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Optimization of Fuel Pellet Parameter from Oil Palm Fronds by using Response Surface Methodology (RSM)

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ABSTRACT

The oil palm tree, which had been producing a plentiful supply of oil palm fronds, had simply been left to rot on the ground. As biomass is a loose substance, pelletization was undertaken so that it could be transported and stored with ease. High-quality pellet production was studied to maximize oil palm frond use. Therefore, the primary goal of this study was to determine the impact of particle size and moisture content on fuel pellet quality. The response surface approach was utilized in this study to optimize the oil palm fronds pellet particle size and the moisture content on the durability, unit density, and calorific value. The particle sizes analyzed were 0.15 mm, 0.500 mm, and 1.00 mm, while the moisture content was 5%, 10.50%, and 16%. The pellets were manufactured using a hydraulic single pellet press, and their calorific value, unit density, and durability were evaluated using a bomb calorimeter, a density formula, and a sieve shaker, respectively. The optimization yielded the maximum desirability (0.5026) for particles with a 16% moisture content and a 0.500 mm particle size. The condition is ideal when the value of desirability is closest to 1.00. It may be concluded that the particle size and moisture content of oil palm fronds affect the durability, unit density, and calorific value of oil palm fronds pellet.

Keywords: Biomass, Oil palm fronds, Energy pellet, Optimization, Response Surface Methodology

1. INTRODUCTION

Oil palms, scientifically known as *Elaeis guineensis*, have been used for generations for their benefits. It is common knowledge that every portion of an oil palm plant can be put to productive use. Humans have found many uses for oil palm fruits, woods, and leaves, thanks to their versatility. Oil palms are one of the ways to substitute non-renewable energy, which is necessary for human survival. Because of this, Malaysia or Asia as a whole, has become a famous source of oil palm to the rest of the world. Interestingly, there have been several studies in the literature reporting that the effects of climate change have compelled humankind to make use of biomass because of the depletion of fossil fuels [1, 2].

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However, biomass has a low bulk density and an energy density. Densification is thus required to overcome handling and storage issues, as well as to increase the energy density of biomass itself. Pelletization was chosen for this study because of its small size, uniformity of pellets, and ease of handling. Water plays a crucial role in the pelletizing process, acting as both a lubricant and a binding agent for the pellet [3, 4]. Smaller particles have smaller gaps between them, whereas larger particles have larger gaps, making the smaller particles stronger than the larger particles [5, 6]. Therefore, the primary objective of this research was to assess the effect of particle size and moisture content on the quality of fuel pellets. As such, the response surface methodology will be used in this study to determine the optimal oil palm frond biomass of the two important factors aforementioned: moisture content and particle size.

The process of choosing between two or more options that came up in the study and is used to determine which option is the most optimal is called optimization. By boosting desired factors and reducing undesirable ones, this method helps identify the alternative with the best performance or cost applicability, given the constraints. A statistical or mathematical method called "response surface methodology" (RSM) is used to examine how variables affect the response [7, 8]. For instance, the variables include particle size, moisture content, and so forth.

2. MATERIAL AND METHODS

The raw material was collected at an oil palm plantation in Sungai Leman, Selangor. The leaves were removed from the fronds and allowed to dry naturally in open, atmospheric air. The feedstock was then cut into smaller parts before being subjected to a woodchipper to produce wood chips. The raw material was ground to smaller particle sizes using a hammer mill. The ground oil palm fronds were randomly selected for the pelleting process.

2.1 Pelletization

The flow chart of the study is depicted in Figure 1. After the materials and samples had been prepared, they were placed in a mould with a diameter of 12 mm and a mass of 2 g for each pellet. Next, the mould was compressed in the chamber, and 3 tonnes of pressure were applied to the material. After a while, the air was let out, and the mould exited the chamber. The bottom of the mould was removed, and then the material was pushed out of the mould. The pellet was produced after this process. The schematic diagram of the experiment is shown in Figure 2.

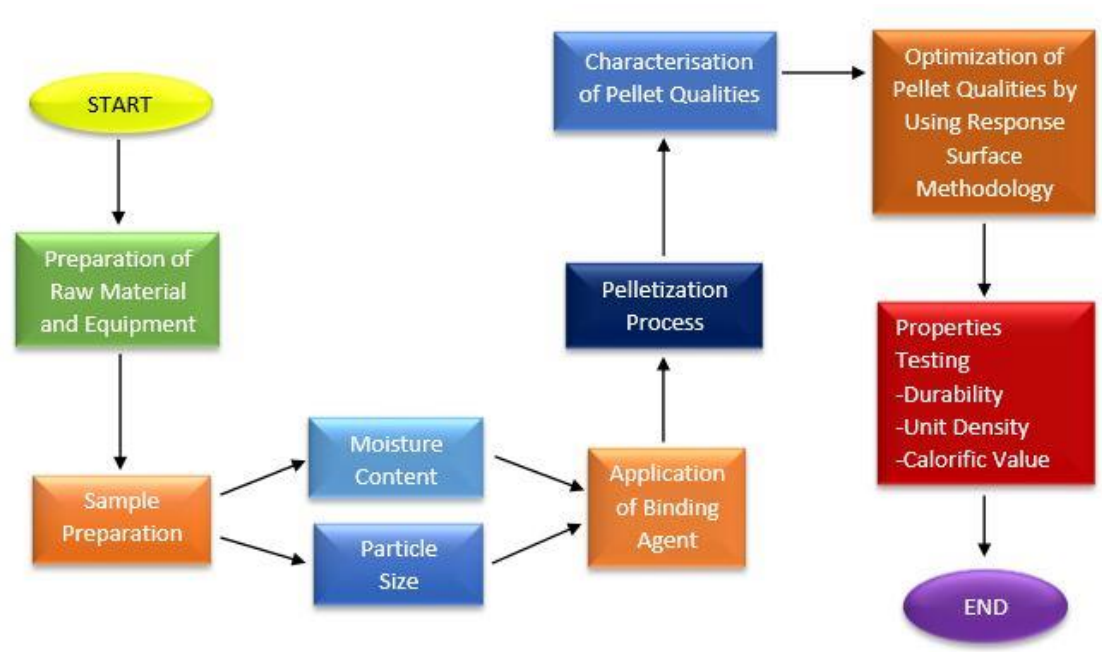


Figure 1: The flow chart of the study.

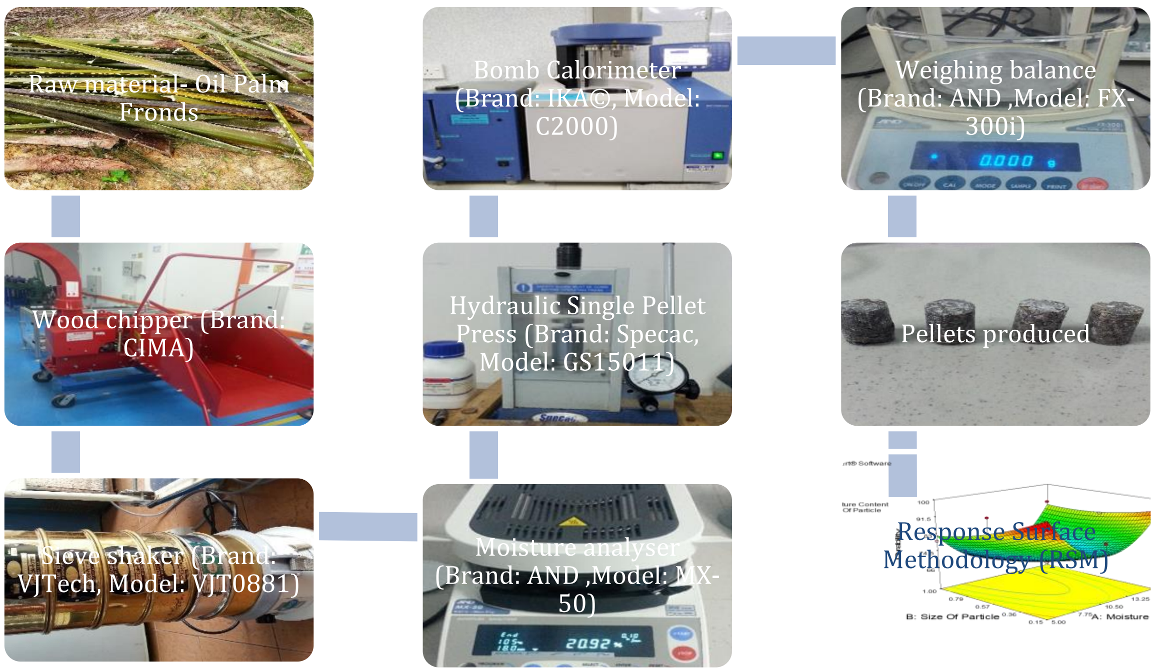


Figure 2: The schematic diagram of the experiment.

2.2 Calorific Value Determination

A bomb calorimeter measures the heating value or calorific value of the material. The material can be in a solid, liquid, or pellet state. The amount of heat released and absorbed by any chemical can be measured using this equipment. The material was inserted into the bomb calorimeter, and the oxygen was supplied adequately into the chamber. After some time, the chamber undergoes combustion, burning the pellet completely. If the biomass is a good type, it will not leave any evidence or particles in the small glass vessel.

2.3 Response Surface Methodology

Several experiments were conducted in Design Expert® to see how the variables interacted. A second-order polynomial response surface, which can forecast a non-linear relationship between variables, can be fitted well using the central composite design (CCD). The results of the experiments were used to adjust the CCD model and track how each variable responded. To produce the best possible pellet, the two factors—moisture content and particle size—are optimised. When optimization takes place, we will obtain the moisture content and particle size values that give the pellet its excellent quality. Additionally, in order to use the data for response surface modelling, a series of single pellets were made to test the material's durability, unit density, and calorific value. These pellets were made using a central composite design (CCD) in the response surface modelling (RSM) [9, 10]. Face-centred design is a design of experiments (DOE) that combines the benefits of a factorial design with the drawbacks of a central composite design (CCD). It involves three levels of experimentation with different experimental factors and is useful in response surface methodology (RSM) as it allows for the estimation of linear, quadratic, and sometimes cubic effects of factors, as well as for the assessment of possible interactions among factors. It is also efficient in terms of the number of experiments required, which can save time and resources. The number of experimental runs is generated by the CCD equation given in the following Equation 1:

$$CCD = 2^k + 2k + 6 \tag{1}$$

The range of levels for the parameters investigated in this study is shown in Table 1 and the experimental design layout is shonw in Table 2.

Table 1: Factors and levels for response surface study.

Factor	**Units**	**Level**		
		(-1)	(0)	(1)
A-Moisture Content	%	5	10.500	16
B-Size of Particle	mm	0.15	0.500	1

Table 2: The experimental design layout of the 2^2 CCD.

			Parameters	
Std	Run	Block	Moisture Content (%)	Particle Size (mm)
7	1	1	10.500	0.500
1	2	1	5	0.15
5	3	1	10.50	0.50
9	4	1	10.50	0.50
2	5	1	16	0.15
8	6	1	10.50	0.50
3	7	1	5	1
4	8	1	16	1
6	9	1	10.50	0.50
10	10	1	5	0.50
11	11	1	16	0.50
12	12	1	10.50	0.15
13	13	1	10.50	1
14	14	1	10.50	0.50

3. RESULTS AND DISCUSSION

3.1 Effect of variables on durability

The Model F-value of 19.19 implies the model is significant based on Table 3. There is only a 0.03 % chance that an "F-value Model" this large could occur due to noise. Noise is the error, misconduct of the experiment and measurement error during the research. Values of "Prob>F" less than 0.0500 indicate that model terms are significant. In this case, particle size (B) and A^2 are significant model terms. Values of Prob>F less than 0.0500 shows that the model terms are significant. Values greater than 0.1000 shows that the model terms are not significant. The size of the particles utilised in the production of fuel pellets can significantly impact the pellets' durability. The pellets may be weak and brittle if the particles are too large, as the larger particles might form weak areas within the pellet structure. This may cause the pellets to fragment or crumble during transit or storage. Alternatively, if the particles utilised are too small, the pellets may not bind effectively during compression. This can also lead to weak pellets that are more likely to break or crumble when subjected to pressure. This result agrees with [11, 12], which suggested that the durability is influenced by the feedstock particle size. Besides, it was found that this result is consistent with the findings of the past study by [13], which stated that a comparison of RSM predictions and test results demonstrated that RSM could accurately predict the durability properties and compressive strength of the material.

Table 3: Analysis of variance (ANOVA) for durability response.

Response 1		Durability	
ANOVA for Response Surface Quadratic Model			
Analysis of variance table			
Source	F Value	p-value Prob > F	
Model	19.19	0.0003	significant
A-Moisture Content	0.095	0.7658	
B-Size of Particle	11.56	0.0094	
AB	1.91	0.2039	
A^2	60.4	< 0.0001	
B^2	1.05	0.3349	

3.2 Effect of variables on unit density

Before proceeding to examine the effects of moisture content and particle size on unit density, it is important to note that a pellet's unit density is critical for transportation and storage. In the current study, response surface methodology was used to examine how the design parameters affected the density of fuel pellets [14]. The model F-value of 4.72, shown in Table 4, implies the model is significant. There is only a 2.64% chance that a "model F-value" this large could occur due to noise. As explained before, noise is the error or misconduct during the experiment or research. Values of "Prob>F" less than 0.0500 indicate that model terms are significant. In this case, Moisture Content (A), Particle Size (B), and A^2 are significant model terms. Values greater than 0.1000 indicate that the model terms are not significant. This shows that the unit density depends on the moisture content and particle size. The space between the particles is small when the particle size is small, which makes the unit density higher. This condition happened because the small particles can be compacted more than the larger-sized particles. The empty space is filled with particles, which affects the unit density of the pellet and makes it more compact [15]. The unit density is higher when the volume of the pellet decreases and the mass of the pellet increases.

Table 4: Analysis of variance for unit density.

Response 2		Unit Density	
ANOVA for Response Surface Quadratic Model			
Analysis of variance table			
Source	F Value	p-value Prob > F	
Model	4.72	0.0264	significant
A-Moisture Content	9.25	0.016	
B-Size of Particle	6.34	0.036	
AB	2	0.1954	
A^2	5.96	0.0405	
B^2	1.52	0.2524	

3.3 Effect of variables on calorific value

Another crucial factor was a fuel's calorific value, which shows its efficacy and efficiency by calculating the quantity of heat produced from a unit mass (MJ/kg) [16]. The model F-value shown in Table 5 for this calorific value response is 10.88, indicating that the model is significant. The likelihood of the F-value being positive is 0.21%. This large of a model might be the result of the noise. The model terms are relevant because their value, 0.0021, is less than 0.0500. Also, if the value is greater than 0.1000, the model terms are insignificant to the study. The study by [7] investigated the effects of biomass moisture content (MC=14–20%) and pelletization temperature (T=50–80 °C) on lower heating value (LHV) and energy density, pine sawdust pellet quality using response surface methodology. In this particular study, the results obtained are consistent with the values of calorific value gained from [17], which showed that the calorific value ranges from 15.222 MJ/kg to 16.503 MJ/kg from different particle sizes.

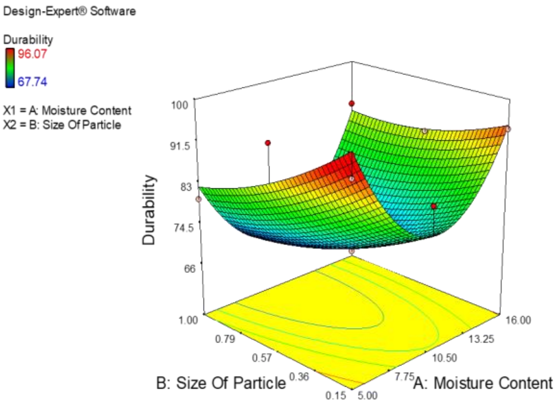
Table 5: Analysis of variance for a calorific value response.

Response 3		Calorific Value	
ANOVA for Response Surface Quadratic Model			
Analysis of variance table			
Source	F Value	p-value Prob > F	
Model	10.88	0.0021	significant
A-Moisture Content	12.46	0.0077	
B-Size of Particle	39.96	0.0002	
AB	1.28	0.2905	
A^2	0.29	0.6038	
B^2	0.12	0.7356	

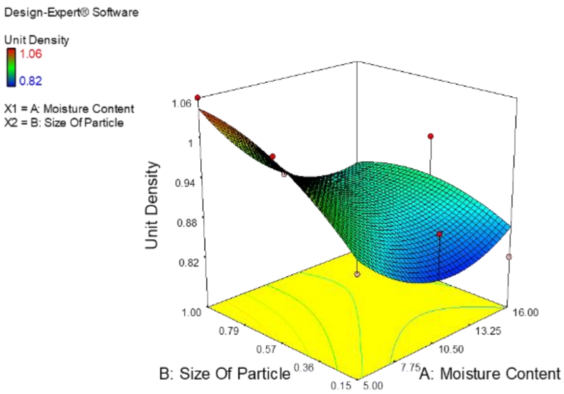
3.4 Three-dimensional graph of the variables and responses

Figure 3 shows the relationship between the variables and the responses. Figures 3 (a), 3 (b), and 3 (c) are the 3D graph of the durability, unit density, and calorific value responses, where they are affected by the moisture content and particle size. From the optimization, the highest unit density was detected at 1.06 g/cm^3 at 1 mm particle size and 5% moisture content. For the oil palm frond fuel pellet durability, it can be seen from the 3D graph that the maximum durability was achieved at 96.07% moisture content and 0.15 mm particle size. High moisture content can improve the binding of the feedstock particles during the pelletizing process, as it allows for better bonding between the particles. This results in a denser, more tightly packed pellet less likely to break apart or disintegrate. Similarly, using small feedstock can create a more uniform and consistent pellet size, contributing to better compaction and tighter packing of the feedstock particles during pelletizing and increasing the pellet's durability [4].

Turning to the experimental evidence on the calorific value of oil palm frond fuel pellets. It was observed that the maximum calorific value of 16.36 MJ/kg could be obtained from a 1 mm oil palm frond particle size and 5% moisture content. On the contrary, the minimum calorific value was seen at 14.68 MJ/kg for pellets pelletized with 16% moisture content and 0.15 mm feedstock particle size. This is attributed to the high moisture content and small feedstock particle size that reduces the overall energy density of biomass, leading to a lower calorific value and incomplete combustion [18]. Therefore, it is desirable to use biomass with a low moisture content and larger particle size to maximise its energy density and regenerate response.



(a)



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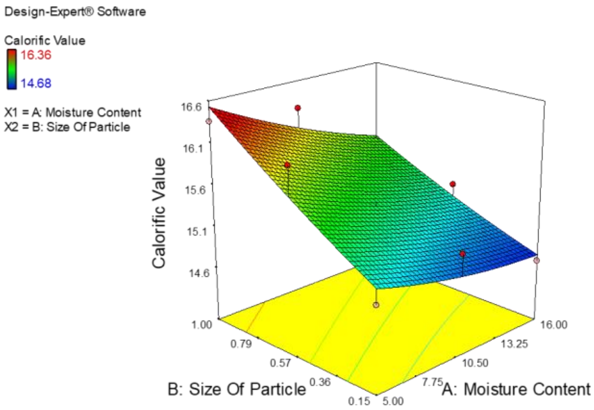

(c)

Figure 3: 3D graph for variables and response.

4. CONCLUSION

In this paper, an effort was made to create an ideal pellet in terms of quality parameters like durability, calorific value, and unit density. Oil palm frond pellet qualities have been determined to be influenced by moisture content and particle size, and the response surface methodology has been used to optimise both moisture content and pellet particle size for oil palm fronds. The value that was optimised has a moisture content of 16%, a particle size of 0.50 mm, a durability of 89.5321%, a unit density of 0.908634g/cm^3, and a calorific value of 15.1433 MJ/Kg. The result that the software provided for moisture content is typical because the pellet needs a range of 5% to 16% water to bind the pellet firmly.

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