EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2023, 24(8), 133–142
https://doi.org/10.12912/27197050/171443
ISSN 2719–7050, License CC-BY 4.0

Received: 2023.07.26
Accepted: 2023.09.25
Published: 2023.10.10

Utilizing Pyrolysis of Plastic Debris for Refuse-Derived Fuel Production and Viable Substitute to Wood Debris

Mega Mutiara Sari[1*], Takanobu Inoue[2], Regil Kentaurus Harryes[3], Iva Yenis Septiariva[4], Kuriko Yokota[2], Suprihanto Notodarmodjo[5], Shigeru Kato[2], Rizal Muhammad Al Ghifari [1], Sapta Suhardono[6], I Wayan Koko Suryawan[1], Wisnu Prayogo[7], Nur Novilina Arifianingsih[5]

[1] Department of Environmental Engineering, Faculty of Infrastructure Planning, Universitas Pertamina, Komplek Universitas Pertamina, Jakarta, Jakarta Selatan, Indonesia

[2] Department of Architecture and Civil Engineering, Toyohashi University of Technology, Japan

[3] Faculty of Vocational Studies, Indonesia Defense University, Indonesia

[4] Study Program of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret, Jalan Ir Sutami 36A Surakarta, Jawa Tengah 57126, Indonesia

[5] Department of Environmental Engineering, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Jl. Ganesha no. 10, Bandung 40132, Indonesia

[6] Environmental Sciences Study Program, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta, 57126, Indonesia

[7] Universitas Negeri Medan, Medan, Indonesia

[*] Corresponding author's email: mega.ms@universitaspertamina.ac.id

ABSTRACT

This research explores the viability of converting discarded Polyethylene Terephthalate (PET) plastic waste into a valuable resource through the implementation of pyrolysis and refuse-derived fuel (RDF) technologies. The objective is to assess the potential of PET charcoal waste as an efficient source for RDF generation, surpassing the energy recovery and recycling potential of PET waste. The study introduces three RDF variants: RDF PET100, RDF PET50, and RDF PET0. RDF PET100 is comprised entirely of PET charcoal, RDF PET50 combines 50% PET charcoal with 50% wood debris, and RDF PET0 consists entirely of wood debris. Comprehensive assessments of water content, ash content, and calorific value were conducted to evaluate the quality of these RDF formulations. Results indicate that RDF PET100 exhibits a water content of 2.63%, ash content of 0.73%, and calorific value of 5,976 MJ/kg. Similarly, RDF PET50 showcases a water content of 3.6%, ash content of 1.05%, and calorific value of 5,587 MJ/kg. RDF PET0 presents a water content of 7.51%, ash content of 1.36%, and calorific value of 4,198 MJ/kg. The outcomes underline the potential of PET plastic waste repurposing through RDF and pyrolysis techniques. Particularly, RDF PET100 emerges as a high-caliber fuel option characterized by its minimal water and ash content, coupled with a substantial calorific value. This innovation holds promise in mitigating plastic waste challenges, particularly pertinent in the context of Indonesia.

Keywords: plastic debris, refuse-derived fuel, PET, caloric value.

INTRODUCTION

In Indonesia, the waste hierarchy used for waste management and environmental conservation follows a structure that aligns with international waste management strategies. This hierarchy establishes a priority order for waste management approaches based on environmental impact and sustainability. The stages of the waste hierarchy in Indonesia encompass source reduction and prevention, reuse, recycling and recovery, treatment, and disposal. The recycling and recovery phase involves collecting, segregating, and processing materials such as paper, plastics, metals, and glass that can be recycled. These materials are diverted from disposal and reprocessed for new purposes. In instances where recycling is not feasible, the treatment phase comes into play. This phase employs incineration, anaerobic digestion, or composting methods to reduce the volume and potential environmental impact of non-recyclable waste. As a last resort, the disposal stage is considered. If all other avenues are exhausted, waste is disposed of in landfills or specialized waste management facilities. Efforts are made to ensure that these disposal methods minimize adverse environmental consequences.

The potential for plastic waste in Indonesia is still a problem, especially in Jakarta (Nurhati and Cordova 2020; Suryawan and Lee 2023). In addition, the previous study found that waste transported from Jakarta's main waterways daily is dominated by plastic waste. Waste originating from the Jakarta river is transported to a temporary storage location before finally being taken to the Bantar Gebang landfill (Sari et al. 2022a). The Pluit emplacement has an area of 0.28 hectares located downstream of the DKI Jakarta river. There is no recycling processing at the emplacement, and it is feared that a leak occurs. River debris, especially plastic debris, will contaminate the coastal estuary area of DKI Jakarta, damaging the mangrove ecosystem, coral reefs, and seagrass beds and causing loss of marine biota. In addition, the river debris entering the Bantar Gebang landfill has increased compared to land waste from 2017–2019. This will exacerbate the conditions at the Bantar Gebang landfill is estimated that will not accommodate the amount of waste generated (Machmud 2017).

In response to these problems, efforts are needed to reuse plastic waste by processing Polyethylene Terephthalate (PET) plastic waste into alternative fuels using refuse-derived fuel (RDF) using pyrolysis technology. The selection of PET plastic waste is based on the composition of PET waste, which occupies the highest position from inorganic types at 22% of the amount of waste generation, so it is the right effort to reduce PET waste generation (Sari et al. 2022a). RDF is a material with a high calorific value fraction formed from municipal solid waste (Suryawan et al. 2022). RDF is a material/substance quickly burned from urban solid waste. RDF's composition consists of wood, plastic, paper, and other dry materials. The process of separating solid waste between volatile and non-combustible components. However, the presence of water content is one of the factors that cause the calorific value to be low. Therefore, additional treatments and materials are needed to remove the water content and increase the calorific value of the RDF.

In general, developed countries such as Finland, England, Germany, and Sweden use RDF as a fuel that will be mixed with coal (Al-Mansour and Zuwala 2010; Shafie et al. 2013). Utilization of RDF is only used in boilers to produce steam. Therefore, the percentage of mixture between RDF and coal varies. An initial process is needed to utilize urban waste in RDF. This is done to prevent problems with environmental quality. RDF as fuel in cement factories has begun to be used in Indonesia and worldwide. The operationalization of RDF facilities can be a turning point for waste management in Indonesia (Rachman et al. 2020; Sarwono et al. 2021; Sari et al. 2022b). The RDF implementation program is also one of the efforts and applications in waste management, which is regulated in laws and regulations that correlate or are directly related to waste management. Policy directions for reducing and handling household waste and household-like waste, and program strategies and targets for reducing and handling household waste and household-like waste. In the period from 2017 to 2025. This target is measured by reducing waste by 30% and handling waste by 70% (Sari et al. 2021). One that contributes to waste handling, among others, is the development of the application of appropriate household waste and household-like waste handling technology through waste as a substitute fuel for the cement industry or RDF.

The pyrolysis process is a thermal process that utilizes temperatures between 350°C to 520°C without the involvement of oxygen (Singh and Ruj 2016). Products from the pyrolysis process include solids (charcoal), gas (fuel gas), and liquid (bio-oil) (Vamvuka 2011). The large percentage of residue generated will reduce efforts to reduce waste generation at the Bantar Gebang TPST. The application of the zero waste concept aims to turn waste into another form by recycling, burning, or biological decomposition so that the waste produced is close to 0%. So it is necessary to reuse residue from PET charcoal into fuel in the form of RDF. The reuse of PET charcoal into RDF is based on the potential calorific value possessed by PET charcoal of 6124.40 kcal/g (Haryono 2020). Efforts to reuse residue from the pyrolysis of PET waste are the right step in maximizing efforts to reduce waste generation that goes into landfills. Therefore, this study aims to analyze the potential for PET charcoal waste to become RDF, which is expected to overcome the PET debris energy recovery and recycling process.

RESEARCH METHOD

This research involved both a literature review and laboratory experiments. The study aimed to investigate the possibility of using charcoal obtained from the pyrolysis process of PET bottle waste as raw material for RDF. The study produced RDF by mixing PET charcoal with starch-based adhesive. The quality of the RDF was evaluated through tests to determine the water content, ash content, and calorific value. The research also explored the potential of utilizing RDF charcoal at Emplacement Pluit (as shown in Figure 1) as an alternative fuel in the cement industry. Material testing for this research was conducted at the laboratory facilities of Universitas Pertamina, Jakarta in an ex-situ setting. The primary materials subjected to testing were PET bottle waste and the resulting charcoal obtained through the pyrolysis process.

This study focus on PET that already recovered by production of charcoal through pyrolysis procrss. The raw PET bottle waste was collected from Emplacement Pluit. After the pyrolysis process, the charcoal was collected and subjected to further processing and testing within the laboratory. This included thorough drying to remove any residual moisture that might impact subsequent testing. The material's characteristics, such as water content, ash content, and calorific value, were analyzed to determine its suitability for use as RDF.

This study used both primary and secondary data collection methods. Primary data was obtained through laboratory experiments on the remaining charcoal from the pyrolysis of PET bottle waste at Pluit Emplacement. The tests conducted on the RDF of PET charcoal included measurements of water content, ash content, and calorific value. Secondary data was obtained from various literature sources, including information on RDF quality requirements in different countries and the generation and composition of waste at Pluit Emplacement.

The primary data collection was conducted to support and validate the secondary data obtained. The laboratory tests on RDF were performed using parameters such as ash content, water

Figure 1. Sampling location

content, and caloric value. The method used to determine the water content of RDF was adjusted to American Standard Testing and Material (ASTM) D.3173. The water content of RDF was calculated by placing the RDF sample in a porcelain cup and measuring its weight before and after it was placed in an oven at a set temperature. The cup was then removed from the oven and reweighed to determine the water content of the RDF sample. The calorific value of RDF charcoal PET was adjusted to ASTM D.5865 using a bomb calorimeter. This value is used to obtain data regarding the heat energy that can be released by a material/fuel in the presence of a combustion reaction. The caloric value will be compared with the RDF quality standards. The ash content value contained in the RDF charcoal PET is compared with the standard ash content set for RDF. Determination of RDF ash content adjusted to ASTM D.3174. Drying the porcelain cup in the furnace at 600 °C for 30 minutes and weighing the empty weight. According to ASTM E 856–83 (2006), this type of RDF with the essential ingredients of PET charcoal and organic waste is included in RDF category five or is called densified RDF. The characteristic of RDF category 5 is that it has a pellet-like shape. The flow of PET charcoal utilization follows Figure 2.

The production of RDF pellets starts with the utilization of the residual PET char obtained from the pyrolysis of PET waste. This char is subjected to a crushing process until its particle size is reduced to less than ten mesh per inch. To ensure the complete breakdown of the PET char, tools like shredders are employed. After the crushing process, the resulting PET charcoal powder is sieved to remove any particles exceeding ten mesh in size. It's important to note that the residual PET char, having undergone pyrolysis or similar treatments, exhibits altered structural properties. This could mean that its unique physical characteristics either warrant or enhance the shredding action before pelletizing. There's also a possibility that the char's form is already granulated enough, which allows it to skip the initial shredding and move directly to the hammer mill stage. The hammer mill then further refines its size to make it suitable for the subsequent stages of pelletizing. Particles found to be oversized during the sieving process are sent back for additional crushing until they achieve the desired size specification. The entire process of creating RDF pellets is undertaken within the charcoal briquette industry. Figure 3 visually presents the procedure of processing PET charcoal powder sourced from river debris.

We used starch-based adhesive serves in pellet making. The primary role of starch-based adhesive in pellet making is to act as a binding agent that holds together the particles or fibers of the raw material, forming cohesive and durable pellets (Suryawan et al. 2022; Zahra et al. 2022). In processes like pyrolysis, the adhesive can aid in the formation of solid and well-structured pellets that are conducive to effective conversion into char or biochar.

In the manufacturing process of RDF, the first step is to mix the charcoal powder with an adhesive. In this study, tapioca flour was used as the adhesive, which was added to the mixture in a percentage of 5% of the total weight. The choice of tapioca flour as an adhesive was based on its high carbohydrate content and stickiness. The mixture of RDF and adhesive is adjusted depending on various factors, such as the type and amount of adhesive, the amount

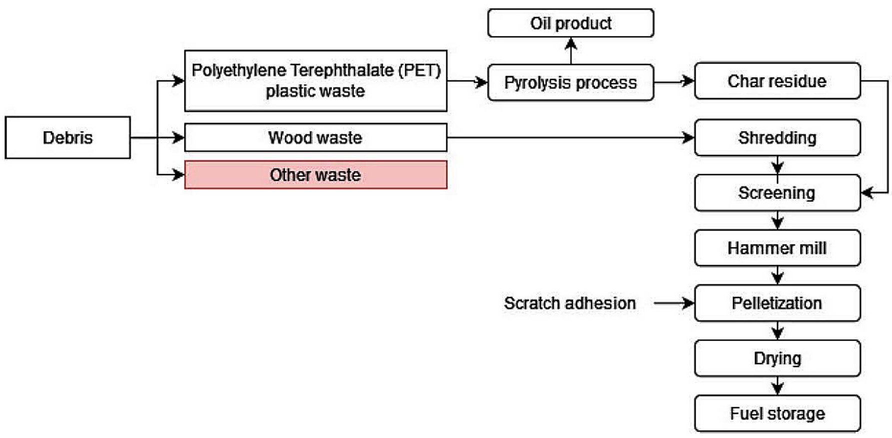

Figure 2. Process flow for making RDF from PET debris and Wood Debris

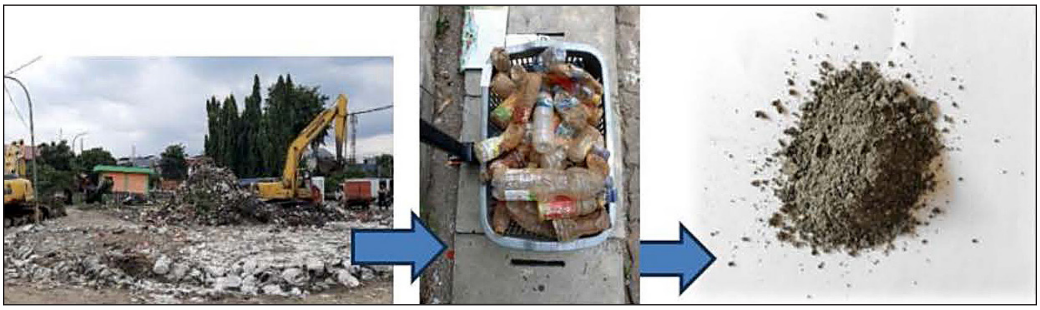

Figure 3. Processing step of PET charcoal powder material from river debris

of charcoal powder and wood debris, and the pressing pressure used. The effectiveness of the mixer and the composition of the adhesive also have an impact on the quality of the final product. The aim is to obtain a solid texture resulting from the mixing process, which can be compressed using a compression or extrusion tool to form pellets or briquettes. The use of an appropriate adhesive is crucial to ensure the strength and durability of the RDF pellets or briquettes, which are then used as an alternative fuel source in various industries.

In the production of RDF, compression or extrusion tools are utilized as printing devices. The compression process can be divided into two ways: exceeding the elastic limit of the raw material and not yet exceeding the elastic limit of the raw material. The former involves applying pressure to the raw material (PET charcoal and starch) beyond the elastic limit, resulting in deformation and the formation of RDF. The latter involves applying pressure to the raw material (PET charcoal and starch) without exceeding the elastic limit, resulting in the formation of RDF. In this study, compression tools were used to produce RDF, which had a length of 4 cm and a diameter of 0.9 cm. This method of RDF production is efficient and cost-effective as it can be done using existing equipment in the charcoal briquette industry. The produced RDF can be utilized as an alternative fuel source in the cement industry. Figure 4 provides an image of the size of the RDF produced using compression tools, which can be further optimized to meet the specific requirements of different industries.

During the printing stage, the RDF contains around 50% water content. Thus, it is necessary to dry the RDF using tools such as an oven or direct sunlight (Septiariva et al. 2022). In this study, the oven drying process is conducted at a temperature of 60°C for 6 hours to ensure that the RDF's water content meets the required provisions for RDF water content. The main objective of producing RDF is to evaluate its characteristics, including water content, ash content, and calorific value. To determine the RDF's quality, the mixture percentage in the RDF production is varied at 50% intervals, with a total RDF mass of 0.5 kg. This variation is conducted to investigate the RDF composition's quality. The variations of RDF samples are presented in Table 1 and Figure 5. The mixture percentage in the RDF production is adjusted based on various factors, such as the type and amount of adhesive, charcoal powder, wood debris, and pressing pressure.

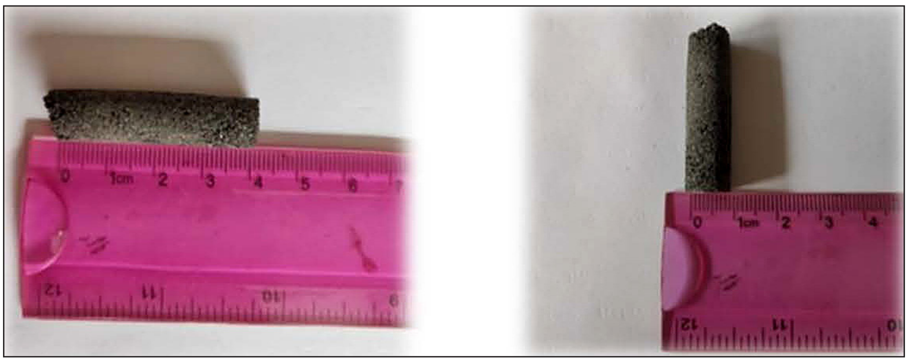

Figure 4. RDF dimensions

Table 1. Variation of waste samples on RDF

RDF	Variation	
	PET charcoal	Wood powder
PET100	0.5 kg (100%)	0 kg (0%)
PET50	0.25 kg (50%)	0.25 kg (50%)
PET0	0 kg (0%)	0.5 kg (100%)

Figure 5. RDF of the three variations

Additionally, the effectiveness of the mixer and the adhesive composition also affects the RDF's quality.

RESULT AND DISCUSSION

PET and organic waste at pluit emplacement obtained a total waste generation of 3167.1 kg/day with 2586.3 kg/day of organic waste and 580.8 kg/day of PET charcoal. Besides, PET charcoal's initial characteristics have a caloric value of 25.6416 (Haryono 2020), and organic waste in the form of wood has a caloric value (Zahra et al. 2022). Therefore, the calorific value and large waste generation from these two types of waste have the potential to be reused into fuel in the form of RDF pellets. Besides that, RDF form of effort to realize the concept of zero waste will be achieved (Sapuay 2016).

The pyrolysis process, also known as destructive distillation, is a process of irregular decomposition of a material caused by heating without direct contact with outside air. This process will produce three types of products: liquid, residue in the form of solids, and gas (Maafa 2021; Harussani et al. 2022). Figure 2 describes the flow chart of the pyrolysis process with the input data in the form of PET bottle waste of 725.9 kg/day. PET bottle waste that is decomposed by pyrolysis produces gas with a percentage of 17.5%, charcoal with a percentage of 80%, and liquid with a percentage of 2.5%.

On the other hand, the percentage of liquid produced from PET bottle waste is only 18.2 kg/day, while the resulting charcoal is 580.8 kg/day. Therefore, the charcoal produced will cause less than optimal reduction efforts from the waste generation entering the landfill. So further utilization is needed by PET charcoal as fuel in the form of RDF. Refused derived fuel that has been printed will undergo laboratory testing to determine the quality value of each parameter, such as water content, ash content, and caloric value. Furthermore, the test results were compared with predetermined standards to determine the quality of RDF from the three types of RDF variations. Table 2 shows that the standard water content from South Korea is lower than the standard used in cement kilns in Indonesia, where plastic has water-resistant properties, which causes the water content value to be low (Zahra et al. 2022). In the results of testing the water content of the three variations of RDF shown in Table 2, there is a difference in the water content value of each RDF. For example, PET0 shows a water content value of 8.36%, PET0 shows a water content value of 4.9%, and PET100 shows a water content value of 2.6%. The decrease in the value of the water content of the three RDF variations is due to a change in the composition of the RDF. Where every addition of 50% PET charcoal powder, plastic waste, can reduce the water content.

Testing the value of ash content is obtained from the residue/residue of combustion products. The residue is a mineral substance that cannot be broken down during combustion. Silica, a constituent of ash, has an unfavorable effect on the calorific value (Putri & Sukandar, 2013). Table 2 shows that the ash content of the

Table 2. RDF quality test results

Variation	Arang PET (kg)	Wood powder (kg)	Water content (%)		Ash content (%)		Caloric value (MJ/kg)	
			Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
PET100	0.5	0	2.6	0.01	0.8	0.1	26.9	1.2
PET50	0.25	0.25	4.9	0.4	1.1	0.1	22.5	0.1
PET0	0	0.5	8.4	1.2	1.5	0.1	17	0.9

three RDF variations from PET100 to PET0 is 0.8%, 1.2%, and 1.5%, respectively. In general, the higher the value of the ash content of charcoal/coal, the calorific value will decrease (Heberlein et al. 2022). In addition, the high ash content will produce a large amount of residue after the RDF combustion process. So, efforts to reduce the generation of Pluit Emplacement waste that will enter the Bantar Gebang landfill will be less than optimal.

The calorific value of RDF was tested using a bomb calorimeter test. Table 2 shows the results of testing the calorific value from lowest to highest, namely PET0 at 17 MJ/kg, PET50 at 22.5 MJ/kg, and PET100 at 26.95 MJ/kg. The different values of the water content and ash content influence the difference in the calorific values of the three RDF variations. This value is influenced by the water content and ash content of RDF PET100, which has the lowest value of the three RDF variations at 2.6% and 0.7%, while RDF PET0 has a caloric value of 17.6 MJ/kg. This value is influenced by the value of water content and ash content of RDF PET0, which obtained the highest values of the three RDF variations of 7.5% and 1.4%. This indicates an inverse relationship between the calorific value and the water and ash content. If the water and ash content value is low, the calorific value will be high. According to previous studies (Suryawan et al. 2022; Gałko et al. 2023), RDF, which has a high calorific value, will produce good fuel quality because the combustion process occurs effectively and efficiently.

Multiple linear equation models are used to optimize the calorific value of the RDF produced in this study. The models are tested through multiple linear regression tests to determine the simultaneous effect of both quality and quantity of independent variables, such as the addition of wood powder, water content, and ash counter, on the dependent variable, which is the calorific value. The results show that adding wood powder has a negative and significant effect on the calorific value. This means that the higher the wood powder, the lower the calorific value. Similarly, the water content in the RDF significantly and negatively affects the caloric value. Table 3 shows the complete model, which has an R Square value of 99.6%. The R Square value represents the proportion of the variation in the dependent variable that can be explained by the independent variables included in the model. The high R Square value of 99.6% indicates that the model can explain 99.6% of the variation in the calorific value of RDF.

The regression equation model is a tool that can be used to predict the relationship between variables in a population outside of the sampled data. In this study, the regression equation model was used to analyze the relationship between the variables of wood powder, water content, ash content, and calorific value of RDF. The ANOVA (Analysis of Variance) results in Table 4 show

Table 3. Multiple linear equation models in determining the calorific value of RDF

Parameters	Unstandardized coefficients		Standardized coefficients	t	*p*-value
	Beta	Standard error	Beta		
(Constant)	24.073	2.209		10.898	0.008
Wood powder	-0.017	0.004	-0.838	-3.819	0.062
Water content	-1.154	0.369	-0.677	-3.125	0.089
Ash content	7.399	3.164	0.522	2.338	0.144
Model summary					
R square	0.996				
Adjusted R square	0.99				

that the given model is significant, which indicates that the three variables (wood powder, water content, and ash content) have a simultaneous effect on the calorific value of RDF. This means that changes in any of these three variables can affect the calorific value of RDF. The ANOVA results also show that the model's coefficient of determination (R2) value is 98.2%, which means that the model can explain 98.2% of the variation in the calorific value of RDF. Therefore, this model can be used as a guideline for predicting the calorific value of RDF based on the values of wood powder, water content, and ash content.

Based on the findings of this study, it can be recommended that RDF pellets made from a combination of PET charcoal and wood debris can be a potential alternative fuel source. RDF PET50, which consists of 50% PET charcoal and 50% wood debris, has the potential to be the most feasible RDF variation based on its water content, ash content, and caloric value. In comparison to previous studies, this study provides a new perspective on the use of PET charcoal as a component of RDF pellets. Previous studies have mainly focused on using wood waste, agricultural waste, and municipal solid waste as the main component of RDF pellets. However, this study shows that PET charcoal, which is a waste material from PET bottle recycling, can also be used to produce RDF pellets. Additionally, this study provides insight into the potential of pyrolysis as a method to convert PET bottle waste into useful products such as charcoal, liquid, and gas. This can contribute to reducing the amount of PET bottle waste sent to landfills and can potentially reduce greenhouse gas emissions.

The Strengths Weaknesses Opportunities and Threats (SWOT) analysis (Table 5) shows that the implementation of RDF pellets as a waste-to-energy solution in Jakarta and other developing countries has great potential, but also faces some challenges. One of the strengths of this technology is its ability to reduce waste and generate energy at the same time. This can contribute to the development of a circular economy and help address the issue of waste management. In addition, the high calorific value of RDF pellets makes them a viable alternative to fossil fuels, which can reduce greenhouse gas emissions and mitigate climate change. However, the implementation of RDF pellets also faces some weaknesses and threats (Suryawan et al. 2022). One of the weaknesses is the high initial investment required for setting up the infrastructure and equipment needed to produce RDF pellets. Moreover, the low public awareness and acceptance of this technology may hinder its adoption (Suryawan et al. 2023). Some of the threats to this technology include the

Table 4. Analyst results of ANOVA equation model

Model	Sum of squares	df	Mean square	F	*p*-value
Regression	102.282	3	34.094	158.252	0.006
Residual	0.431	2	0.215		
Total	102.713	5			

Table 5. SWOT analysis implementation of RDF pellets as a waste-to-energy solution

Strengths:	Weaknesses:
• Addresses the issue of waste management and provides an alternative to landfilling. • Produces a renewable energy source that can potentially reduce reliance on non-renewable sources. • Can potentially create job opportunities in the waste management and renewable energy sectors. • Provides a solution for managing PET waste, which can be challenging to recycle through traditional methods.	• Requires significant investment in equipment and facilities for pyrolysis and RDF production. • May face resistance from communities who are not familiar with the technology or may be skeptical about its effectiveness. • Requires a steady stream of waste inputs to sustain operations. • Potential for air pollution during the pyrolysis process if not properly controlled.
Opportunities: • Collaboration with local governments and waste management organizations to implement the technology at a larger scale. • Potential for partnerships with industries and businesses to provide a sustainable waste management solution. • Potential for export of RDF pellets to countries with high demand for renewable energy sources. • Can contribute to achieving sustainable development goals related to waste management and renewable energy.	Threats: • Potential for competition with existing waste management solutions or renewable energy sources. • Lack of awareness or understanding about the technology among potential investors or customers. • Changes in government policies or regulations that could impact the viability of the technology. • Dependence on a steady supply of waste inputs, which may be affected by changes in waste generation patterns or availability.

fluctuation of raw material prices and the availability of waste feedstock, which can affect the feasibility and profitability of the RDF pellet production. The research highlights the potential of RDF pellets as a sustainable energy source and provides insights into the quality and characteristics of RDF pellets produced from different waste compositions. The SWOT analysis also provides a comprehensive evaluation of the implementation of RDF pellets as a waste-to-energy solution in Jakarta and other developing countries, which can guide decision-makers and stakeholders in the development of sustainable waste management strategies.

CONLUSIONS

The residual waste generated at Pluit Emplacement was utilized to produce RDF with variations of composition. Three types of RDF variations were produced, namely RDF PET100, RDF PET50, and RDF PET0. RDF PET100 had a composition of 100% PET charcoal, RDF PET50 had a composition of 50% PET charcoal and 50% wood debris, and RDF PET0 had a composition of 100% wood debris. Laboratory tests were conducted to determine the quality of RDF based on three parameters, namely water content, ash content, and calorific value. The results of the tests showed that RDF PET100 had a water content of 2.6%, an ash content of 0.7%, and a caloric value of 5976 MJ/kg. RDF PET50 had a water content of 3.6%, an ash content of 1.05%, and a caloric value of 5587 MJ/kg. RDF PET0 had a water content of 7.5%, an ash content of 1.4%, and a calorific value of 4198 MJ/kg. These results provide insights into the potential use of RDF from residual waste as an alternative fuel source.

The best RDF PET variant based on thorough analysis of laboratory test results. They considered crucial parameters such as water content, ash content, and calorific value. Among the variations tested, RDF PET100, consisting entirely of PET charcoal, demonstrated the most favorable attributes – low water and ash content, along with a high calorific value. These qualities indicate efficient combustion and superior energy output. This informed choice aligns with the study's purpose of producing RDF with optimal energy content and minimal non-combustible residue, and it reflects on sustainable fuel alternatives.

REFERENCES

1. Al-Mansour F., Zuwala J. (2010) An evaluation of biomass co-firing in Europe. Biomass and Bioenergy 34: 620–629. https://doi.org/https://doi.org/10.1016/j.biombioe.2010.01.004
2. Gałko G., Mazur I, Rejdak M., et al (2023) Evaluation of alternative refuse-derived fuel use as a valuable resource in various valorised applications. Energy 263: 125920. https://doi.org/https://doi.org/10.1016/j.energy.2022.125920
3. Harussani M.M., Sapuan S.M., Rashid U., et al (2022) Pyrolysis of polypropylene plastic waste into carbonaceous char: Priority of plastic waste management amidst COVID-19 pandemic. Sci Total Environ 803: 149911. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.149911
4. Haryono H. (2020) Uji Kualitas Briket dari Tongkol Jagung dengan Perekat Kanji/PET dan Komposisi Gas Buang Pembakarannya. J Ilmu dan Inov Fis 4: 131–139. https://doi.org/10.24198/jiif.v4i2.28606
5. Heberlein S., Chan W.P., Veksha A., et al (2022) High temperature slagging gasification of municipal solid waste with biomass charcoal as a greener auxiliary fuel. J Hazard Mater 423: 127057. https://doi.org/https://doi.org/10.1016/j.jhazmat.2021.127057
6. Maafa I.M. (2021) Pyrolysis of Polystyrene Waste: A Review. Polymers (Basel). 13.
7. Machmud M. (2017) Solid Waste Management in Jakarta and Surabaya BT – Observing Policy-Making in Indonesia. In: Friedberg E, Hilderbrand ME (eds). Springer Singapore, Singapore, pp. 187–221.
8. Nurhati I.S., Cordova M.R. (2020) Marine plastic debris in Indonesia: Baseline estimates (2010–2019) and monitoring strategies (2021–2025). Mar Res Indones 45: 97–102. https://doi.org/10.14203/mri.v45i2.581
9. Rachman S.A., Hamdi M., Djaenuri A., Sartika I. (2020) Model of Public Policy Implementation for Refused Derived Fuel (RDF) Waste Management in Cilacap Regency. Int J Sci Soc 2. https://doi.org/10.200609/ijsoc.v2i4.239
10. Sapuay G.P. (2016) Resource Recovery through RDF: Current Trends in Solid Waste Management in the Philippines. Procedia Environ Sci 35: 464–473. https://doi.org/https://doi.org/10.1016/j.proenv.2016.07.030
11. Sari D.A.A., Suryanto, Sudarwanto A.S., et al (2021) Reduce marine debris policy in Indonesia. IOP Conf Ser Earth Environ Sci 724: 12118. https://doi.org/10.1088/1755–1315/724/1/012118
12. Sari M.M., Inoue T., Harryes R.K., et al (2022a) Potential of Recycle Marine Debris in Pluit Emplacement , Jakarta to Achieve Sustainable Reduction of Marine Waste Generation. Int J Sustain Dev Plan 17: 119–125.

13. Sari M.M., Inoue T., Septiariva I.Y., et al (2022b) Identification of Face Mask Waste Generation and Processing in Tourist Areas with Thermo-Chemical Process. Arch Environ Prot 48: 79–85.
14. Sarwono A., Septiariva I.Y., Qonitan F.D., et al (2021) Refuse Derived Fuel for Energy Recovery by Thermal Processes. A Case Study in Depok City, Indonesia. J Adv Res Fluid Mech Therm Sci 88: 12–23.
15. Septiariva I.Y., Suryawan I.W.K., Zahra N.L., et al (2022) Characterization Sludge from Drying Area and Sludge Drying Bed in Sludge Treatment Plant Surabaya City for Waste to Energy Approach. J Ecol Eng 23: 268–275.
16. Shafie S.M., Mahlia T.M.I., Masjuki H.H. (2013) Life cycle assessment of rice straw co-firing with coal power generation in Malaysia. Energy 57: 284–294. https://doi.org/https://doi.org/10.1016/j.energy.2013.06.002
17. Singh R.K., Ruj B. (2016) Time and temperature depended fuel gas generation from pyrolysis of real world municipal plastic waste. Fuel 174: 164–171. https://doi.org/https://doi.org/10.1016/j.fuel.2016.01.049
18. Suryawan I.W.K., Lee C-H. (2023) Citizens' willingness to pay for adaptive municipal solid waste management services in Jakarta, Indonesia. Sustain Cities Soc 97. https://doi.org/https://doi.org/10.1016/j.scs.2023.104765
19. Suryawan I.W.K., Septiariva IY, Fauziah EN, et al (2022) Municipal solid waste to energy : palletization of paper and garden waste into refuse derived fuel. J Ecol Eng 23: 64–74.
20. Suryawan I.W.K., Septiariva I.Y., Sari M.M., et al (2023) Acceptance of Waste to Energy (WtE) Technology by Local Residents of Jakarta City, Indonesia to Achieve Sustainable Clean and Environmentally Friendly Energy. J Sustain Dev Energy, Water Environ Syst 11: 1004.
21. Vamvuka D. (2011) Bio-oil, solid and gaseous biofuels from biomass pyrolysis processes–An overview. Int J Energy Res 35:835–862. https://doi.org/https://doi.org/10.1002/er.1804
22. Zahra N.L., Septiariva I.Y., Sarwono A., et al (2022) Substitution Garden and Polyethylene Terephthalate (PET) Plastic Waste as Refused Derived Fuel (RDF). Int J Renew Energy Dev 11: 523–532. https://doi.org/10.14710/ijred.2022.44328