Cilacap. The secondary data used in this study were obtained from publicly available databases, such as journals. Details of the data and sources of data collection are presented in **Table 1**.

Table 1. Data collection

Data	Data type	Data Source
<b>Refuse-Derived Fuel Production</b>		
<i>Input</i>		
MSW, Fuel, electricity, water, chemicals, transport	Primary	Direct observation
<i>Output</i>		
RDF, leachate, sludge	Primary	Direct observation
Emission	Secondary	IPCC, 2006
<b>Energy for clinker production</b>		
<i>Input</i>		
Fine coal, IDO, electricity, fuel, RDF, Ricehusk, Sawdust	Primary	Direct observation
<i>Output</i>		
Clinker	Primary	Direct observation
Emission	Secondary	IPCC, 2006

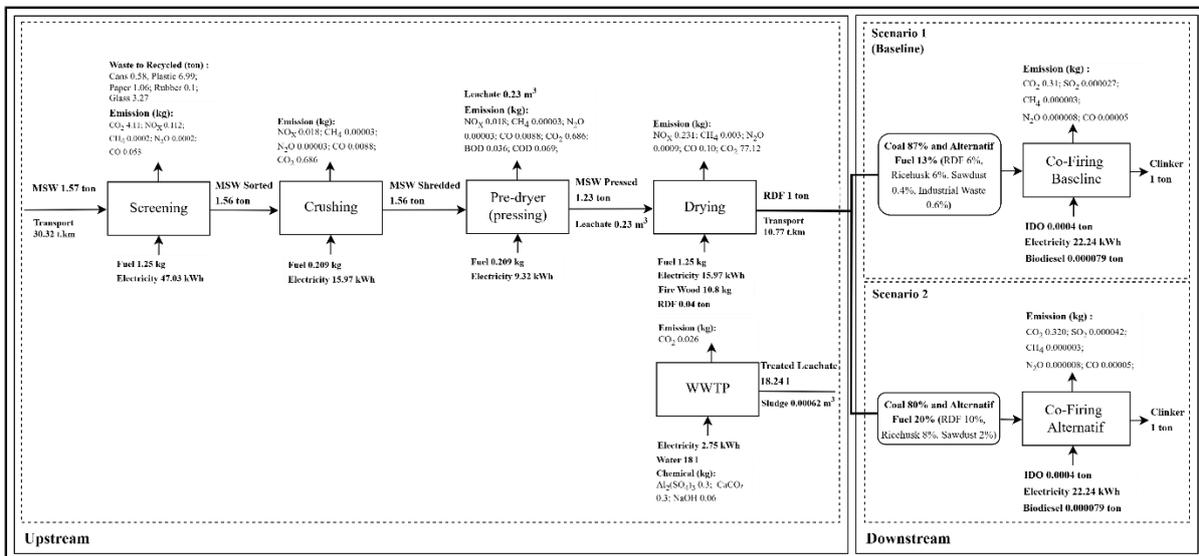


Figure 2. System Boundary life cycle assessment of refuse-derived fuel (RDF)

### 2.2.3 Life Cycle Impact Assessment

LCA was used to evaluate the effects of each inventory analysis method on the environment. OpenLCA 2.3 software with Ecoinvent databases was used to analyze process input and output data. The Ecoinvent database offers an extensive collection of LCA data across sectors, such as industrial manufacturing, energy, and chemistry. Considering the objectives and parameters of the study, the selected impact categories should reflect the range of possible environmental impacts associated with the product system (Ghony, 2017). The impact categories to be analyzed are in accordance with Minister of Environment Regulations No. 1 of 2021. The methods used in the impact assessment were CML IA-Baseline, ReCiPe 2016 Midpoint (H), and cumulative energy demand (CED).

### 2.2.4 Interpretation

Interpretation of the results of the Life Cycle Impact Assessment is the final stage in LCA. This stage is used to identify and compare scenarios that make the greatest contribution to each environmental impact indicator. The results are used to formulate recommendations for the development

of improvement strategies to reduce environmental impacts.

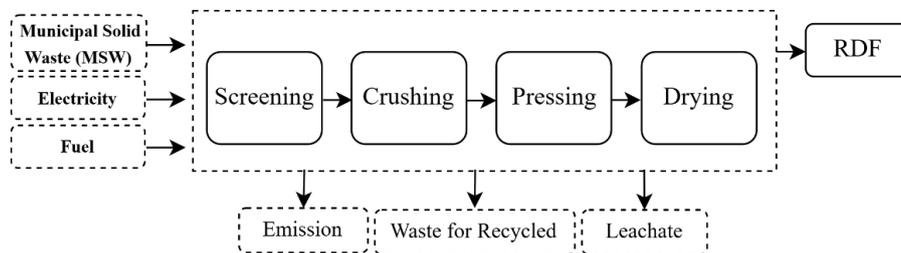
### 3. Result and Discussion

#### 3.1 RDF Production

RDF production was based on MSW processing operations at the integrated waste management site. The RDF production process was carried out using mechanical treatment technology. RDF production involves several stages, starting with the collection of waste from its source and processing it into RDF products that meet the specified criteria and quality standards. Solid waste inputs were sorted into organic and inorganic waste. Sorting was performed manually or mechanically. Manual sorting is the initial stage of waste management, which aims to separate hazardous and recyclable materials to support the circular economy (Shehata et al., 2022). Inorganic waste was passed through a sieve and entered the shredder. Wet waste was directed towards pressing. Both types of waste can be converted into RDF after drying. The flow of the RDF production process is illustrated in **Figure 3**.

Paramita (2017) explained that there are 3 drying methods in the RDF production process, namely solar drying, steam drying, and biodrying. Solar drying is a drying method by utilizing heat energy from the sun. Steam drying utilizes hot steam to dry the material (rotary dryer). Biodrying utilizes heat generated from the activity of microorganisms in degrading organic matter (Maulidayanti et al., 2024).

Based on this study, RDF mechanical treatment can reduce water content to 36%. In other words, 392.8 metric tons of MSW can be converted into 249.5 metric tons of RDF. The remaining waste (2%) is a recycled material comprising 5% cans, 59% plastic, 9% paper and cardboard, 1% rubber, and 27% glass. Leachate generation from MSW ranges from 0.079 to 0.148 m<sup>3</sup> per metric ton of waste under humid and semi-arid climates (Abunama et al., 2021). Thus, the volume of leachate produced is approximately 57.7 m<sup>3</sup>.



**Figure 3.** Refuse-derived fuel (RDF) production process flow

Certain criteria and standards exist for RDF production to describe the quality of RDF products. RDF quality standard testing parameters include calorific value, moisture content, ash content, chlorine, sulfur, and particle size (**Table 2.**). The characteristics of the RDF met the national standard SNI 8966:2021.

**Table 2.** Refuse-derived fuel (RDF) characteristics

Parameters	Unit	RDF	SNI
Calorific Value	MJ/t	15098.20	≥10.000
Moisture content	%b	27.06	<25
Ash content	%b	10.48	<25
Size	mm	30-50	<50
Chlorine	%b	0.25	≤1
Sulfur	%b	0.26	<1.5

### 3.2 Alternative Fuel at Cement Industry

The cement industry requires significant amounts of fossil fuels (coal), energy (heat and electricity), and natural resources (raw materials). The cement production process begins in the first stage: extraction (quarry) and preparation of raw materials (raw mill); second stage: clinkerization; and third stage: grinding and distribution of cement (Mohammad et al., 2021). RDF is currently used as an alternative fuel during the clinkerization stage. This requirement reflects the emission profile of cement manufacturing, where fuel combustion accounts for nearly one-third of the total CO<sub>2</sub> releases, and the remainder is attributed to limestone decarbonation during clinker production (Izumi et al., 2021). The carbon footprint of cement production is approximately 0.83 metric tons of CO<sub>2</sub> per metric ton, with kiln-related combustion contributing the dominant share of emissions (Guo et al., 2022). Energy diversification, or replacing fossil fuels with waste-derived alternative fuels for kiln combustion, is one approach to reduce CO<sub>2</sub> emissions (Kemala et al., 2023).

### 3.3 Life Cycle Assessment

#### 3.3.1 Life Cycle Inventory Analysis RDF

Data gathering and methods for calculating the product system's inputs and outputs are components of inventory analysis. Table 3 presents the input and output statistics for energy, fuel, raw materials, and emissions in the RDF production process.

**Table 3.** Life cycle inventory refuse-derived fuel (RDF) production

Input/Output	Inventory Data	Process	Unit
<b>Input Fuel/Energy</b>	Biodiesel	3.137	l
	Electricity	91.04	kWh
	RDF	0.04	t
	Fire wood	10.82	kg
<b>Input Material</b>	Municipal Solid Waste	1.574	t
	Water	18	l
<b>Input Chemical</b>	Aluminium sulfate (Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> )	0.3	kg
	Calcium carbonate (CaCO <sub>3</sub> )	0.06	kg
	Sodium hydroxide (NaOH)	0.3	kg
<b>Transport</b>	MSW Collection	30.323	t.km
	RDF Delivery	8.077	t.km
<b>Output Product</b>	RDF	1	t
<b>Output Waste</b>	Leachate	0.231	l
	Sludge	0.0006	m <sup>3</sup>
<b>Output Side Product</b>	Cans	0.581	kg
	Plastic, mix	6.999	kg
	Paper	1.066	kg
	Rubber	0.100	kg
	Glass	3.269	kg
<b>Output Emission</b>	CO <sub>2</sub>	82.204	kg
	CO	0.172	kg
	NO <sub>x</sub>	0.301	kg
	N <sub>2</sub> O	0.001	kg
	CH <sub>4</sub>	0.006	kg
	BOD	0.035	kg
	COD	0.069	kg

Inventory data for co-firing alternative fuels in cement kilns are provided in **Table 4**. There are two

scenarios in the co-firing kiln: (1) baseline scenario, which shows the existing conditions, and (2) scenario that projects the use of alternative fuel up to 20%.

**Table 4.** Life cycle inventory co-firing kiln cement

Input/Output	Inventory Data	Process		Unit
		Scenario 1	Scenario 2	
<b>Input Fuel/Energy</b>	Fine coal	0.15	0.14	ton
		2843.58	2614.40	MJ
	IDO	0.00045	0.00045	ton
		19.07	19.07	MJ
	Electricity	22.24	22.24	kWh
	Biodiesel	0.00008	0.00008	ton
<b>Input Alternatif Fuel</b>	RDF	0.01	0.02	ton
		196.092	294.12	MJ
	Rice Husk	0.02	0.03	ton
		201.71	277.78	MJ
	Sawdust	0.0006	0.01	ton
		5.98	81.70	MJ
	Mix Industrial Waste	0.0017	-	ton
	20.64	-	MJ	
<b>Output product</b>	Clinker	1	1	ton
<b>Output Emission</b>	CO <sub>2</sub>	0.3143	0.3205	ton
	CO	0.00005	0.00002	ton
	N <sub>2</sub> O	0.000008	0.000009	ton
	SO <sub>2</sub>	0.00002	0.00004	ton
	CH <sub>4</sub>	0.000003	0.000005	ton

In the baseline scenario, the cement industry uses 13% alternative fuel (6% RDF, 6% rice husk, 0.4% sawdust, and mixed industrial waste at 0.6%) and 87% coal. In scenario 2, the use of alternative fuel is increased to reach a TSR of 20%, with the proportions of RDF, rice husk, and sawdust at 10 %, 8 %, and 2%, respectively, and the use of coal is reduced to 80%. This scenario aims to shift energy use away from fossil fuels toward alternative fuels, consistent with the national target for the Indonesian cement sector to attain a 20% AFR-based TSR by 2030 (SIG, 2022).

The calorific value of materials is a decisive factor in enabling the adoption of alternative energy within the cement industry (Setiawan et al., 2021). Given the substantial energy requirements of clinker production, alternative fuels with higher calorific values contribute to increasing thermal substitution rates (TSR). In the cement industry, Cilacap, rice husk, sawdust, and refuse-derived fuel (RDF) are utilized as alternative fuels. Rice husk has a calorific value of approximately 3000 kcal/kg, representing approximately half the energy content of coal (Maryoto and Sudiby, 2018). Sawdust or wood residues offer a higher calorific value of up to 4387 kcal/kg, further supporting their applicability in coal co-firing systems (Kemala et al., 2023). Moreover, RDF used for clinker co-firing must meet specific quality standards, including a minimum calorific value of 10000 kcal/kg, moisture <25%, chlorine ≤1%, and sulfur content <1.5% (Table 2).

### 3.3.2 Life Cycle Impact Assessment and Interpretation

The Life Cycle Impact Assessment (LCIA) results for the co-firing scenario are presented in Table 5. Significant differences in potential impacts were observed between the baseline and co-firing scenarios in this study. This reduction is associated with the application of alternative fuels, leading to a decreased reliance on coal. The results demonstrate that the composition of alternative fuels for co-firing clinker

with the same thermal substitution rate affects the study results. The LCIA results show that the potential environmental impacts of cement kilns in Scenario 1, co-firing several alternative fuels (rice husk, sawdust, and RDF) with a thermal substitution rate of 20%, result in lower environmental impacts for all impact categories, as shown in the impact reduction (Figure 4). Overall, Scenario 2, co-firing TSR 20%, can reduce potential environmental impacts by 14%.

Table 5. Impact assessment of co-firing scenario

Impact Category	Unit	Scenario 1	Scenario 2
<b>Primary Impact</b>			
Global Warming	kg CO <sub>2</sub> eq	879.46	823.02
Acidification	kg SO <sub>2</sub> eq	5.34	4.62
Eutrophication	kg PO <sub>4</sub> eq	1.70	1.48
Ozone Depletion	kg CFC11 eq	0.00010	0.00009
Impact of Energy Use			
a. Non Renewable	MJ	5805.29	4928.30
b. Renewable	MJ	98.92	91.02
<b>Secondary Impact</b>			
Abiotic Depletion (Fossil Fuel)	MJ	5472.11	4640.81
Abiotic Depletion	kg Sb eq	0.00003	0.00003
Marine Ecotoxicity	kg 1,4-DB eq	16.18	13.99
Freshwater Ecotoxicity	kg 1,4-DB eq	11.14	9.65
Terrestrial Ecotoxicity	kg 1,4-DB eq	852.58	729.21
Human Toxicity	kg 1,4-DB	428.99	365.78
Water Consumption	m <sup>3</sup>	21.61	18.15

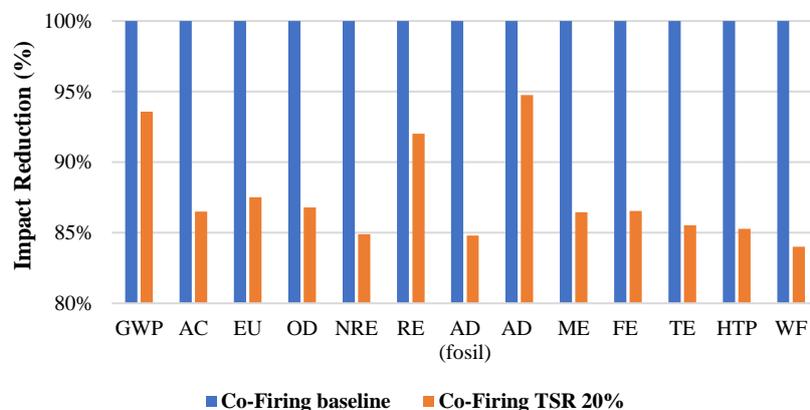


Figure 4. Impact reduction co-firing scenario

The global warming potential (GWP) impact category is primarily driven by the emissions of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and other greenhouse gases originating from fossil fuel combustion, vehicle operations, and electricity consumption (Havukainen et al., 2017). Electrical energy use represents a contributing factor to the sudden increase in GWP because it still comes from steam power plants that use coal as fuel (Mahmud et al., 2022). The GWP impact category in scenario 1 has a value of 879.46 kg CO<sub>2</sub>-eq, and in scenario 2, the value is 823.02 kg CO<sub>2</sub>-eq, indicating a potential reduction in impact by 6%. The results show that the use of alternative fuels with 20% TSR can reduce emissions by 56.44 kg CO<sub>2</sub>-eq per ton of clinker produced. Comparable to the results documented in the literature, the GWP attributed to the production of one ton of clinker under alternative scenarios, such as alternative fuels and raw materials (AFR) or other alternative technologies, ranges between 780 and 938 kg CO<sub>2</sub>-eq per ton of clinker

(Panahandeh et al., 2017; Güereca et al., 2015). The main contributors to this impact category are the use of coal, RDF, and electrical energy.

Emissions caused by clinker production have regional effects, such as acidification (AD) and eutrophication (EU). The eutrophication impact category is influenced by micronutrients such as nitrogen, phosphate, and chemical oxygen demand (COD) parameters. In this study, the AD impact category value of 5.34 kg SO<sub>2</sub> eq was obtained for the first scenario and 4.62 kg SO<sub>2</sub> eq for the second scenario. Meanwhile, in the EU impact category, the values for scenarios 1 and 2 were 1.70 kg PO<sub>4</sub> eq and 1.48 kg PO<sub>4</sub> eq, respectively. As shown in **Table 5**, the use of alternative fuels up to 20% can reduce the potential AD by 13% and EU by 12%. Furthermore, implementing a 20% TSR scenario lowers the ozone depletion potential from 0.00010 to 0.00009 kg CFC-11 eq, yielding a 13% improvement compared to the baseline scenario. Coal, electricity, sawdust, and rice husk were identified as the key contributors to these impact categories.

The energy use impacts were evaluated for both non-renewable (NRE) and renewable energy (RE) sources. The assessment results show that the baseline co-firing uses 5805.29 MJ of NRE and 98.92 MJ of RE, whereas the 20% TSR co-firing scenarios lower energy use to 4928.30 MJ of NRE and 91.02 MJ of RE. These changes represent a 15% reduction in NRE and an 8% reduction in RE potential impacts. The main contributors to the NRE impact category are coal and electricity, whereas in the RE impact category, coal, electricity, rice husk, and sawdust consumption are the main contributors.

Fossil fuel production associated with coal use is the dominant contributor to the abiotic depletion of fossil fuels (AD-fuel) impact category. Increasing the proportion of alternative fuels for clinker production in scenario 2 achieves a 15% reduction in impact (4,640.81 MJ) relative to the baseline (5,472.11 MJ). However, electricity generation remains a major contributor to this category, reflecting its continued dependence on fossil-based energy sources, such as coal and natural gas (Srafford et al., 2016).

The abiotic depletion (non-fossil) impact category is quantified in kg Sb eq. The calculated potential impact for each ton of clinker produced is 0.000035 kg Sb eq in the baseline scenario and 0.000033 kg Sb eq in the 20% TSR co-firing scenario. Therefore, the increased substitution of conventional fuels with alternative fuels achieves a 5% reduction in this impact category. The main contributing factors remain coal-based electricity and rice husk consumption. In the baseline co-firing scenario, the use of waste cans and textile waste as alternative fuels positively contributes to abiotic depletion impact.

The potential biotic environmental impacts assessed in this study included marine ecotoxicity (ME), freshwater ecotoxicity (FE), and terrestrial ecotoxicity (TE). The use of coal, electricity, and RDF was identified as the main contributor to these impacts. In the baseline co-firing scenario (Scenario 2.1), the potential impact values were 16.18 kg 1,4-DB eq for ME, 11.14 kg 1,4-DB eq for FE, and 852.58 kg 1,4-DB eq for TE. In contrast, the 20% TSR co-firing scenario resulted in lower impact values, with ME at 13.99 kg 1,4-DB eq, FE at 9.65 kg 1,4-DB eq, and TE at 729.21 kg 1,4-DB eq. In addition, RDF produced through mechanical treatment (RDF MT) consistently showed lower potential impacts than RDF from mechanical-biological treatment (RDF MBT) across all three categories.

The HTP impact category on cement kiln combustion has the potential to endanger human health through inhalation and contact hazards (Setiawan et al., 2021). The HTP impact category is influenced by the emission of PM, SO<sub>x</sub>, NO<sub>x</sub>, and heavy metal pollutants, which affect human health (Anasstasia, 2018; Ghony, 2019). In the HTP impact category, there was a decrease with the values of scenarios 1 and 2, amounting to 428.99 kg 1,4-DBeq and 729.21 kg 1,4-DBeq, respectively. The main contributors to the HTP impact category are the use of coal and electricity.

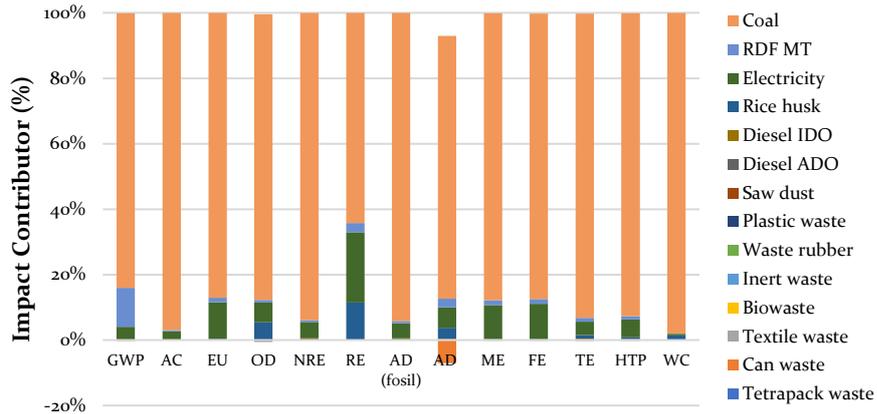


Figure 5. Impact contribution scenario 1 co-firing baseline

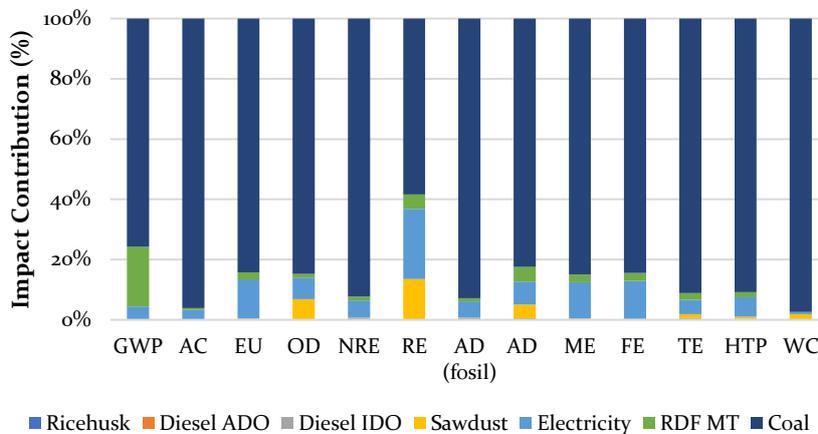


Figure 6. Impact contribution scenario 2 co-firing thermal substitution rate (TSR) 20%

The impact contributors to the co-firing scenario are shown in **Figures 5 and 6**. The main contributors to Scenario 1 are coal, electricity, RDF, and rice husks, whereas the main contributors to Scenario 2 are coal, electricity, RDF, and sawdust. Sawdust is one of the main contributors to the impact in the alternative scenario because, based on calculations, its calorific value increases significantly from 0.6 kg in the baseline scenario to 10 kg in the 20% TSR scenario. This substantial increase highlights the role of sawdust as a substitute fuel, which directly affects the overall environmental performance of Scenario 2. In contrast, the contribution of rice husks decreased, indicating a shift in the dominant biomass source between the two scenarios.

#### 4. Conclusions

The assessment results indicate that producing one ton of clinker in the RDF co-firing system is associated with high resource and energy demands, which causes significant environmental impacts in various categories. These include global warming, acidification, eutrophication, ozone depletion, fossil and mineral resource depletion, ecotoxicity, human toxicity, and water use, with quantified impacts of 879.46 kg CO<sub>2</sub> eq, 5.34 kg SO<sub>2</sub> eq, 1.70 kg PO<sub>4</sub> eq, 0.0001 kg CFC-11 eq, 5,471.11 MJ, 0.00003 kg Sb eq, 11.14 kg, 852.58 kg, 428.99 kg 1,4-DB eq, and 21.61 m<sup>3</sup>, respectively. These findings confirm that clinker production is a major contributor to greenhouse gas (GHG) emissions, abiotic resource use, and environmental toxicity loads. However, the implementation of co-firing with RDF shows significant environmental benefits, with a scenario of 20% thermal substitution rate (TSR) reducing the total environmental impact by 14%. This shows that RDF is effective in reducing dependence on fossil fuels,

thereby lowering emissions and potential toxicity. Further research is needed to expand the assessment by applying a more comprehensive life cycle assessment (LCA) approach that combines environmental, social, and cost perspectives. In addition, the scope of the analysis should be expanded from gate-to-grave to cradle-to-grave by including upstream stages such as raw material extraction, waste collection and sorting, RDF pre-treatment, and transportation to assess the overall environmental impact of the RDF supply chain

## **Acknowledgement**

We would like to express our sincere gratitude to everyone who has participated, contributed, and supported this event. Without your involvement and cooperation, this would not have been possible

## **Ethics Statement**

This research involved no human subjects, identifiable personal data, or animal experimentation. All data used in this study were obtained from direct field observations at waste management and industrial facilities as well as secondary data from publicly available databases and literature sources. The study was conducted in accordance with relevant institutional guidelines and standard research ethics, ensuring data integrity, transparency, and responsible reporting of the results.

## **CRedit Author Statement**

**Eyda Firdausi:** Conceptualization, Methodology, Data Curation, Formal Analysis, Investigation, Software, Visualization, Writing. **Hashfi Hawali Abdul Matin:** Supervision, Validation, Review. **Siti Rachmawati:** Supervision, Methodology Review, Review. **Yoyon Wahyono:** Technical Support, Data Validation, Review. **Purwono:** Methodological Guidance and Critical Revision of The Manuscript. **Budiyono:** Analytical Support, Interpretation of Results, and Manuscript Revision. **Larasati Gumilang Kencanawardhani:** Language Editing, Structural Revision, Final Proofreading.

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