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Quality Test of Utilization of Palm Oil Solid Waste as a Raw Material for Refuse Derived Fuel (RDF) for Alternative Fuels

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ABSTRACT

The use of palm oil solid waste as a raw material for refuse derived fuel (RDF) is a promising alternative to overcome environmental and energy problems. This study aims to test the quality of RDF produced from palm solid waste by paying attention to the composition of the mixture and treatment method through quantitative experimental methods, which are divided into two stages: processing and quality testing. The results showed that the average calorific value of RDF reached 4,216.75 cal/g, moisture content 10.76%, ash content 4.37%, volatile matter 58.11%, and fixed carbon 26.75%, all of which showed great potential as an alternative energy source. Although the RDF calorific value of palm solid waste is higher than the industry standard, the moisture content and ash content are still below international standards, and the calorific value is slightly below the SNI class 1 standard but higher than that of class 2 and 3. These findings indicate that RDF from palm oil solid waste has the potential to be a good quality alternative fuel.

I. Introduction

It is known that since 2006, Indonesia has been the largest producer of palm oil in the world. Indonesia was able to outperform Malaysia in 2016. Indonesia now produces 53.4% of all crude palm oil (CPO) produced in the world, with Malaysia producing 32%. The exploitation of oil palm plantations in Indonesia underwent a revolution between 1990 and 2015, which was marked by the rapid expansion of smallholder plantations (24% per year between 1990 and 2015) [1]. Existing oil palm plantations in Indonesia will reach 16.83 million hectares by 2023, with 6.3 million hectares of smallholder plantations and 9 million hectares of state-owned and private plantations. Compared to the previous year which reached 14.58 million hectares, this number increased by 15.43% [2]. One ton of fresh palm fruit bunches produces 20-23% crude palm oil (CPO), 5-7% palm kernel oil (PKO), and the rest in the form of solid waste consisting of 20-23% empty palm bunches. Palm fruit fiber 10-12%, and palm shell 7-9% [3].

Solid waste from the palm oil industry often contains a lot of organic matter that causes environmental damage. Environmental pollution is caused by improper waste management. To treat and increase commercial solid waste from palm oil production, a number of efforts have been made. Empty shells, fibers, fronds and fruit bunches are examples of solid waste of palm oil. Efforts to reduce waste generation without sacrificing the benefits and economic value of alternatives. Energy recycling is one of the strategies that can be used. In this method, palm oil waste is processed into refuse derived fuel (RDF), which is then regenerated into biomass energy [4]. Indonesia is the world's largest palm oil producer, with production reaching 46.7 million tons in 2022. This significant output results in a substantial amount of palm solid waste generated each year. Effective management of this waste is crucial for sustainability and environmental protection. Table 1 shows the percentage of palm solid waste in Indonesia [5].

Table 1. Percentage of Palm Solid Waste in Indonesia

Types of Palm Solid Waste	Percentage (%)
Palm fronds	61.56
Empty Bunches of oil palm	17.47
Palm fiber	9.11
Palm Shell	6.83

Source: [5]

PKS Kertajaya Banten is one of the Palm Oil Mills (PKS) in Indonesia.PKS Kertajaya Banten is located in Lebak Regency, Banten. PKS Kertajaya Banten has a processing capacity of 60 tons of Fresh Fruit Bunches per hour. Table 2 shows the percentage of Palm Solid Waste in PKS Kertajaya Banten [6].

Table 2. Percentage of Palm Solid Waste at PKS Kertajaya Banten

Types of Palm Solid Waste	Percentage (%)
Palm fronds	22.51
Empty Bunches of oil palm	30.28
Palm fiber	24.11
Palm Shell	18.08

Source: [6]

Rati Yuliarningsih's research in 2019 with palm oil waste consisting of oil sludge and shells (palm shells), revealed that samples with a mixture of oil sludge and shells (palm shells) with a composition of 1:1 plus 5% tapioca flour adhesive had a moisture content of 9.8%, and a calorific value of 6413.17 kcal/gram [7]. Research on RDF is not the first thing to be done. RDF raw materials have been the subject of many studies using appropriate percentages of wood, paper, fabric, rubber, and plastic. In a journal made by Gathut Imam Gunadi, et al in 2023 regarding environmentally friendly RDF, with wood, paper and fabric still meeting industry standards [8]. In this study, the difference is that RDF raw materials focus on palm oil waste which is carried out by conducting quality tests as Refuse Derived Fuel (RDF) for alternative fuels.

RDF test parameters that are important to determine quality as an alternative fuel include calorific value, moisture content, ash content, fixed carbon, and volatile matter. Calorific value is a measure of the energy that can be produced when a fuel is burned, which indicates its potential as an energy source; The higher the calorific value, the more efficient the fuel is [9]. Moisture content refers to the percentage of moisture in RDF, where low levels increase combustion efficiency and reduce the energy required to evaporate water during the combustion process [10]. Ash content refers to the residue left after combustion, which can affect the nature of combustion and possibly pollute the environment. Fixed carbon is the component that remains after volatile matter is burned, serving as a stable and desirable source of energy in the fuel. Volatile matter is a volatile fraction of a fuel, contributing to the fuel's ability to burn well. The combination of these five parameters determines the quality and efficiency of RDF as an alternative fuel [11].

II. Method

This research was carried out using an experimental and theoretical approach or method. Theoretical studies are used to determine parameters related to Refuse Derived Fuel (RDF) with palm oil waste raw materials obtained through various literature sources in the form of textbooks and related journals. Meanwhile, the experimental approach is carried out by RDF testing to obtain the magnitude of calorific value, moisture content, ash content and volatile matter as well as fix carbon. RDF quality testing will be compared to four different standards: PT Indocement Standard; Industry

Standard and Eco-Friendly; International Standards (Finland, Italy, United Kingdom); and Indonesia National Standard (SNI).

In this study, eight RDF samples were made with a variety of raw materials from palm solid waste, where each sample had a different composition. Sample 1 used empty bunches, sample 2 consisted of palm fibers, and sample 3 used palm fronds. Sample 4 is made from palm shells, while sample 5 uses palm solid waste according to data in Indonesia, and sample 6 is palm solid waste from the same data but without palm shells, because the shells still have a selling value in the market. Sample 7 uses palm solid waste based on data from PKS Kertajaya, while sample 8 is the same solid waste but without palm shells, for similar reasons. All samples were collected by adding 5 % tapioca flour as an adhesive to improve the paste and physical performance of the RDF produced. This variation in the selection of raw materials aims to explore the potential of each type of waste in producing quality RDF that can be used as an alternative fuel. Figure 1 shows the RDF structure of palm solid waste, all of which are composed of solid palm oil waste with adhesives. In addition, analysis was carried out to determine the value of heat, moisture content and ash content, fixed carbon and volatile matter.

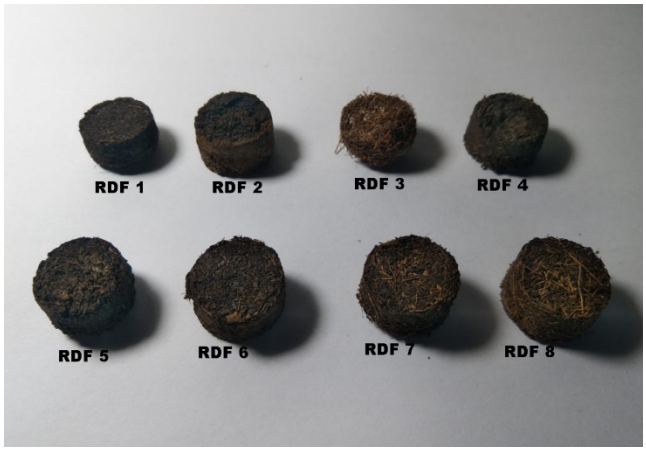

Fig. 1. Eight RDF samples from Palm Oil Solid Waste in their Composition

III. Results and Discussion

Solid waste from the palm oil industry has become a major concern in the context of environmental sustainability and the use of alternative energy. An in-depth analysis of these key components of solid waste is key in developing effective strategies for energy conversion and sustainable waste management. The following are the results of the study on the influence of RDF raw materials from palm solid waste on RDF performance reviewed from the calorific value, moisture content, ash content, volatile matter, and fix carbon, Comparison of RDF Quality Analysis with PT Indocement Standards, Industry Standard and Eco-Friendly, International Standards and Indonesia National Standards (SNI).

A. Comparison of Calorific Value of Palm Solid Waste RDF Materials

The calorific value test of 8 samples of palm solid waste RDF material showed that this material had an average calorific value of 4,216.75 cal/g. These results indicate that RDF materials from palm solid waste have the potential to be a good alternative energy source. However, to ensure the quality and consistency of this fuel, it is necessary to carry out more homogeneous processing and strict quality control. By understanding the characteristics of the calorific value of RDF materials for palm solid waste, its use can be optimized in various energy applications and support more sustainable waste management efforts. Table 3 is the results of the calorific value test of 8 samples of RDF material from palm solid waste.

Table 3. RDF Calorific Value

RDF Sample	Calorific Value (cal/g)
Sample 1	3590.588 - 3863.716
Sample 2	4370.134 – 4463.194
Sample 3	4259.268 – 4468.713
Sample 4	4701.132 – 4752.529
Sample 5	4076.915 – 4087.326
Sample 6	3856.812 – 3875.303
Sample 7	4208.293 – 4218.111
Sample 8	4300.460 – 4375.357

Source: Laboratory test results

B. Comparison of Moisture Content of Palm Solid Waste RDF Materials

Moisture content testing of 8 samples of palm solid waste RDF material showed that this material had an average moisture content of 10.76%. These results indicate that the RDF material from palm solid waste has a fairly low and consistent moisture content, which is good for combustion efficiency. By understanding the moisture content characteristics of palm solid waste RDF materials, its use can be optimized in various energy applications and support more sustainable waste management efforts. Strict quality control in the processing and storage of palm solid waste is essential to ensure optimal moisture content in RDF materials. Table 4 is the results of moisture content testing from 8 samples of palm solid waste RDF material.

Table 4. RDF Moisture Content

RDF Sample	Moisture Content (%)
Sample 1	14.625 - 15.000
Sample 2	5.825 – 5.886
Sample 3	13.814 – 13.933
Sample 4	5.543 – 5.692
Sample 5	12.090 – 12.342
Sample 6	12.975 – 12.999
Sample 7	10.096 – 10.220
Sample 8	10.478 – 10.634

Source: Laboratory test results

C. Comparison of Ash Content from RDF Materials of Palm Solid Waste

Testing of the ash content of 8 samples of palm solid waste RDF material showed that this material had an average ash content of 4.37%. These results indicate that the RDF material from palm solid waste has a fairly low and consistent ash content, which is good for combustion efficiency and reducing environmental impact. By understanding the characteristics of the ash content of RDF material from palm solid waste, its use can be optimized in various energy applications and support more sustainable waste management efforts. Strict quality control in the palm solid waste treatment process is essential to ensure optimal ash content in RDF materials. Table 5 is the results of ash content testing from 8 samples of RDF material from palm solid waste.

Table 5. RDF Ash Content

RDF Sample	Ash Content (%)
Sample 1	5.708 - 6.948
Sample 2	4.980 – 5.267
Sample 3	1.148 – 1.162
Sample 4	4.230 – 4.373
Sample 5	4.914 – 5.189
Sample 6	5.481 – 5.694
Sample 7	3.507 – 3.894
Sample 8	3.459 – 4.006

Source: Laboratory test results

D. Comparison of Volatile Matter from Palm Solid Waste RDF Materials

From the testing of eight samples of RDF of palm solid waste, an average volatile matter of 58.11% was obtained. These results show that palm solid waste has a high volatile material content, which makes it suitable as an alternative fuel. Further development in palm solid waste processing and utilization technology can support efforts to utilize renewable energy. Table 6 is the results of volatile matter testing from 8 samples of RDF solid palm waste.

Table 6. Volatile Matter RDF

RDF Sample	Volatile Matter (%)
Sample 1	48.683 - 49.536
Sample 2	67.361 – 67.521
Sample 3	58.730 – 59.218
Sample 4	61.669 – 61.701
Sample 5	53.871 – 54.155
Sample 6	54.072 – 54.146
Sample 7	59.607 – 60.0159
Sample 8	59.677 – 59.819

Source: Laboratory test results

E. Comparison of Fix carbon from Palm Solid Waste RDF Material

The average fixed carbon RDF from palm solid waste is 26.75%. This shows that palm solid waste has a significant fixed carbon content. The fairly high fixed carbon value in the RDF of palm solid waste shows that this material has good potential for efficient combustion. Fixed carbon is an indicator of solid residues that can burn in the final stages of combustion, contributing to the total energy produced. Variations in fixed carbon values between samples can be caused by differences in the chemical composition and physical structure of palm solid waste. Factors such as mineral content, moisture content, and waste treatment methods can also affect the value of fixed carbon. Table 7 is the results of the fix carbon test of 8 samples of RDF material from palm solid waste.

Table 7. Fix Carbon RDF

RDF Sample	Fix Carbon (%)
Sample 1	30.984 - 28.515
Sample 2	21.387 – 21.773
Sample 3	25.806 – 26.189
Sample 4	28.377 – 28.415
Sample 5	28.589 – 28.855
Sample 6	27.235 – 27.398
Sample 7	26.214 – 26.403
Sample 8	25.697 – 26.230

Source: Laboratory test results

F. Comparison of RDF Quality Analysis with PT Indocement Standards

In the next discussion, the quality of RDF from palm solid waste will be compared with the standard RDF used by PT Indocement. The parameters compared include calorific value, moisture content, and biomass percentage, which are very important in determining the energy performance of each type of RDF. By making this comparison, the study aims to identify the potential and advantages of RDF of palm solid waste when compared to industry standards.

PT Indocement's RDF standard has a high calorific value, so it is efficient in producing energy. The average calorific value of the palm solid waste sample was 4216.75 kcal/kg, which was higher than the standard calorific value of PT Indocement of above 3001.91536 cal/g. This shows that RDF from palm solid waste has the potential as an alternative fuel. Table 8 is the result of the Comparison of the Quality of RDF Calorific Value Parameters with PT Indocement Standards.

Table 8. Comparison of RDF Quality of Calorific Value Parameters with PT Indocement Standards

RDF Sample	Calorific Value (cal/g)	Indocement RDF Values
Sample 1	3590.588 - 3863.716	**Normal:**
Sample 2	4370.134 – 4463.194	>12.56 MJ/kg
Sample 3	4259.268 – 4468.713	(>3001.91 cal/g)
Sample 4	4701.132 – 4752.529	**Moderate:**
Sample 5	4076.915 – 4087.326	12.56-10.47 MJ/kg
Sample 6	3856.812 – 3875.303	(3001.91 - 2502.29 cal/g)
Sample 7	4208.293 – 4218.111	**Low:**
Sample 8	4300.460 – 4375.357	<10.47 MJ/kg
		(<2502.39 cal/g)

Source: Laboratory test results & [12]

The percentage of biomass in RDF determines how much of the fuel comes from renewable organic matter. The average biomass percentage of palm solid waste samples is 100%, which is higher than PT Indocement's standard biomass percentage of above 50%. This shows that RDF from palm solid waste has a biomass content that comes entirely from high biomass, so it is in accordance with PT Indocement's standards. Table 9 is the result of the Comparison of RDF Quality of biomass parameters with PT Indocement Standards.

Table 9. Comparison of RDF Quality of Biomass Percentage Parameters with PT Indocement Standards

RDF Sample	Biomass (%)	Indocement RDF Values
Sample 1	100	**Normal:**
Sample 2	100	>50%
Sample 3	100	
Sample 4	100	**Moderate:**
Sample 5	100	>50%
Sample 6	100	
Sample 7	100	**Low:**
Sample 8	100	<50%

Source: Laboratory test results & [12]

The moisture content in the fuel affects the efficiency of combustion. The higher the moisture content, the lower the combustion efficiency because the energy is used to evaporate the water. The average moisture content of the palm solid waste sample was 10.76%, which was lower than PT Indocement's standard moisture content of below 20%. This shows that palm solid waste has a fairly low moisture content, which can add to the efficiency of combustion. Table 10 is the result of the Comparison of RDF Quality of moisture content parameters with PT Indocement Standards.

Table 10. Comparison of RDF Quality Moisture Content Percentage Parameters with PT Indocement Standards

RDF Sample	Moisture Content (%)	Indocement RDF Values
Sample 1	14.625 - 15.000	**Normal:**
Sample 2	5.825 – 5.886	>50%
Sample 3	13.814 – 13.933	
Sample 4	5.543 – 5.692	**Moderate:**
Sample 5	12.090 – 12.342	>50%
Sample 6	12.975 – 12.999	
Sample 7	10.096 – 10.220	**Low:**
Sample 8	10.478 – 10.634	<50%

Source: Laboratory test results & [12]

G. Comparison of RDF Quality Analysis with Industry Standard and Environmentally Friendly Raw Materials

In this section, a comparison of the quality of RDF produced from eight samples of RDF testing of palm solid waste with RDF using environmentally friendly industry standard raw materials will be carried out. The main focus of this analysis is on the calorific value, which is a key parameter in determining the energy efficiency of the fuel. In addition, special attention will be paid to the use of environmentally friendly raw materials, namely materials that are free from plastic and rubber.

The average calorific value of the RDF sample of palm solid waste was 4216.75 cal/g. For comparison, the calorific value of the industry-standard RDF using non-plastic and non-rubber materials is 3781.07492 cal/g. From this, it can be seen that the calorific value of RDF from palm solid waste is higher than that of the industry standard RDF and is environmentally friendly. Table

11 is the result of the Comparison of the Quality of RDF of palm solid waste with RDF without the use of Plastic and rubber waste.

Table 11. Comparison of the Quality of RDF of palm solid waste with RDF without the use of Plastic and rubber waste

RDF Sample	Calorific Value (cal/g)	RDF without Plastic and Rubber
Sample 1	3590.588 - 3863.716	15.82 MJ/kg
Sample 2	4370.134 – 4463.194	(3781.07 cal/g)
Sample 3	4259.268 – 4468.713	
Sample 4	4701.132 – 4752.529	
Sample 5	4076.915 – 4087.326	
Sample 6	3856.812 – 3875.303	
Sample 7	4208.293 – 4218.111	
Sample 8	4300.460 – 4375.357	

Source: Laboratory test results & [8]

H. Comparison of RDF Quality Analysis with International Standards

The quality of RDF is determined by several important parameters such as calorific value, moisture content, and ash content. In this section, the quality of RDF produced from palm solid waste will be compared with eight test samples against international standard RDF from Finland, Italy, and the United Kingdom.

The average calorific value of the RDF sample of palm solid waste was 4216.75 cal/g. This value is lower than the international standard from the United Kingdom (4469.4122 cal/g), but higher than Finland (3824.096 kcal/kg), and Italy (3585.09 kcal/kg). This shows that RDF from palm solid waste requires quality improvement to achieve energy efficiency higher than United Kingdom standards. Table 12 is the result of the Comparison of RDF Quality Parameter Calorific Value with International Standards.

Table 12. Comparison of RDF Quality Parameters Calorific Value with International Standards

RDF Palm Solid Waste		RDF International Standards		
RDF Sample	Calorific Value (cal/g)	Finland	Italy	United Kingdom
Sample 1	3590.588 - 3863.716	13 – 16 MJ/kg	15 MJ/kg	18.7 MJ/kg
Sample 2	4370.134 – 4463.194	(3107.07 – 3824.09 cal/g)	(3585.09 cal/g)	(4469.41 cal/g)
Sample 3	4259.268 – 4468.713			
Sample 4	4701.132 – 4752.529			
Sample 5	4076.915 – 4087.326			
Sample 6	3856.812 – 3875.303			
Sample 7	4208.293 – 4218.111			
Sample 8	4300.460 – 4375.357			

Source: Laboratory test results & [13]

The average moisture content of the RDF sample of palm solid waste was 10.76%. This is lower compared to international standards of Finland (25-35%), Italy (<25%), and United Kingdom (7-28%). The low moisture content can increase combustion efficiency and lower drying costs. Table 13 is the result of the Comparison of RDF Quality Parameter Moisture Content with International Standards.

Table 13. Comparison of RDF Quality of Moisture Content Parameters with International Standards

RDF Palm Solid Waste		**RDF International Standards**		
RDF Sample	**Moisture Content (%)**	**Finland**	**Italy**	**United Kingdom**
Sample 1	14.625 - 15.000	25 – 35 %	<25 %	7 – 28 %
Sample 2	5.825 – 5.886			
Sample 3	13.814 – 13.933			
Sample 4	5.543 – 5.692			
Sample 5	12.090 – 12.342			
Sample 6	12.975 – 12.999			
Sample 7	10.096 – 10.220			
Sample 8	10.478 – 10.634			

Source: Laboratory test results & [13]

The average ash content from the RDF sample of palm solid waste was 4.37%. It is also lower compared to international standards from Finland (5-10%), Italy (20%), and the United Kingdom (12%). The low ash content can reduce the buildup of residue in the combustion system and reduce more intensive maintenance. Table 14 is the result of the Comparison of RDF Quality Parameter Ash Content with International Standards.

Table 14. Comparison of RDF Quality of Ash Content Parameters with International Standards

RDF Palm Solid Waste		**RDF International Standards**		
RDF Sample	**Ash Content (%)**	**Finland**	**Italy**	**United Kingdom**
Sample 1	5.708 - 6.948	5 – 10 %	20 %	12 %
Sample 2	4.980 – 5.267			
Sample 3	1.148 – 1.162			
Sample 4	4.230 – 4.373			
Sample 5	4.914 – 5.189			
Sample 6	5.481 – 5.694			
Sample 7	3.507 – 3.894			
Sample 8	3.459 – 4.006			

Source: Laboratory test results & [13]

RDF from palm solid waste shows potential as an alternative fuel, and from several parameters it is already very good in meeting international standards. Higher calorific value, lower moisture content, and lower ash content are the main challenges that have been addressed.

I. Comparison of RDF Quality Analysis with Indonesia National Standards

This section will present the results of the RDF quality analysis which includes parameters such as calorific value, moisture content, ash content, volatile matter, and fixed carbon. This data includes the results of direct testing on RDF samples generated from palm solid waste. The main parameters that determine the quality of RDF are calorific value, moisture content, ash content, volatile matter, and fixed carbon. In this sub-chapter, the quality of RDF produced from palm solid waste will be compared with eight test samples against the RDF of the SNI (Indonesia National Standard) standard.

The average calorific value of the RDF sample of palm solid waste was 4216.75 cal/g. This value is lower than the SNI class 1 standard of 4780.12 cal/g, but higher than the SNI class 2 standard (3585.09 cal/g) and the SNI class 3 standard (2390.06 cal/g). This shows that RDF from palm solid waste requires quality improvement to achieve higher energy efficiency to be better in terms of calorific value of SNI class 1 standard. Table 15 is the result of the Comparison of the Quality of RDF Calorific Value Parameters with Indonesia National Standards.

Table 15. Comparison of RDF Quality of Calorific Value Parameters with Indonesia National Standards

RDF Palm Solid Waste		**RDF Indonesia's National Standard**		
RDF Sample	**Calorific Value (cal/g)**	**Class 1**	**Class 2**	**Class 3**
Sample 1	3590.588 - 3863.716	≥ 20 MJ/kg	≥ 15 MJ/kg	≥ 10 MJ/kg
Sample 2	4370.134 – 4463.194	(≥ 4780.12 cal/g)	(3585.09 cal/g)	(2390.06 cal/g)
Sample 3	4259.268 – 4468.713			
Sample 4	4701.132 – 4752.529			
Sample 5	4076.915 – 4087.326			
Sample 6	3856.812 – 3875.303			
Sample 7	4208.293 – 4218.111			
Sample 8	4300.460 – 4375.357			

Source: Laboratory test results & [14]

The average moisture content of the RDF sample of palm solid waste was 10.76%, lower than the SNI standards of class 1, class 2 and class 3. The low moisture content can increase combustion efficiency and lower drying costs. Table 16 is the result of the Comparison of RDF Quality of Moisture Content Parameters with Indonesia National Standards.

Table 16. Comparison of RDF Quality of Moisture Content Parameters with Indonesia National Standards

RDF Palm Solid Waste		**RDF Indonesia's National Standard**		
RDF Sample	**Moisture Content (%)**	**Class 1**	**Class 2**	**Class 3**
Sample 1	14.625 - 15.000	< 15 %	< 20 %	< 25 %
Sample 2	5.825 – 5.886			
Sample 3	13.814 – 13.933			
Sample 4	5.543 – 5.692			
Sample 5	12.090 – 12.342			
Sample 6	12.975 – 12.999			
Sample 7	10.096 – 10.220			
Sample 8	10.478 – 10.634			

Source: Laboratory test results & [14]

The average ash content from the RDF sample of palm solid waste was 4.37%, lower than the SNI standards of class 1, class 2 and class 3. The low ash content can reduce the buildup of residue in the combustion system and reduce more intensive maintenance. Table 17 is the result of the Comparison of RDF Quality Ash Content Parameters with Indonesia National Standards.

Table 17. Comparison of RDF Quality of Ash Content Parameters with Indonesia National Standards

RDF Palm Solid Waste		**RDF Indonesia's National Standard**		
RDF Sample	**Ash Content (%)**	**Class 1**	**Class 2**	**Class 3**
Sample 1	5.708 - 6.948	< 15 %	< 20 %	< 25 %
Sample 2	4.980 – 5.267			
Sample 3	1.148 – 1.162			
Sample 4	4.230 – 4.373			
Sample 5	4.914 – 5.189			
Sample 6	5.481 – 5.694			
Sample 7	3.507 – 3.894			
Sample 8	3.459 – 4.006			

Source: Laboratory test results & [14]

The average volatile matter of the RDF sample of palm solid waste was 58.11%, lower than the SNI standard of class 1, class 2 and class 3. Low volatile matter can increase fuel combustion efficiency. Table 18 is the result of the Comparison of RDF Quality of volatile matter parameters with Indonesia National Standards.

Table 18. Comparison of RDF Quality of Volatile Matter Parameters with Indonesia National Standards

RDF Palm Solid Waste		**RDF Indonesia's National Standard**		
RDF Sample	**Volatile Matter (%)**	**Class 1**	**Class 2**	**Class 3**
Sample 1	48.683 - 49.536	65 %	70 %	75 %
Sample 2	67.361 – 67.521	Maximum	Maximum	Maximum
Sample 3	58.730 – 59.218			
Sample 4	61.669 – 61.701			
Sample 5	53.871 – 54.155			
Sample 6	54.072 – 54.146			
Sample 7	59.607 – 60.0159			
Sample 8	59.677 – 59.819			

Source: Laboratory test results & [14]

The average fixed carbon in RDF samples from palm oil solid waste reached 26.75%, which is higher than the SNI standards for classes 1, 2, and 3. This high fixed carbon value indicates a stable carbon content and is resistant to rapid combustion, thus providing the potential for increased fuel efficiency. This is important because fixed carbon plays a role in determining the length of combustion time and the amount of energy produced. The higher the fixed carbon content, the longer

the combustion process lasts, which means more energy can be released gradually and efficiently. Thus, RDF from palm oil waste has good prospects for use as a more economical and efficient alternative fuel.

Table 19 contains a comparison of RDF quality based on fixed carbon parameters with Indonesia National Standards. This data shows that the RDF of palm oil solid waste not only meets, but also exceeds the criteria set out in the SNI standard. This indicates the potential of RDF from palm oil waste to be used in a wider range of applications in the energy industry. With a higher fixed carbon value, RDF can be a superior fuel compared to other alternative fuels that generally have a lower fixed carbon content. Further optimization can be focused on adjusting the RDF production process to maintain or even increase the fixed carbon content without sacrificing other important parameters such as ash content and volatile matter.

In addition, this increase in the value of fixed carbon can also support sustainability initiatives in the renewable energy industry. By utilizing palm solid waste as a high-quality RDF, the palm oil industry can contribute to reducing dependence on fossil fuels while reducing environmental concerns associated with waste disposal. These efforts not only provide economic benefits, but also have a positive impact on the environment and the sustainability of energy resources.

Table 19. Comparison of RDF Quality of Fix Carbon Parameters with Indonesia National Standards

RDF Palm Solid Waste		**RDF Indonesia's National Standard**		
RDF Sample	**Fix Carbon (%)**	**Class 1**	**Class 2**	**Class 3**
Sample 1	30.984 - 28.515	> 15 %	> 10 %	> 5 %
Sample 2	21.387 – 21.773			
Sample 3	25.806 – 26.189			
Sample 4	28.377 – 28.415			
Sample 5	28.589 – 28.855			
Sample 6	27.235 – 27.398			
Sample 7	26.214 – 26.403			
Sample 8	25.697 – 26.230			

Source: Laboratory test results & [14]

RDF from palm solid waste shows promising potential as an alternative fuel, but there are still several aspects that need to be optimized to meet SNI standards. One of the main challenges is the lower calorific value compared to SNI Standard class 1. The low calorific value indicates that the amount of energy released during combustion is still not optimal, so the efficiency of its use as a fuel is not optimal. This can be caused by several factors, such as high moisture and ash content, or the composition of raw materials that are not yet ideal.

In addition to the SNI standard, the RDF calorific value of palm solid waste is also still below the standards of developed countries such as the United Kingdom. This shows that in order to compete in the international market, further efforts are needed to improve the quality of these RDFs. One strategy that can be applied is through an additional drying process to lower the moisture content, which can directly increase the calorific value. Drying can be done using more efficient technologies such as sunlight drying combined with mechanical drying systems or drying based on residual heat energy from other industrial processes. In addition, mixing with high-calorie ingredients can be a solution to increase the calorific value of RDF. The use of the right additives can also help in improving combustion quality and increasing energy content. For example, the addition of drier biomass or other organic matter that has a higher calorific value.

Improving the quality of RDF from palm solid waste can also be achieved through the application of pyrolysis or torrefaction technology. These two technologies function to reduce

moisture content and volatile matter, as well as increase the content of fixed carbon. The pyrolysis process, for example, can produce biochar with a higher energy content, while torrefaction is able to produce a more homogeneous and more flammable product, thereby improving overall combustion efficiency. In addition, optimization of production processes such as temperature and pressure control during the RDF manufacturing process can improve the homogeneity of the final product, resulting in more consistent RDF quality and performance. The implementation of strict quality control throughout the production process is also important to ensure that each batch of RDF produced has characteristics that meet standards, both national and international.

Finally, this RDF quality improvement effort not only aims to meet SNI and international standards, but also opens up opportunities for market expansion and the use of RDF from palm solid waste in the wider industrial sector. By meeting higher standards, RDF from palm waste can be a more competitive renewable energy solution, support sustainability, and reduce dependence on fossil fuels. This will make a positive contribution not only to the palm oil industry, but also to global efforts to meet the challenges of climate change and the need for cleaner and renewable energy sources.

IV. Conclusion

This study analyzes the potential of palm oil waste, especially palm shells, as raw materials for Refuse Derived Fuel (RDF) by focusing on five parameters: calorific value, moisture content, ash content, volatile matter, and fixed carbon. As a result, RDF from palm shells shows high calorific value, approaching international standards and exceeding several industry standards, making it a competitive alternative energy source. Although the quality of RDF is slightly below class 1 of Indonesia's National Standard, this study shows that with further optimization, palm oil waste has great potential as an efficient and environmentally friendly alternative fuel for industrial scale, helping to reduce waste and support sustainable energy.

The recommendations of this study emphasize the need for further research to improve the quality of RDF from palm solid waste, especially palm shells, with a focus on optimizing calorific value, moisture content, ash, volatile matter, and fixed carbon to meet SNI and international standards. Palm shells have proven to be superior due to their high volatile matter and fixed carbon content, so it is recommended to be the main raw material for RDF to increase economic value and create new market opportunities in the renewable energy sector. Applicable methods include drying, mixing of high-calorie materials, compaction, and the use of technologies such as torrefaction and pyrolysis to improve the efficiency and quality of RDF, thereby supporting the development of alternative fuels that are more environmentally friendly and sustainable.

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