Densification process of Merbau (*Intsia bijuga*) and Matoa (*Pometia pinnata J.R. Forster & J.G Forster*) Sawdust Waste for Biomass Based Solid Fuel Source in West Papua Indonesia: Optimization using Response Surface Methodology (RSM)

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A B S T R A C T

Merbau (*Intsia bijuga*) and matoa (*Pometia pinnata J.R. Forster & J.G Forster*) are two amongst many prominent biomass sources from West Papua, Indonesia. With their versatile characteristics, merbau and matoa wood are used in many industries such as furniture, music instrument, and many other specialty products. However, wood processing industries can emit up to 60% of the residue. In this study, the usage of both merbau and matoa sawdust wastes as solid fuel was studied using response surface methodology (RSM). merbau and matoa sawdust are sieved to get the desired particle size (-20+50 mesh). Two kinds of the sawdust are then mixed in various compositions (70, 50, and 30% merbau). The mixed sawdust is then mixed with varied sticky starch solutions (1, 5, and 10%) to be formed in pellets with various moulding compression force (50, 100, and 150 kg/cm^2). The pellets are then analyzed for its characteristics such as ash, moisture contents, and calorific value to be compared with its initial conditions. A full three-level factorial design under RSM was applied to explain the correlation between independent and dependent variables. The results show that statistically, merbau content, binder content, and compressive force showed relatively significant effects on the studied responses (ash content, moisture content, and calorific value). In addition, ANOVA analysis proved that each variable has significant effects on the responses that are confirmed by practically zero P-value. The coefficient of determinations (R^2) are all above 0.96 and the normal probability plots confirm that the proposed models adequate the experimental results.

Keywords: biomass waste; densification; merbau; matoa; RSM

A B S T R A K

Merbau (Intsia bijuga) dan matoa (Pometia pinnata Forster) adalah dua di antara sumber biomassa potensial yang berasal dari Papua Barat, Indonesia. Dengan karakteristiknya yang serbaguna, merbau dan matoa digunakan di banyak industri seperti furnitur, alat musik, dan banyak produk khusus lainnya. Namun, industri pengolahan kayu dapat menghasilkan hingga 60% residu. Di Pada penelitian ini, pemanfaatan limbah serbuk gergaji merbau dan matoa sebagai bahan bakar padat dipelajari dengan menggunakan response surface method (RSM). Serbuk gergaji merbau dan matoa diayak untuk mendapatkan ukuran partikel yang diinginkan (-20+50 mesh). Dua jenis serbuk gergaji kemudian dicampur dalam berbagai komposisi (70, 50, dan 30% merbau). Serbuk gergaji yang sudah tercampur kemudian dicampur dengan bahan perekat yang bervariasi larutan pati (1, 5, dan 10%) untuk dibentuk dalam pelet dengan berbagai gaya tekan cetakan (50, 100, dan 150 kg/cm²). Pelet kemudian dianalisis karakteristiknya seperti abu, kadar air, dan nilai kalor untuk dibandingkan dengan kondisi awalnya. Sebuah desain RSM tiga faktorial penuh diterapkan untuk menjelaskan korelasi antara variabel independen dan variabel terikat. Secara statistik, hasil penelitian menunjukkan bahwa kadar merbau, kadar pengikat, dan gaya tekan menunjukkan efek yang relatif signifikan pada respons yang dipelajari (abu kadar air, kadar air, dan nilai kalor). Selain itu, analisis ANOVA membuktikan bahwa masing-masing variabel memiliki efek signifikan pada tanggapan yang dikonfirmasi oleh nilai P yang mendekati nol. Koefisien determinasi (R²) seluruhnya berada di atas 0,96 dan grafik probabilitas normal mengonfirmasi bahwa model yang diusulkan cukup sesuai dengan hasil eksperimen.

Kata kunci: limbah biomassa; densifikasi; merbau; matoa; RSM

1. Introduction

In recent years, there has been an increasing interest in renewable and sustainable energy utilization around the world to slowly supersede fossil fuels usage. Several main issues about fossil fuels such as carbon emission, environmental and health impacts, and its shortage in the future are starting to be highly considered (Dunlap & Jorgenson, 2012; Heede, 2014; Kampa & Castanas, 2008). One of the most promising energy sources to be utilized as a substitute is the biomass as solid fuel due to its abundance and easy implementation (Henderson et al., 2017; Stelte et al., 2012). However, one of the most important things to be considered is its sustainability. Sustainable biomass solid fuel usage should not compete with food crops, cause land-clearing, or create a higher possibility of CO_2 emission (Tilman et al., 2009).

The raw material itself should not be used directly as a fuel. In terms of physical characteristics, the quality of a solid fuel is strongly influenced by its density (Kaliyan & Morey, 2009; Poddar et al., 2014; Wang et al., 2018). A densified solid fuel will have smaller volume and uniformed shape that will optimize the cost of handling, transportation, and storage (Kaliyan & Morey, 2009). However, most importantly, it will have a higher energy density. A work by Majid, et al. (2017) suggested that densification can be done with binder and fructose was found to be the best binder for spruce wood shavings(Soleimani et al., 2017). Another work that was conducted by Weerapong, et al. (2011) successfully increased solid fuel

heating value by 21.8% by torrefaction and almost 400% by densification process (Wattananoi et al., 2011), suggesting that densification process played a vital role on its energy density. Several works also had been done to compare different biomass sources as solid fuel. A work by Miranda et al. (2015) suggested that wastes from wood industry and forest produced higher heating value than herbaceous and fruit biomass wastes due to higher C percentages gives higher High Heating Value (HHV). Another work found that in general, bamboo and pine have almost the same net calorific value. However, pine wood has a much lower heat release rate from its bark content, giving it a benefit to maintaining combustion time (Liu et al., 2016).

On the other hand, West Papua, Indonesia holds a significant amount of biomass residue. Forest residues and sustainably harvested wood are among its main sources. With a total forest production area of 2.19 million hectares (Forestry, 2015), its own wood processing production reached 150,537.50 m³ in 2015(BPS, 2017). Unfortunately, the normal percentage of biomass residue that will be produced from wood processing can be 60% (FAO, 1990), suggesting that there is more residue generated than that of its own production.

In this research, the raw materials for the solid fuels are merbau (*Intsia bijuga*) and matoa (*Pometia pinnata J.R. Forster & J.G Forster*), native plants from West Papua. With their special characteristics, merbau and matoa are ideal raw materials for flooring, furniture, and other specialty products (Wood-database; Woodsolutions). In addition, as much as 93.83% merbau log production comes from Maluku and Papua (BPS, 2015). As Maluku and Papua do not have well established facility yet, the densification of biomass waste is very promising to support the energy demands. A simple technology and product valorization are the major reasons of densification implementation of wood processing industry waste. Concerning on the limited works that have been done on the native wood from West Papua, this work is focused on studying energy density upgrading of the mentioned wood using densification process. The study aims to convert the waste produced from wood processing industries into solid fuel and evaluate the optimum parameters during the process.

2. Methodology

2.1 Physical and Chemical Characteristics of the Raw Materials

The raw materials (merbau and matoa sawdust waste) were obtained from St. Paul Catholic Polytechnic, Sorong, West Papua, Indonesia. The initial calorific value, moisture, and ash contents of the wood powder wastes were analyzed using proximate analysis in dry basis, as listed in Table 1. It was found that the initial calorific values were 18,031.37 and 17,261.55 kJ/kg. Compared to the gross calorific value of some various lignite coal, which vary between 15,800.00 and 22,060.00 kJ/kg (Feng et al., 2015), this numbers are considerably high.

Table 1. The proximate analysis result of the raw materials (dry basis)

Raw Material	Moisture Content (%)	Ash Content (%)	Fixed Carbon Content (%)	Calorific Value (kJ/kg)
Merbau	12.5567	3.0678	24.2201	18,031.37
Matoa	15.1222	1.9629	19.2271	17,261.55

During 2003-2006, 27 technical specifications for solid biofuel had been issued by the European Committee for Standardization, CEN under committee TC335. The technical specifications are known as European Standards (EN) nowadays (Alakangas, 2011). For general uses, EN 14961-1 "Solid biofuels - Fuel specifications and classes - Part 1: General requirements" is used. As for international standards, the specifications are determined in ISO 17225-2 "Solid biofuels — Fuel specifications and classes — Part 2: Graded wood pellets" (Alakangas, 2015).

Table 2. Solid fuel standards

Standards	Class	Moisture Content (%)	Ash Content (%)	Calorific Value (kJ/kg)
European Standard (EN 14961-1)	-	$\leq$10.00	$\leq$1.00	$\geq$16,500
International Standard (ISO 17225-2)	1	$\leq$10.00	$\leq$1.00	$\geq$16,500
	2	$\leq$10.00	$\leq$1.50	$\geq$16,500
	3	$\leq$10.00	$\leq$3.00	$\geq$16,500

Source:(Alakangas, 2011, 2015)

From the table, it is clear that the moisture of the raw materials is above the suggested standards. However, after densification and drying process, the result can be different and satisfying. Ash content of merbau Wood is slightly above the third-class standard but matoa wood is still acceptable. However, both raw materials have considerably satisfying calorific value. In addition, the calorific value of merbau wood is higher than the matoa, suggesting that the mixture between them can improve the pellet's quality.

2.2 Solid Fuel Making Process

In this research, merbau and matoa wood powder wastes were formed into wood pellet to be used as the solid fuel. The powders were ground and screened into – 20+50 mesh. On the other side, the starch that was obtained from a local market in Yogyakarta, Indonesia was used as a binder. As much as 25 grams wood powder with varied compositions as described in Table 2 was mixed with 25 grams of water and various amounts of starch.

Several studies proved that the addition of the binder, especially starch, will enhance the briquettes' strength in the densification process. During the process, heating is an important part because it will help the mixture become gelatinous and sticky (Bazargan et al., 2014). Several studies also tested the binder with considerably high mass percentage compared to the solid fuel, such as 10%, 25%, or even 50% (Arzola et al., 2012; Bazargan et al., 2014). In this research, the starch was varied from 1% to 10% (starch weight/water weight) in order to focus the study on energy density upgrading via densification of the raw material itself.

As much as approximately 16 grams of the mixed wood powder and starch slurry was then formed with various mould forming compressions using Universal Testing Machine (Torsee's UTM AMU-5DE) as it can be seen in Figure 2. With a total of 27 samples were created and tested, the overall process and the variations can be seen in Figure 1 and Table 2. After the moulding process was done, the pellets were then dried in an oven at 102°C for 3 hours. The pellets were then analyzed by proximate analysis.

Table 2. Experimental Sample Variations of the Pellets

Independent variables	Range and level		
	+1	0	-1
merbau content, % (X_1)	70[a]	50[b]	30[c]
Binder content, % (X_2)	10	5	1
Compression force, kg/cm² (X_3)	150	100	5
[a] Mass of matoa = 30%			
[b] Mass of matoa = 50%			
[c] Mass of matoa = 70%			

2.3. Design of experiment and statistical analysis

This experiment's goal is to optimize several parameters which influence the solid fuel's characteristics (moisture, ash contents, and calorific value). In this study, Response Surface Methodology (RSM) is chosen as the tool because it can reduce the number of experiments to evaluate the parameters and their interactions to the result (Rahayuningsih et al., 2018). There are three independent variables used (wood content, binder content, and compression force) and three levels denoted as +1, 0, and -1 that represent as high, mid, and low level respectively as it can be seen in Table 2.
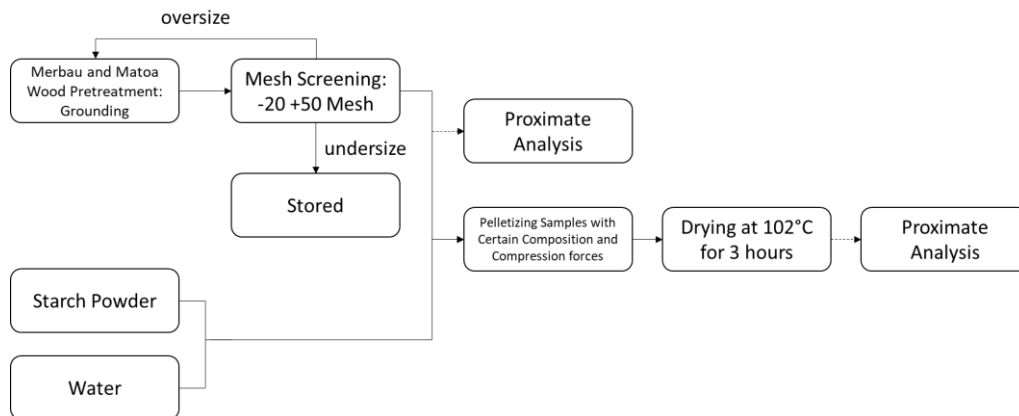
Figure 1. Flow chart of the overall experiment

Figure 2. Laboratory-scale pelletizing machine

The response, however, was analyzed using a second-order polynomial equation to correlate the response (dependent variable) and factors (independent variables). The equation can be written as Eq. (1) (Bezerra et al., 2008).

$$Y = \beta_0 + \sum_{i-1}^{k} \beta_i x_i + \sum_{i-1}^{k} \beta_{ii} x^2_{ii} + \sum_{1 \le i \le j}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

where Y is the response; x_i and x_j are the factors (i and j is the range from 1 to k); β_0 is the constant coefficient; β_i, β_{ii}, β_{ij} are the coefficients for the linear; quadratic and interaction effect; and ε is the error. The model's accuracy was analyzed using the coefficient of determination (R^2). The R^2 has a value, ranged from 0 to 1. If R^2 is close to 1, it indicates that the model is highly accurate (Vedaraman et al., 2017).

3. Results and Discussion

3.1. Statistical analysis and data-fitting of second order polynomial equation

The experiment was done based on a full three-level factorial design to optimize the pellet's characteristics (moisture, ash content, and calorific value). In terms of calorific value, compressive moulding force (X_3) gives insignificant influence. This result is in agreement with the previous study) which found that there is a little rise in the heating value of the pellet with different pelletizing pressures (Poddar et al., 2014). Merbau content (X_1) significantly influence the pellet's ash content. Only with 30% or lower merbau content in the sample, the average ash content can be classified in the third class of ISO 17225-2 standard. On the contrary, the moisture content for all samples is satisfactory for any standards mentioned in Table 2. However, the average calorific value for all samples is 17,550 kJ/kg. Compared to its raw material initial condition, which is averagely 17,650 kJ/kg, the calorific values were approximately similar due to the high initial calorific value of the materials and the physical pelleting process without any treatments such as torrefaction and pyrolysis. Meanwhile, the previous research by Weerapong, et al. (2011) was successfully increased the energy density in the pellet as much as 400% by implementing torrefaction before densification process occurred (Wattananoi et al., 2011). Furthermore, the torrefaction would be difficult to be implemented in such of a remote area in West Papua Indonesia due to limited expertise. For various reasons, the densification process was chosen to minimize the installed equipment for utilizing merbau and matoa sawdust waste.

Minitab® 18 software was used to process the data with the satisfactory result as it can be seen in Table 3. In addition, the empirical relationships between responses and the independent variables are expressed in the equations 2-5.

Table 3. Experimental design matrix and responses

Run Code	X_1, %	X_2, %	X_3, kg/cm^2	Moisture, %		Ash Content, %		Fixed carbon, %		Calorific Value, kJ/kg	
				Experiment	Predicted	Experiment	Predicted	Experiment	Predicted	Experiment	Predicted
1	70	1	50	5.57	5.52	3.69	3.76	22.14	22.33	18,193.16	18,226.95
2	70	1	100	5.43	5.49	3.80	3.86	22.51	22.68	18,321.86	18,351.01
3	70	1	150	5.35	5.39	3.90	3.95	22.93	23.04	18,448.85	18,556.11
4	70	5	50	6.85	6.70	3.62	3.59	20.69	20.46	17,670.96	17,573.68
5	70	5	100	6.61	6.60	3.70	3.71	21.31	20.89	17,914.09	17,777.83
6	70	5	150	6.46	6.42	3.84	3.81	21.60	21.32	18,022.75	18,063.01
7	70	10	50	7.45	7.57	3.42	3.35	18.60	18.80	16,960.35	17,073.81
8	70	10	100	7.32	7.38	3.53	3.48	19.32	19.32	17,200.47	17,378.07
9	70	10	150	7.22	7.12	3.63	3.61	19.60	19.83	18,031.37	17,763.37
10	50	1	50	5.31	5.34	3.63	3.50	21.49	21.40	17,959.53	17,928.96
11	50	1	100	5.26	5.28	3.70	3.59	21.71	21.69	18,059.73	17,975.48
12	50	1	150	5.16	5.14	3.76	3.68	22.14	21.99	18,189.27	18,103.04
13	50	5	50	6.46	6.49	3.21	3.25	19.52	19.58	17,270.05	17,232.70

Table 3. Experimental design matrix and responses (continued)

Run Code	X_1, %	X_2, %	X_3, kg/cm²	Moisture, %		Ash Content, %		Fixed carbon, %		Calorific Value, kJ/kg	
				Experiment	Predicted	Experiment	Predicted	Experiment	Predicted	Experiment	Predicted
14	50	5	100	6.31	6.36	3.36	3.36	19.81	19.95	17,344.90	17,359.31
15	50	5	150	6.24	6.15	3.48	3.46	19.95	20.32	17,408.29	17,566.96
16	50	10	50	7.41	7.33	2.77	2.91	18.11	17.99	16,760.43	16,679.10
17	50	10	100	7.19	7.10	2.95	3.04	18.48	18.45	16,878.34	16,905.82
18	50	10	150	6.69	6.80	3.09	3.16	19.10	18.91	17,094.40	17,213.58
19	30	1	50	5.30	5.29	2.96	3.05	21.14	21.11	17,838.32	17,957.01
20	30	1	100	5.35	5.19	3.08	3.14	21.40	21.35	17,925.64	17,925.99
21	30	1	150	4.99	5.02	3.23	3.22	21.74	21.59	18,064.21	17,976.01
22	30	5	50	6.31	6.41	2.79	2.72	19.31	19.35	17,184.94	17,217.76
23	30	5	100	6.14	6.24	2.79	2.82	19.58	19.66	17,281.68	17,266.83
24	30	5	150	6.03	6.00	2.85	2.92	19.77	19.98	17,357.37	17,396.94
25	30	10	50	7.25	7.21	2.31	2.27	17.85	17.82	16,662.65	16,610.42
26	30	10	100	7.02	6.95	2.48	2.39	18.13	18.23	16,773.24	16,759.60
27	30	10	150	6.57	6.62	2.56	2.51	18.82	18.63	17,012.35	16,989.82

$$Moisture\ content, \% = 5.182 - 0.0122X_1 + 0.3675X_2 - 0.00059X_3 +$$
$$0.000157X_1^2 - 0.01343X_2^2 - 0.000014X_3^2 + 0.000374X_1 X_2 +$$
$$0.000035X_1 X_3 - 0.000359X_2 X_3 \tag{2}$$

$$Ash\ content, \% = 2.034 + 0.04071X_1 - 0.1135X_2 +$$
$$0.00171X_3 - 0.00064X_1^2 - 0.000001X_2^2 - 0.000014X_3^2 + 0.001027X_1 X_2 +$$
$$0.000005X_1 X_3 - 0.000071X_2 X_3 \tag{3}$$

$$Fixed\ Carbon, \% = 22.246 - 0.0525X_1 - 0.5278X_2 + 0.00281X_3 + 0.000809X_1^2 +$$
$$0.01495X_2^2 - 0.00X_3^2 - 0.000669X_1 X_2 + 0.000056X_1 X_3 + 0.000361X_2 X_3 \tag{4}$$

$$Calorific\ value, \frac{kJ}{kg} = 19,095 - 38.4X_1 - 263.2X_2 - 5.78X_3 + 0.408X_1^2 + 7.04X_2^2 + 0.0162X_3^2 +$$
$$0.537X_1 X_2 + 0.0775X_1 X_3 + 0.4X_2 X_3 \tag{5}$$

Table 4. ANOVA analysis results and statistical parameters of the model

Source of variation	Coefficient estimate	DF	Adj. Sum of square	Adj. Mean square	F-value	P-value
Moisture content (Y_1)						
Model		9	16.4163	1.8240	200.64	< 0.001
X_1	0.1834	1	0.6042	0.6042	66.46	< 0.001
X_2	0.9114	1	14.9509	14.9509	1.644.56	< 0.001
X_3	-0.1797	1	0.5798	0.5798	63.77	< 0.001
X_1X_2	0.0336	1	0.0136	0.0136	1.50	0.2380
X_1X_3	0.0353	1	0.0150	0.0150	1.65	0.2170
X_2X_3	-0.0808	1	0.0787	0.0787	8.66	0.0090
X_1^2	0.0629	1	0.0238	0.0238	2.61	0.1240
X_2^2	-0.2720	1	0.4311	0.4311	47.42	< 0.001
X_3^3	-0.0349	1	0.0073	0.0073	0.81	0.3820
Error		17	0.1545	0.0091		
R^2	0.9907	Adj- R^2	0.9857	Pred- R^2	0.9752	

Table 4. ANOVA analysis results and statistical parameters of the model (continued)

Source of variation	Coefficient estimate	DF	Adj. Sum of square	Adj. Mean square	F-value	P-value
Ash content (Y_2)						
Model		9	5.43875	0.6043	86.32	< 0.001
X_1	0.4534	1	3.69266	3.6927	527.46	< 0.001
X_2	-0.2799	1	1.4103	1.4103	201.45	< 0.001
X_3	0.1085	1	0.2114	0.2114	30.20	< 0.001
X_1X_2	0.0924	1	0.10297	0.1030	14.71	0.0010
X_1X_3	0.0054	1	0.00036	0.0004	0.05	0.8240
X_2X_3	0.0159	1	0.00303	0.0030	0.43	0.5190
X_1^2	-0.0969	1	0.05637	0.0564	8.05	0.0110
X_2^2	-0.0130	1	0.00099	0.0010	0.14	0.7120
X_3^3	-0.0026	1	0.00004	0.0000	0.01	0.9410
Error		17	0.11901	0.0070		
R^2	0.9786	Adj- R^2	0.9672	Pred- R^2	0.9451	
Fixed carbon (Y_3)						
Model		9	57.5192	6.3910	127.78	< 0.001
X_1	0.6064	1	6.6059	6.6059	132.07	< 0.001
X_2	-1.6228	1	47.4046	47.4046	947.77	< 0.001
X_3	0.3811	1	2.6088	2.6088	52.16	< 0.001
X_1X_2	-0.0602	1	0.0436	0.0436	0.87	0.3630
X_1X_3	0.0562	1	0.0379	0.0379	0.76	0.3960
X_2X_3	0.0812	1	0.0794	0.0794	1.59	0.2250
X_1^2	0.3234	1	0.6277	0.6277	12.55	0.0030
X_2^2	0.3028	1	0.5345	0.5345	10.69	0.0050
X_3^3	0.0002	1	0.0000	0.0000	0.00	0.9990
Error		17	0.8503	0.0500		
R^2	0.9854	Adj- R^2	0.9777	Pred- R^2	0.9625	
Calorific value (Y_4)						
Model		9	7307896	811988	54.92	< 0.001
X_1	260.9	1	1222466	1222466	82.68	< 0.001
X_2	-534.8	1	5148804	5148804	348.23	< 0.001
X_3	177.1	1	563661	563661	38.12	< 0.001
X_1X_2	48.4	1	28184	28184	1.91	0.1850
X_1X_3	77.5	1	72149	72149	4.88	0.0410
X_2X_3	90.1	1	97813	97813	6.62	0.0200
X_1^2	163	1	159454	159454	10.79	0.0040
X_2^2	142.5	1	118405	118405	8.01	0.0120
X_3^3	40.5	1	9851	9851	0.67	0.4260
Error		17	251363	14786		
R^2	0.9667	Adj- R^2	0.9491	Pred- R^2	0.8950	

The data satisfactoriness and the model's fitness were assessed by regression and analysis of variance (ANOVA), a statistical technique that distributes the total variability into several component parts associated with particular sources of variation for the testing of model parameters (Maran & Manikandan, 2012). In addition, F-test and p-value are also assessed to determine the statistically significant variables which can be seen in Table 4.

As it can be seen from Table 4, the p-value for all linear independent variables (merbau content, binder content, and compressive force) were less than 0.001 for all responses. For a value lower than the level of significant, that is 0.05, the variable is considered as statistically significant for the proposed model (Sinha et al., 2012).

The results are also shown in response and contour plot in Figure 5. For each plot there are two various independent variables, with a fixed middle value of the third independent variable, giving influence on the observed (A) ash content, (B) moisture, (C) fixed carbon content, and (D) calorific value responses. As

it can be seen in the figure, there is no single optimization that can be made because each variable tends to make only increasing or decreasing data trend, with no peak response in the selected interval. Trend of every parameter is symbolized with positive and negative gradient value as seen in Table 5. It means that a positive gradient gives a positive result regarding on the addition of each parameter and vice versa.

The ash content, fixed carbon content, and calorific value have the same trend which were positive result regarding merbau content and compression force. However, it was negative result regarding binder content. It is accordance with the data that merbau has higher ash content, fixed carbon content, and calorific value, thus, the higher addition of merbau and compression force gives positive

affect on the densified wood. Due to higher moisture content with the increasing of binder content, it leads to decreasing the calorific value of densified wood, also fixed carbon and ash content.

Interestingly, the higher moisture content of matoa did not give positive effect on the moisture content of densified wood. matoa wood has instability of moisture content. Thus, the densification process (compressing and drying) enacts crucial role to move away moisture content of matoa sawdust. The higher the binder content, the higher the moisture content was because the higher binder content needs more water for the dilution process. Meanwhile, mechanical compression reduced the moisture content of the densified wood.
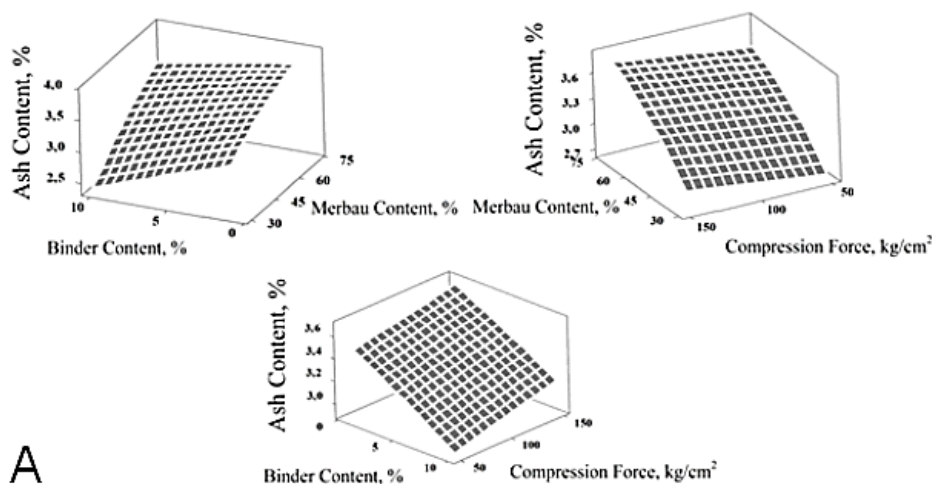

Figure 5. Response surface analysis and contour plot of (A) ash content, (B) moisture content, (C) Fixed carbon content, and (D) calorific value versus merbau content, binder content, and compression force
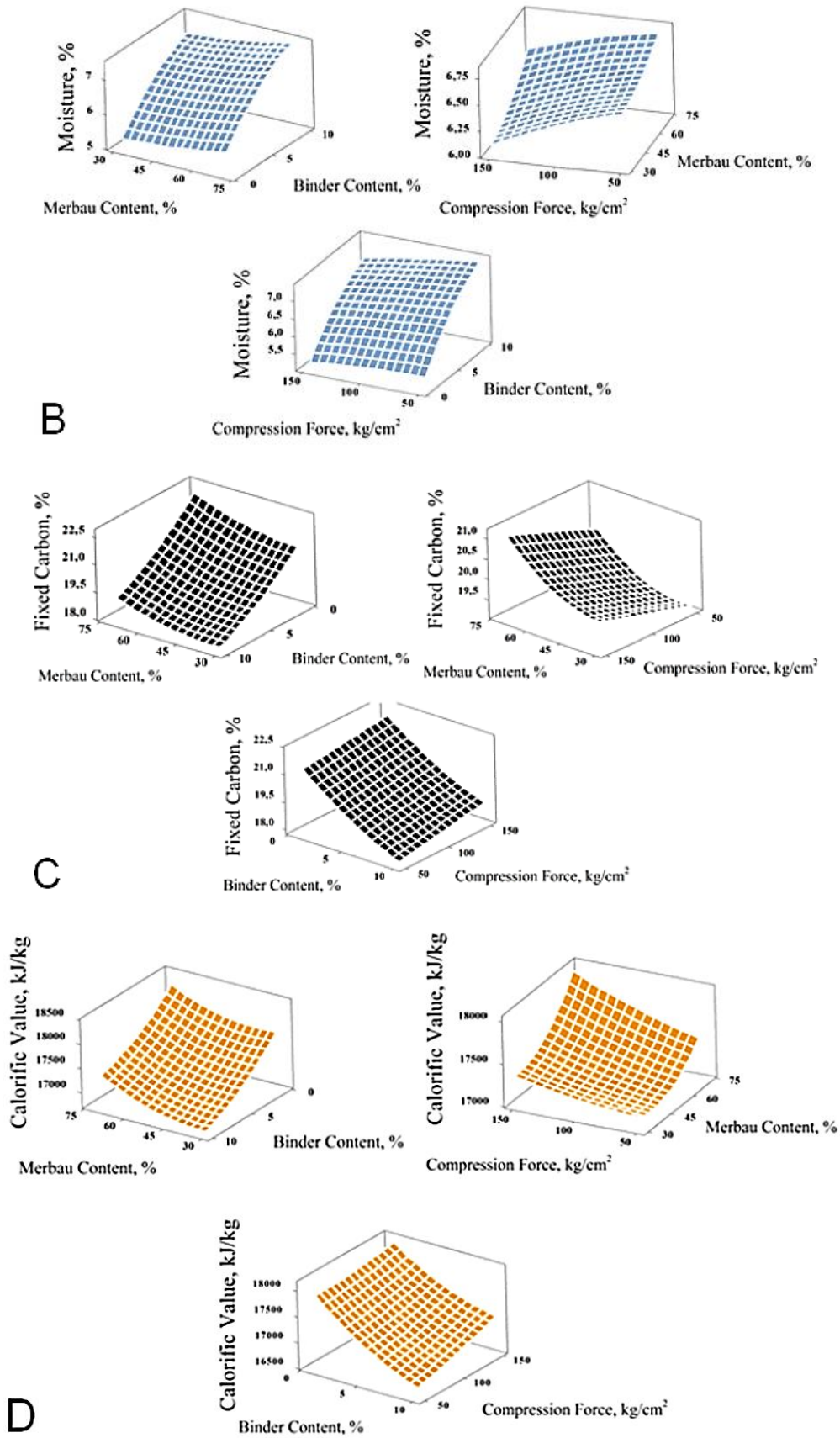
Figure 5. Response surface analysis and contour plot of (A) ash content, (B) moisture content, (C) Fixed carbon content, and (D) calorific value versus merbau content, binder content, and compression force (continued)

**Table 5.** Factorial effect against the respond parameter in this study

Effect	Moisture, %	Ash Content, %	Fixed carbon, %	Calorific Value, kJ/kg
X_1, %	+	+	+	+
X_2, %	+	–	–	–
X_3, kg/cm²	–	+	+	+

The models concluded that the higher merbau content (X_1) and compression force (X_3) are favourable to obtain better densified solid from merbau and matoa. Contrary, the addition of binder content (X_2) should be minimalized. However, due to the two factors of the resulting parameter should be optimized, the optimization had been analysed by Minitab® 18 software with maximization of caloric value and minimization of ash content. The moisture content and fixed carbon in this study were not optimized because those variable are still in the required standards of densified solid. The result showed that 30%, 1 %, and 50 kg/cm² of the input variables (X_1, X_2, and X_3 respectively) gave the optimum value at 3.0463% and 17957.0 kJ/kg of the output variables (ash content and caloric value respectively).

3.2. The validity of the models

For verifying the proposed model, it is crucial to ensure the adequacy of predicted with actual (experimental) values. In this case, the experimental and predicted values are fitted as it can be seen in Figure 6. The data points on this plot are considered close with the straight lines. The results suggest that the models used in this study are compatible to depict the conditions (with all R^2 values are above 0.96) with high accuracies.

Figure 7 shows whether the data are normally distributed, other variables are influencing the responses, or outliers exist in the data. In addition, residual values explain the variation between predicted and experimental values. A highly accurate model is characterized by its small residual value (Agarry & Ogunleye, 2012). The results show that the data are normally distributed, as it is visually visible because the data points are positioned close to the reference line and the outlier data are minimal.
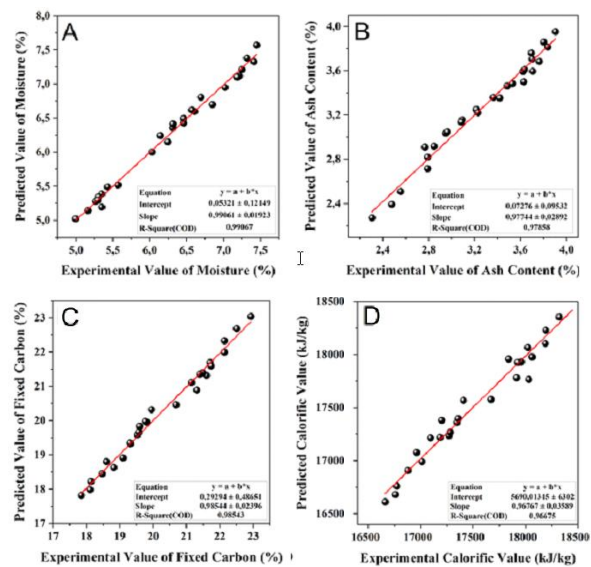
Figure 6. Comparison between experimental and predicted values on responses of (A) moisture content, (B) ash, (C) Fixed carbon content, and (D) calorific value of the pellets.

3.3. Model implementation

Hereby, the models have been precisely predicted the moisture, ash, fixed carbon content, and calorific value from every treatment applied. This model can be used as significant tools to predict those values regarding on the operation condition selection. The moisture, ash, fixed carbon content, and calorific value are some parameters required by ISO 17225-2 standards for solid biomass. Furthermore, the

models can be applied in solid biomass production from merbau and matoa sawdust waste to upgrade the characteristics as it is standardized. Even though the densification process could not increase the calorific value significantly, the densification process has several advantages such as reducing the volumetric of biomass, decreasing ash and moisture content, and increasing fixed carbon and energy density. Furthermore, the calorific value of biomass is a highly useful parameter for bio-energy system design and analysis. The implementation of solid fuel from merbau and matoa sawdust waste primarily depends on the market demand regarding on the specifications. With the precise prediction of the calorific value, the scale up production cost of biomass utilization can be calculated accordingly. Moreover, the valorization of waste from wood processing industry would compensate the income and reduce the waste processing fee. Meanwhile, there are no specific waste utilization of merbau and matoa sawdust.
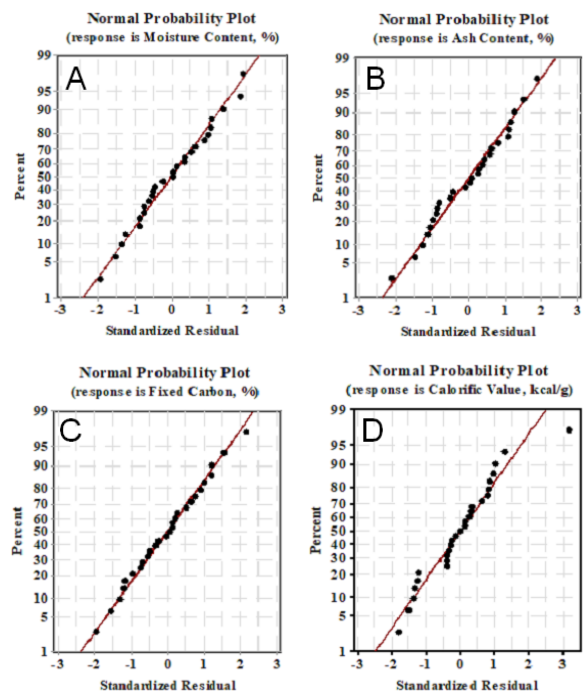

Figure 7. Normal probability plots of studentized residuals for (A) moisture content, (B) ash, (C) fixed carbon content, and (D) calorific value.

Table 6. Result comparison with other studies

No.	Biomass	Calorific Value of raw material, kJ/kg	Calorific Value of densification, kJ/kg	Process	Improvement, %[a]	Reference
1	Lignite Coal	17,800	-	-	-	(COMMISSION, 2006)
2	Meranti	19,000	23,979	Pyrolysis- Densification	26%	(Patabang, 2013)
3	Teak	16,794	26,378	Pyrolysis- Densification	57%	(Yudanto & Kusumaningrum, 2009)
4	Acacia	17,314	29,485	Pyrolysis- Densification	70%	(Sutapa & Irawati, 2013)
5	Mahogany	17,236	23,906	Pyrolysis- Densification	39%	(Rizal Mubarok & Wayan Susila, 2015)
6	Sengon (*Albizia chinensis*)	17,785	28,510	Pyrolysis- Densification	60%	(Satmoko et al., 2013)
7	Merbau	18,031	18,692	Densification	4%	this study
8	Matoa	17,262	17,920	Densification	4%	this study
9	Merbau-matoa	17,800	18,449	Densification	4%	this study

[a]*Calculated by comparing the calorific value of densification solid and initial solid*

As seen in Table 6, the comparison of this study with other studies are presented. The study can upgrade the calorific value of the raw material around 4% without any thermal treatment before conducting densification processes. The increasing of calorific value mainly was caused by compression during densification process.

4. Conclusions

A full three-level response surface method is proved to be effective for depicting the phenomenon on the densification of merbau and matoa sawdust as solid fuel. The independent variables (merbau content, binder content, and compressive force) showed relatively significant effects on the studied responses (ash content, moisture, fixed carbon content, and calorific value). However, despite the results for all samples are satisfactory for the moisture content and calorific value –compared to the ISO 17225-2 standard–, only samples with 30% or lower merbau content can pass the average ash content limit in the third class of ISO 17225-2 standard. The optimum process was carried out to maximize the caloric value and minimize the ash content. The optimum conditions were resulted at 30%, 1 %, and 50 kg/cm^2 of the input variables (X_1, X_2, and X_3 respectively) which gave the optimum value at 3.0463% and 17957.0 kJ/kg of the output variables (ash content and caloric value respectively). In addition, ANOVA analysis proved that each variable has significant effects on the responses that is confirmed by less than 0.001 P-value. The coefficient of determinations (R^2) are all above 0.96 and the normal probability plots confirm that the proposed models adequate the experimental results. The precise models obtained in this study could briefly calculate the economic factors of scale up process to utilize merbau and matoa sawdust waste as prospective bio-energy sources.

Acknowledgments

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