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Evaluating the Potential of Refuse Derived Fuel (RDF) in Cement Production: a Comparative Analysis of RDF Variations In Indonesia's Emplacement Pluit, Jakarta

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Abstract

This study critically evaluated the potential of Refuse Derived Fuel (RDF) as a sustainable substitute for coal in the cement manufacturing process. Using Emplacement Pluit's waste as a primary source, three distinct RDF variations were analyzed: RDF A (comprised purely of PET Charcoal), RDF B (a 50-50 combination of PET Charcoal and organic waste), and RDF C (solely organic waste). Among the parameters evaluated were moisture content, ash content, and calorific value. The results indicated RDF A's superior quality, with a moisture content of 2.6%, ash content of 0.7%, and a calorific value of 25.1 MJ/kg. In stark contrast, RDF C exhibited a high waste reduction potential at 80.5%, but its calorific value fell short of Korean standards. RDF B, balancing quality and reduction potential, achieved a 98.9% waste reduction and met Korean RDF standards, making it the most viable alternative to coal in cement production. The study underscores the significant potential of integrating RDF in industrial practices, particularly cement kilns. It offers insight into optimizing waste management strategies in line with the 'zero-waste' vision.

INTRODUCTION

As urban populations burgeon and consumption patterns evolve, waste generation rates have seen an unprecedented surge (Suryawan & Lee 2023). With urbanization trends projecting an upward trajectory, waste volumes are only expected to escalate. Among the myriad types of waste, plastics, particularly PET (Polyethylene Terephthalate), have emerged as dominant pollutants (Alfahdawi et al. 2019; Zahra et al. 2022). With their non-biodegradable nature, PET bottles and similar plastic items linger in the environment for hundreds to thousands of years, wreaking havoc on ecosystems, especially marine ones (Iskandar et al. 2022; Sari et al. 2022c). Approximately 8 million metric tons of plastic are in our oceans annually (Suryawan et al. 2024), with PET products contributing significantly (Jambeck et al. 2015). Situated in a densely populated urban

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setting, Emplasement Pluit encapsulates the waste management challenges cities globally grapple with (Sari et al. 2022a).

The site's waste composition, dominated by PET bottles accounting for 63% of total waste, mirrors the larger global narrative where plastics have emerged as primary pollutants. Converting waste to energy has been spotlighted as a potential solution to tackle the mounting waste crisis. Methods like pyrolysis have garnered attention for their dual benefits: waste reduction and energy generation. For instance, when subjected to pyrolysis, PET can be transformed into valuable byproducts with significant energy potential (Yang et al. 2018; Singh et al. 2019; Zahra et al. 2022). The philosophy here is to view waste as a problem and an opportunity for resource extraction. While plastics pose significant challenges, organic waste, which constitutes a substantial fraction of urban waste, cannot be overlooked. Composting, an age-old method, offers one way to manage organic waste. Alternative solutions are imperative in contexts like Emplasement Pluit, where only a small fraction (5.6%) of organic waste is deemed suitable for composting (Sari et al. 2022b). Industries, particularly energy-intensive ones like cement production, are in perpetual need of fuel. With the environmental implications of fossil fuels becoming increasingly evident, there's been a shift in focus towards alternative fuels. Refuse Derived Fuel (RDF), manufactured from combustible waste components, offers a promising alternative. The potential of RDF, particularly from sources like PET and organic waste, in industries can lead to a circular economy model where waste is repurposed to meet energy demands (Suryawan et al. 2022b; Zahra et al. 2022). Many cities and countries have embraced the 'Zero Waste' vision, aiming to minimize waste sent to landfills and maximize recycling and repurposing. Emplasement Pluit's waste scenario, rife with challenges, also offers opportunities. With significant volumes of PET and organic waste, there exists a potential for waste repurposing, aligning with broader sustainable development goals.

The urgency of sustainable waste management solutions is evident across global scientific literature. As urbanization progresses and populations surge, effective waste management has evolved from an infrastructural challenge to an environmental, economic, and public health imperative (Ismiyati et al. 2016; Suryawan & Lee 2023). The prevalence of PET waste, especially in urban settings, has been highlighted by multiple studies (Qiao et al. 2018; Müller et al. 2020). As a non-biodegradable plastic, PET poses significant environmental threats, particularly in marine environments (Anani and Adetunji 2021; Zhao et al. 2023). However, research has also shed light on its latent energy value. The potential of PET waste as a valuable resource when subjected to thermal processes such as pyrolysis (Czajczyńska et al. 2017) discussed. Their findings resonate with the observations made for Emplasement Pluit, where PET waste's transformation through pyrolysis resulted in various energy-rich outputs. Pyrolysis, a thermochemical decomposition process occurring without oxygen, has been extensively studied as a viable method for converting waste to energy (Lam & Chase 2012; Guerrero et al. 2014). Results from studies like that of (Sari et al. 2023), align with previous literature where different outputs (gas, char, and liquid) from PET pyrolysis have been explored for energy generation and other applications.

The conversion of waste to RDF has been of significant interest to the research community. the role of RDF in reducing the dependence on fossil fuels, and a sentiment echoed in the present study of Emplasement Pluit's waste. The suitability of RDF, primarily when derived from organic waste and PET char, as an alternative to coal in industries, has been supported by previous research (Sarquah et al. 2023). Organic waste's potential, especially in urban settings, has been explored extensively. However, as observed in Emplasement Pluit, not all organic waste is suitable for composting, leading to the exploration of alternative uses, such as conversion to RDF. The cement industry's significant energy demands have directed researchers towards alternative fuels. Studies have highlighted the industry's gradual shift from coal to alternative fuels, including RDF (Sagala et al. 2018; Shumal et al. 2020). This aligns with the present study's findings, which advocate for RDF's use Emplasement in cement kilns derived from Emplasement Pluit's waste. While waste repurposing, especially through methods like pyrolysis, offers promising solutions, these processes' environmental and economic implications cannot be ignored. Various studies have pointed to challenges like emissions during pyrolysis (Conesa et al. 2020; Su et al. 2021). The literature underscores the pertinence of the findings from the Emplasement Pluit study. The transformation of PET and organic waste through pyrolysis and their potential repurposing into RDF is aligned with global research trends. However, the study can benefit from a more in-depth exploration of the environmental and economic impacts of such waste-to-energy processes moving forward.

Additionally, the broader 'Zero Waste' vision adopted by many cities and countries aims to minimize waste sent to landfills and maximize recycling and repurposing (Ghazali et al. 2021; Chen et al. 2022; Kurniawan et al. 2022). While Emplasement Pluit's waste scenario presents significant challenges, it also offers opportunities for waste repurposing to align with sustainable development goals. However, there is a gap in understanding how such zero-waste initiatives can be effectively implemented in densely populated urban settings, considering the specific waste composition and local socioeconomic conditions. In summary, this study addresses the gaps in effective PET and organic waste management in urban settings, the feasibility of implementing technologies like pyrolysis and RDF at scale, and the practical application of zero-waste principles in contexts similar to Emplasement Pluit. These gaps highlight the need for innovative, integrated waste management strategies that reduce waste and repurpose it to meet energy demands, thus supporting broader sustainability objectives.

METHOD

This research focuses on the potential of waste management and repurposing at Emplasement Pluit. With PET bottles comprising a significant portion of waste, the opportunity for waste conversion, particularly for energy generation, is evident. Pyrolysis presents an effective thermal decomposition technique for PET, producing gas, char, and liquid outputs. Previous research by (Sari et al. 2023), provides a breakdown of these outputs, revealing the potential for each byproduct.The predominant output, PET char, and a significant portion of non-compostable organic waste can be transformed into RDF. Given the calorific value of both PET char and organic waste, their conversion into RDF makes them apt candidates as coal substitutes, especially in industries like cement production. The research method then focuses on quantifying the potential waste reduction by creating different RDF mixes. Three variations of RDF were studied: RDF A (100% PET charcoal), RDF B (50% PET charcoal and 50% organic waste), and RDF C (100% organic waste). Each variant's quality was assessed based on moisture, ash, and calorific values. These values were benchmarked against RDF standards of Korea and Indonesia. The potential reduction was calculated using laboratory test results, particularly ash content results, representing the residue left after the RDF was burned. In addition to these RDF variations, the study also explores the potential of creating pellets using single-use masks and paper waste. The composition variations used in this study are based on previous research on RDF production, such as studies conducted by Zahra et al. (2022) and Suryawan et al. (2022b). These studies utilized a 25% interval to assess the quality of RDF produced with different raw material mixtures. A 10% tapioca flour adhesive will be used as the binder to create the pellets. Tapioca flour is chosen as an adhesive because of its ability to produce a good density, resulting in solid and crack-resistant RDF pellets. However, it is crucial to avoid excessive adhesive usage, as adding more than 10% tapioca flour can decrease pellet density, leading to lower pellet homogeneity (Suryawan et al. 2022a, b; Zahra et al. 2022; Sari et al. 2024).The pellet-making process begins with the preparation of materials, where essential materials such as single-use masks and paper waste are collected. The masks are screened to ensure they are free of contaminants, which is crucial for maintaining the quality of the final product. Based on prior studies, mask and paper waste mixtures are prepared following a 25% interval. This method, referenced from studies like Zahra et al. (2022) and Suryawan et al. (2022b), allows for a systematic assessment of RDF quality across different material compositions. The materials are mixed thoroughly to ensure a consistent and even distribution throughout the mixture. To bind the materials, 10% tapioca flour adhesive is added to each mixture. This specific percentage is chosen based on its effectiveness in creating pellets with good density and durability, as too much adhesive can negatively impact the pellet's quality. The mixture is blended well to form a homogenous blend, ensuring effective binding during pellet formation. The homogenous mixture is then processed into pellets using a pellet press or extruder. This machine applies controlled pressure and temperature to the mixture, shaping it into uniform, compact pellets. The precision in pressure and temperature control is key to achieving the desired density and consistency in the pellets. After formation, the pellets undergo a drying and curing process. This step is vital as it enhances the strength of the pellets and prevents them from cracking, which is crucial for their storage and handling. The final step involves conducting quality assessments on the produced RDF pellets. These assessments focus on evaluating the pellets' density, durability, and uniformity. The results from these assessments help determine the most effective material composition for producing high-quality RDF pellets. The pellet-making process in our study is a carefully designed procedure that incorporates established research methods and specific material compositions. The use of tapioca flour as a binder and the controlled processing conditions are critical to producing RDF pellets that are dense, durable, and suitable for their intended use.

RESULTS AND DISCUSSION

Emplasement Pluit's waste composition predominantly comprises PET bottles, accounting for 63% of the total waste. This high percentage presents a significant opportunity for waste repurposing, particularly given the high energy value of PET when subjected to thermal processes. Pyrolysis, a thermal decomposition method that takes place in an oxygen-free environment, is a promising technology for processing PET. Recent research Emplasement (Sari et al. 2023) has shown that PET pyrolysis results in gas (17.5%), char (80%), and liquid (2.5%). The gas can be used for energy generation on-site or sold to industries, while the char, known as 'PET char', can be processed further into Refuse Derived Fuel (RDF) to substitute coal, particularly in cement production. Although a potential alternative to conventional fuels like diesel, the liquid is produced in lower quantities, limiting its overall impact on energy substitution. The organic fraction, making up 37% of the waste, primarily consists of vegetation debris such as twigs, wood, and leaves from river cleaning activities. A secondary segregation divides this easily degradable waste into compostable and non-compostable fractions. From an initial 2113.4 kg/day of easily degradable waste, only 126 kg/day is found suitable for composting, leaving 1987.4 kg/day unutilized. Given that 95.4% of the total organic waste cannot be composted, there's a pressing need for alternative utilization methods. The potential calorific value of organic waste, especially wood (18.3 MJ/kg), makes it a suitable candidate for RDF production, similar to PET char. Emplasement Pluit's organic and inorganic waste holds significant potential for energy recovery. The large volumes of PET char and non-compostable organic waste can be repurposed into RDF, which could serve as a coal substitute in various industries. This approach would not only help in waste volume reduction but also contribute to sustainable energy generation, supporting the "Zero Waste" vision Emplasement (Lee et al. 2020).

An analysis was conducted to determine the most optimal type of RDF to reduce the total waste amount. Initial data revealed a total residue utilization of 3167.1 kg/day, consisting of PET charcoal and organic waste, which was transformed into RDF with a mixture variation of 50% of the total mass. A potential reduction calculation was performed for the organic waste, and PET charcoal was converted into RDF. Figure 1 shows a total waste residue utilization of organic waste and PET at 3167.1 kg/day, with organic waste generation at 2586.3 kg/day and PET charcoal at 580.8 kg/day. Subsequently, these two types of waste were processed into three RDF composition variations with a 50% mixture ratio: RDF A (100% PET charcoal), RDF B (50% PET charcoal and 50% organic), and RDF C (100% organic).

The reduction potential was obtained by calculating the laboratory test results, which included ash content with the mass of organic waste and PET charcoal. The ash content results represent the remaining residue produced from RDF after testing. Based on Figure 1, the reduction values from utilizing organic waste in RDF was 80.5% of the total waste generation. The utilization of PET charcoal in RDF reduced 18.2% of the total waste generation, and using a mixture of PET charcoal and organic waste as RDF resulted in a reduction percentage of 98.9%.

Despite these promising findings, there remains a gap in the comprehensive understanding and implementation of such technologies in urban settings. The feasibility, economic viability, and environmental impact of scaling up RDF production and usage, particularly from sources like PET and organic waste, require further investigation. Moreover, while Emplasemen Pluit's waste scenario presents significant opportunities, practical application of these findings in densely

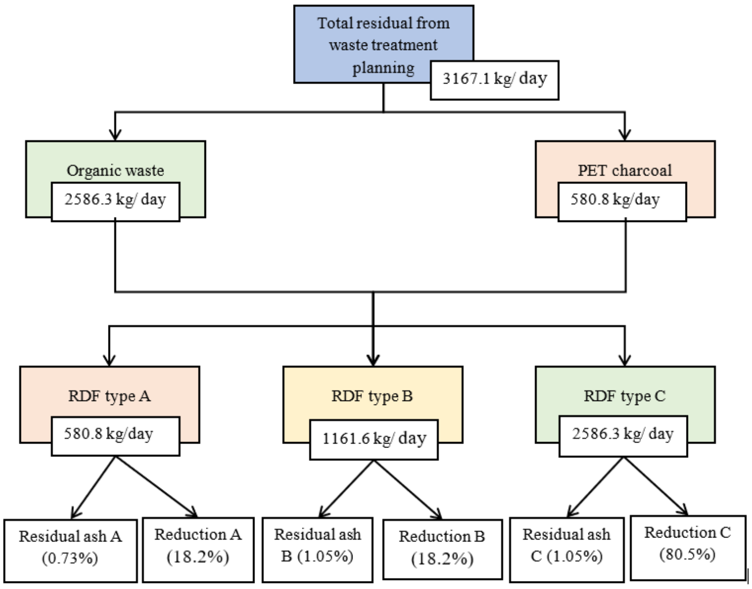

Figure 1. Total waste residue utilization of organic waste and PET.

populated urban areas, considering specific waste composition and local socioeconomic conditions, needs to be explored. This study seeks to address these gaps, providing innovative, integrated waste management strategies that not only reduce waste but also repurpose it to meet energy demands, thereby supporting broader sustainability objectives.

To determine the RDF with the best quality and optimal reduction potential, three key parameters were observed: moisture content, ash content, and calorific value. These parameters were compared to the RDF standards of Korea(Dong and Lee 2009) and Indonesia (Paramita et al. 2018). The reduction potential showed the percentage reduction of waste (PET charcoal and organic) utilized into RDF. Table 1 revealed that RDF A had the best quality, with a moisture content of 2.6%, ash content of 0.7%, and a calorific value of 25.1 MJ/kg. However, the reduction potential of RDF A could only reduce the total waste generation by 18.2%. This differed from RDF C, which had a significant reduction potential of 80.5%, but the calorific value of RDF C was below the standards of Korea (Dong & Lee 2009). On the other hand, RDF B achieved a reduction potential of 98.9% from the total waste generation with a moisture content of 3.6%, ash content of 1.1%, and a calorific value of 23.5 MJ/kg, meeting the RDF standards of Korea.

Based on the above description, it can be concluded that all three RDF variations met the specified standards, with RDF A producing the best quality RDF among the three. However, regarding reduction potential, RDF B was able to reduce the total waste to a maximum of 98.9%. Given the urgency concerning the residue pile-up at the TPST Bantar Gebang and the government's vision to implement the zero-waste concept, RDF type B was chosen as the preferred RDF to replace coal in the cement industry.

Table 1. RDF Quality.

Type	Quality (Sari et al. 2023)			Reduction potential (%)
	Water content (%)	Ash content (%)	Caloric value (MJ/kg)	
A	2.6	0.7	25.1	18.2
B	3.6	1.1	23.5	98.9
C	7.5	1.4	17.6	80.5

The calorific potential of utilizing RDF B with a composition of 50% PET Charcoal and 50% organic waste at the Emplacement Pluit meets the standards and can be used as fuel. The cement industry is one industry that uses RDF as a coal substitute in cement kilns.

The production capacity of these three companies was around 22.5 million tons per year in 2012 (Pratama 2013). The increasing cement production at Cement productionevery year is certainly accompanied by usingal as fuel in the combustion process. According to data, the coal requirement over the past four years has increased by 6% from total coal usage. The great potential of utilizing RDF B when applied to cement kilns can be known by knowing the average monthly coal requirement and the total fluctuating coal usage within 1 year. At the end of the year, the average total coal usage of cement production in 2012 was 168,833 tons/month. The average monthly coal usage will be calculated with the total waste generated to obtain the percentage of potential utilization of RDF as fuel in the cement kiln unit. Here's a calculation of the potential use of RDF as a substitute fuel at cement production:

- Total waste generation (PET Charcoal and organic waste) = 3167.1 kg/day x 30 days/month = 95,010 kg/month = 95 tons/month.
- The value of total waste generation is then calculated with the average total coal usage for 1 month, resulting in the following value: (95 tons/month) / (168,833 tons/month) x 100 = 0.05%.

Based on the calculation results on the use of RDF B as a substitute fuel for coal in cement kilns, the potential utilization is 0.05% of the total coal usage in cement production for one month. This modest percentage, while seemingly small, is a starting point that indicates the feasibility of integrating RDF into industrial processes. The alarming surge in global waste generation has nudged many industries to explore sustainable alternatives in raw materials and energy sources. As per the research findings, one promising alternative is RDF. The study's meticulous examination of different RDF variations and their potential utility holds profound implications for policy-making and industrial practices. Among the three RDF types, RDF B stands out in its unparalleled waste reduction potential, managing to curb a staggering 98.9% of total waste generation. Besides, it satisfies the calorific standards set by Korea (Dong & Lee 2009), making it a formidable contender to replace conventional fuels. This dual achievement of waste reduction and calorific value retention underscores the importance of policies that actively encourage and prioritize the production and utilization of RDF B. Such a move would resonate with the broader vision of sustainable industrial practices, allowing for significant reductions in the environmental footprints of industries, especially the cement sector.

However, the narrative around RDF is not merely about selecting the most efficient type. It delves deeper into striking a balance between quality and sustainability. While RDF A boasts the highest calorific value, its waste reduction potential is comparatively meager. This discrepancy accentuates the need for comprehensive standards. Current benchmarks, which focus predominantly on calorific values, might inadvertently sideline the equally pressing waste management issue. Policy formulations must entail standards that give equal weightage to both calorific value and waste reduction potential to ensure a balanced approach (Shekdar, 2009). By doing so, industries would be nudged to produce RDFs that serve as efficient fuel sources and contribute tangibly to waste redution.

The cement industry's potential transformation through adopting RDF is particularly noteworthy (Shumal et al. 2020). Traditionally reliant on coal, a major pollutant, the industry now has the chance to pivot towards a cleaner and more sustainable alternative (Todeschini et al. 2017). With global coal consumption and its resultant emissions being a significant environmental concern (Bilgen 2014), the urgency to transition cannot be overstated. Policies must, therefore, advocate for a gradual yet decisive shift from coal to sustainable fuels like RDF. This is not merely a call for environmental protection; it is a pragmatic strategy that would ensure the long-term viability of the cement industry amidst tightening global environmental regulations.

However, the current potential utilization of RDF B in cement production, as revealed by the research, stands at a modest 0.05% per month. While seemingly small, it's a starting point that indicates the feasibility of using RDF in industrial processes. Scaling up production and utilization is the next logical step. A practical policy roadmap should incorporate strategies for sourcing more raw materials, optimizing waste management practices, and promoting research to boost the potential of RDF(Suryawan et al. 2023). For instance, places like Emplacement Pluit, which are significant contributors to the RDF feedstock, must adopt more efficient waste segregation and processing methods. Enhanced practices would ensure consistent RDF quality, facilitating widespread adoption across industries. For RDF's potential to be fully realized, stakeholder collaboration is indispensable. Manufacturers, distributors, and end-users in the cement industry must be aware of RDF's environmental and economic advantages. Awareness can stimulate demand, ensuring the transition to RDF remains commercially viable. Policy-makers could consider introducing economic incentives, such as tax breaks or subsidies, to sweeten the deal further, lowering entry barriers for industries looking to adopt RDF. As industries embark on this transformative journey, continuous monitoring becomes essential. Policymakers need a robust feedback mechanism to assess RDF's real-world impacts on waste reduction, emission levels, and the broader environmental footprint. Such continuous assessments can offer valuable insights, helping refine and recalibrate policies as the RDF landscape evolves. Lastly, the pivot to RDF is as much about public perception as it is about industrial change. Grassroots campaigns that elucidate the myriad benefits of RDF from its role in curtailing waste generation to its contribution in diminishing carbon footprints can be pivotal. An informed public can become staunch advocates for the cause, driving market demand and solidifying RDF's place as the fuel of the future.

CONCLUSION

The escalating concerns surrounding environmental sustainability, waste management, and the pressing need to transition to cleaner energy sources have spurred numerous studies and innovations across the globe. This study, centered on the feasibility and implications of utilizing RDF in cement production, offers significant insights into addressing these interconnected challenges. The research highlights the complexities of optimizing calorific value and waste reduction potential through a detailed examination of three RDF types. While each RDF type presented distinct advantages, RDF B emerged as the clear frontrunner, achieving an unparalleled waste reduction potential of 98.9% while meeting Korea's calorific standards. These findings suggest an actionable solution for the dual challenges of waste management and sustainable fuel utilization, particularly in sectors like cement production that traditionally rely on environmentally detrimental sources like coal. However, the potential utilization of RDF B in cement production is currently modest, indicating the early stages of this transformative journey. As industries face increasing demands for sustainability, the transition to RDF B offers a practical pathway toward aligning industrial practices with broader environmental goals. This transition represents a response to regulatory pressures and a proactive step toward a more sustainable and environmentally responsible future.

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