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Optimization of Particle Size and Ramie Fiber Ratio on Hybrid Bio Panel Production from Oil Palm Trunk as Thermal Insulation Materials

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ABSTRACT

The abundant availability of waste oil palm trunks is one of the potential fibers for new thermal insulation materials. While focusing on the manufacturing of thermal insulation materials, the main points to be considered are particle size, reinforcement fiber ratio, and press durations, besides binders type and temperature. This study aimed to optimize the manufacturing process of hybrid bio panels based on oil palm trunks as thermal insulation material. The response surface methodology (RSM), with a Box-Behnken Design (BBD), was used to model and optimize the manufacturing process variables. A total of 17 hybrid bio panels were in operation and the independent variables used were particle size, ramie ratio, and press duration. The dependent variables were water absorption, thickness swelling, MOR, and thermal conductivity. The hybrid bio panel obtained under the optimum conditions was characterized by thermogravimetric analysis to observe thermal stability. On the basis of analysis of variance and the contour plot, it was discovered that the interaction between particle size and ramie fiber ratio was a significant variable to optimize hybrid bio panel manufacture. The thermal resistance and modulus of rupture of hybrid bio panels also improved with higher particle size and ramie fiber ratio. The optimum manufacturing process was obtained at OPT particle size of 0.248 mm, ramie fiber ratio of 19.775, and press duration of 25 min. This condition produces a thermal conductivity of 0.079 W/mK, modulus of rupture of 17.702 MPa, water absorption of 54.428%, and thickness swelling of 21.974%. In addition, the hybrid bio panel resulted in thermal stability of 341 °C.

Keywords: oil palm trunks, hybrid bio panel, thermal insulation, particle size, ramie fiber ratio, RSM.

INTRODUCTION

Energy efficiency has gained attention in recent years due to the concern about the crisis and global warming. In building construction, the investigation on the need of energy efficiency for thermal insulation is rapidly increasing [Awoyera et al., 2022]. This is because thermal insulation is one of the methods of reducing energy loss, specifically in commercial and residential buildings. It is also used to ensure the thermal comfort of people in building structures [Bünning, Huber, Heer, Aboudonia, & Lygeros, 2020; Cintura, Nunes, Esteves, & Faria, 2021].

The building insulation materials are typically synthetic polymer products such as fiberglass, glass wool, polyurethane, and expanded polystyrene with low thermal conductivity. These materials such as glass wool and fiberglass can cause health issues and adverse effects, including biodegradation on the environment during production [Abu-Jdayil, Barkhad, Mourad, & Iqbal, 2021; Lacoste, El Hage, Bergeret, Corn, & Lacroix, 2018; Muthuraj, Lacoste, Lacroix, & Bergeret, 2019; Pásztory, 2021]. Therefore, the replacement of traditional insulation materials with natural ones that have a low impact on the environment is of great concern in the construction industry. Natural fibers are a kind of renewable resource. M Ramesh, Palanikumar, & Reddy, 2017 reviewed the overall characteristics of natural fibers in bio-composites, including source, type, structure, composition, and properties. The properties of the bio-composites are based on the influence of natural fibers combinations. Furthermore, it was also found that there was a negative and positive impact on the environment during the cultivation stage due to the use of pesticides. On the other hand, the disposal of these bio-composites had a clear advantage for the environment. Using natural fiber for reinforcement bio-composites and/or biopolymers has such advantages as low cost, low relative density, high specific strength, renewable nature, and biodegradability.

According to [Tettey, Dodoo, & Gustavsson, 2014], the use of natural fiber as a substitute for synthetic insulating materials such as rock and glass wools reduced 6–8% carbon dioxide emissions and 39% of fossil fuels. Moreover, several reasons that need to be hybridized, such as higher moisture absorption and poor compatibility characteristics, have forced hybridizing with other synthetic/natural fibers. Review properties of hybrid composites such as mechanical, thermal, water absorption, morphological characteristics, tribological behaviour, and other properties have been reported by [Gupta, Ramesh, & Thomas, 2021]. In the field of sustainable thermal insulation materials, several investigations are focused on using renewable resources and waste with lower costs, better insulation properties, and fewer environmental effects [Cetiner & Shea, 2018; Rabbat, Awad, Villot, Rollet, & Andrès, 2022]. Moreover, previous reports on the potency of natural fiber and agricultural waste for insulation materials showed very promoting results [Abu-Jdayil, Mourad, Hittini, Hassan, & Hameedi, 2019; Bakatovich, Davydenko, & Gaspar, 2018; Mawardi, Aprilia, Faisal, & Rizal, 2021a, 2021b].

In Indonesia, one of the largest sources of natural fibers from agricultures waste is oil palm trunks (OPT). Approximately 70% of OPT waste is generated from the plantations process [Abnisa, Arami-Niya, Daud, Sahu, & Noor, 2013] and can be used as a renewable source of fiber for new thermal insulation materials. The statistical data showed that OPT was about 44 million tonnes in 2020 [Indonesia, 2020]. Generally, these wastes are usually burned or the biomass pellet is used [Bakar et al., 2013]. They have also been used as non-structural products such as particleboard [Komariah et al., 2019], lumber [Hashim, Sarmin, Sulaiman, & Yusof, 2011], and plywood [Loh et al., 2010]. The conversion of OPT to natural fiber to substitute synthetic ones as thermal insulation materials provides more benefit and potency. In addition, ramie fiber is one of the natural fibers with a lot of cellulose content and better mechanical properties. Several researchers have previously discussed the reinforcement of ramie fiber for green composites with several focus reviews such as; mechanical, thermal stability, and thermal conductivity [Manickam Ramesh, Rajeshkumar, & Balaji, 2021].

Previous reports were carried out on OPT as one of the potential raw materials for bio panel thermal insulation [Mawardi et al., 2021a, 2021b; Mawardi, Aprilia, Faisal, & Rizal, 2022]. It was discovered that the thermal insulation of hybrid bio panels made from OPT is affected by manufacturing process variables such as particle size, raw material properties, binders and composition, press durations, and fiber ratio. Therefore, there is a need to maximize the selection of manufacturing process variables to obtain bio-panel thermal insulation with good heat resistance performance without compromising physical and mechanical properties. According to [Montgomery, 2017], response surface methodology (RSM) is a statistical strategy for generating, enhancing, and optimizing response variables applicable to various manufacturing processes. RSM is used to analyze problems that optimize all the process parameters collectively [Abnisa, Daud, & Sahu, 2011; Montgomery, 2017]. This method has been applied in some investigations on bio board properties [Baskaran et al., 2015; Nazerian, Beygi, Mohebbi Gargari, & Kool, 2018; Rasyid, Salim, Akil, & Ishak, 2016; Taiwo, Alkarkhi, Ghazali, & Wan Daud, 2017], thermal insulation [Hasanzadeh, Azdast, Doniavi, & Lee, 2019; Rejeb, Yousef, Ghenai, Hassan, & Bettayeb, 2021; Zhang, Hou, Hou, Wei, & Hou, 2019], and concrete materials [Chong et al., 2021; Odeyemi, Abdulwahab, Adeniyi, & Atoyebi, 2020] with reinforcement fiber from renewable sources. However, information on the use of RSM in the manufacturing of hybrid bio panels for thermal insulation based on OPT is limited.

This study aimed to determine the optimal parameters for manufacturing hybrid bio panels based on OPT as thermal insulation using RSM statistical design. The particle size of OPT, ramie fiber ratio and press duration were variables applicable to the manufacturing process. The accuracy of the variables selection will facilitate the analysis of the interaction of physical and mechanical properties to determine the coefficient of thermal conductivity, which is not easily obtained by experimental testing.

MATERIALS AND METHODS

Materials

OPT collected from a local oil palm plantation in Aceh and ramie fibers from an agricultural in Yogyakarta, Indonesia, were used as lignocellulosic raw materials. The material was sawn into rectangles with dimensions of 50×10×10 before being reduced manually into chips with 3×3×0.5 cm. The chips were ground into particles using a Disc Mill with three size levels, namely <0.07 mm (fine), 0.42–0.07 mm (medium), and 0.84–0.42 mm (coarse). The ramie fibers were chopped into strands less than 5 mm long. Subsequently, OPT particles were boiled in hot water for 30 minutes, and ramie fibers were soaked in a 5% NaOH solution for 1 hour. The materials were dried in an oven with a temperature of 80 °C to a moisture content of 10–12%. The chemical composition and the mechanical and physical properties of OPT and ramie fiber are given in Table 1. A natural binder, namely Tapioca was used as an adhesive in the bio panel manufacturing process (amylopectin: 83%, amylose: 17%) [Asrofi, Syafri, Sapuan, & Ilyas, 2020].

Manufacture of hybrid bio panel and testing

A total of 17 hybrid bio panels with 15×15×1 cm was manufactured using hot press equipment manually with the independent variable and OPT, ramie fibers as a co-reinforcement at three levels ratio, namely 0%, 10%, 20%, and tapioca bio binder of 30%. OPT particle and ramie fibers were combined with tapioca starch, followed by 100 ml of hot water. They were stirred with a mixer for 5 minutes until completely mixed and poured into a mold. Furthermore, the materials were pre-pressed for 5 minutes before being compressed at a temperature of 150 °C for 15 and 25 minutes to a target density of 0.80 g/cm^3. The manufacturing variables were specifically selected to optimize bio panel production conditions using RSM. Before testing, the hybrid bio panels were conditioned for one week at room temperature of 25 ± 2 °C and relative humidity of approximately 60%.

Testing of hybrid bio panel

The characteristics of the hybrid bio panels investigated include thermal conductivity (TC), modulus of rupture (MOR), physical properties such as water absorption (WA) and thickness swelling (TS), and thermogravimetric analysis (TGA). The investigation of thermal conductivity based on ASTM C177-97 at a steady-state condition [C.-97 ASTM, 1997] was conducted using an insulated box (Phywe Systeme Gmbh 37070 Göttingen, Germany). MOR according to ASTM D790 [D.-03 ASTM, 2003] was determined using the MTS EXCEED Model E43 universal testing machine with a three-point bending method. Meanwhile, the physical tests were calculated based on the standard of SNI 03-2105-2006 [SNI 03-2105-2006, 2006]. Before and after 24 hours of water immersion, the weight and the thickness of the samples were measured, respectively.

Box-Behnken design of response surface methodology

The software package Design Expert (version 6.0.11) was used for the statistical analysis

Table 1. Content of chemical and physical and mechanical properties of OPT and ramie fiber

Description	OPT (Dungani et al. 2018)	Ramie fiber (Mohammed et al. 2015)
Chemical constituents (%)		
Cellulose	29–37	68.6–76.2
Hemi cellulose	12–17	13–16
Lignin	18–23	0.6–0.7
Mechanical and physical properties		
Tensile strength (MPa)	300–600	500
Young's modulus (GPa)	15–32	44
Density (g/cm^3)	1.1	1.50

Table 2. Design of independent variables and levels

Parameter	Symbol	Unit	Level of variables		
			-1	0	+1
Particle size	X_1	mm	0.074	0.457	0.841
Press duration	X_2	min.	15	10	25
Ramie fiber ratio	X_3	%	0	10	20

Table 3. Design of independent and dependent variables according to BBD

Run	Independent variabel			Dependent value			
	X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_4
1	0.457	20	10	57.25	22.95	15.22	0.069
2	0.457	20	10	57.25	22.95	15.22	0.069
3	0.841	25	10	65.48	30.28	18.15	0.081
4	0.074	20	0	59.80	22.5	12.35	0.181
5	0.074	15	10	55.32	20.44	14.54	0.185
6	0.074	20	20	54.75	18.18	16.26	0.148
7	0.457	20	10	57.25	22.95	15.22	0.069
8	0.457	25	0	61.84	23.08	14.10	0.131
9	0.457	15	20	55.59	25.00	17.83	0.089
10	0.457	25	20	56.76	22.86	17.96	0.085
11	0.841	20	0	65.54	28.85	13.88	0.071
12	0.457	20	10	57.25	22.95	15.22	0.069
13	0.074	25	10	55.42	22.67	16.04	0.071
14	0.841	15	10	66.05	31.22	17.85	0.078
15	0.457	15	0	58.72	29.70	13.73	0.110
16	0.841	20	20	65.12	29.63	18.89	0.067
17	0.457	20	10	57.25	22.95	15.22	0.069

Note: X_1 – particle size (mm), X_2 – press duration (min.), X_3 – ramie fiber ratio (%), Y_1 – water absorption (%), Y_2 – thickness swelling (%), Y_3 – MOR (MPa), Y_4 – thermal conductivity (W/mK).

of the experimental data. This program is used for various purposes, namely regression analysis of experimental data to fit an empirical mathematical equation, analysis of variance (ANOVA), and 3D visualizations of the response surface. In this study, response surface methodology (RSM) was used to investigate the effect of independent variables, which include particle size (X_1), press duration (X_2), and ramie fiber ratio (X_3), on response variables such as water absorption, thickness swelling, MOR, and thermal conductivity. Subsequently, the Box-Behnken Design (BBD) model was used to design the optimum variables of particle size, ramie fibers ratio, and press duration during the manufacturing of the hybrid bio panel as thermal insulation materials. The RSM is one of the statistical programs for a model building to optimize independent variables [Homayoonfal, Khodaiyan, & Mousavi, 2015] and calculate the best-operating factors and the area it meets the operating requirements [Montgomery, 2017]. The number of independent variables and levels used are shown in Table 2. The range of the variables was established and coded to be +1 for axial, center 0, and factorial points -1. According to BBD, 17 manufacturing conditions were randomly carried out as summarized in Table 3.

RESULTS AND DISCUSSION

Regression model of analysis of variance

Table 2 shows the correlation results between the independent and dependent variables obtained from the BBD for the suggested design of manufacturing hybrid bio panels. Furthermore, a quadratic model was selected to show the interactions between all variables. The result quadratic models form the effect of independent variables water absorption (Y_1), thickness swelling (Y_2) and MOR

(Y_3), and thermal conductivity (Y_4) as a function of particle size (X_1), press duration (X_2), and ramie fiber ratio (X_3) are given in regression Equations 1–4.

$$\text{Water absorption } (Y_1) = 57.52 - 9.13X_1 + 0.038X_2 - 0.28X_3 - 0.08X_1X_2 + 0.30X_1X_3 - 0.009X_2X_3 + 21.73X_1^2 + 0.004X_2^2 + 0.008X_3^2 \quad (1)$$

$$\text{Thickness swelling } (Y_2) = 55.58 + 7.92X_1 - 3.07X_2 - 0.79X_3 - 0.41X_1X_2 + 0.33X_1X_3 + 0.022\,X_2X_3 + 9.62X_1^2 + 0.07X_2^2 + 0.004X_3^2 \quad (2)$$

$$\text{MOR } (Y_3) = 25.37 + 2.84X_1 - 1.44X_2 + 0.26X_3 - 0.15X_1X_2 + 0.07X_1X_3 - 0.001X_2X_3 + 2.94X_1^2 + 0.03X_2^2 - 0.003X_3^2 \quad (3)$$

$$\text{Thermal conductivity } (Y_4) = 0.527 - 0.56X_1 - 0.02X_2 - 0.004X_3 + 0.01X_1X_2 + 0.001X_1X_3 - 0.0001X_2X_3 + 0.16X_1^2 + 0.0004X_2^2 + 0.0002X_3^2 \quad (4)$$

The actual and predicted values of the experimental results were calculated based on Equations 1-4 (Table 4). The result showed no significant

Table 4. Result from experimental design to manufacture hybrid bio panels based on OPT

Run	Independent variable			Responses											
	X_1	X_2	X_3	Y_1			Y_2			Y_3			Y_4		
				A	*P*	*R*	*A*	*P*	*R*	*A*	*P*	*R*	*A*	*P*	*R*
1	0.458	20	10	57.25	57.25	0.00	22.95	22.95	0.00	15.22	15.22	0.00	0.069	0.069	0.00
2	0.458	20	10	57.25	57.25	0.00	22.95	22.95	0.00	15.22	15.22	0.00	0.069	0.069	0.00
3	0.841	25	10	65.48	65.49	-0.01	30.28	28.95	1.33	18.15	17.83	0.32	0.081	0.085	0.00
4	0.074	20	0	59.80	59.55	0.24	22.50	22.60	-0.09	12.35	12.31	0.03	0.181	0.173	0.01
5	0.074	15	10	55.32	55.31	0.01	20.44	21.77	-1.33	14.54	14.8	-0.32	0.185	0.180	0.00
6	0.074	20	20	54.75	53.82	0.92	18.18	17.93	0.246	16.26	15.98	0.27	0.148	0.132	0.02
7	0.458	20	10	57.25	57.25	0.00	22.95	22.95	0.00	15.22	15.22	0.00	0.069	0.069	0.00
8	0.458	25	0	61.84	60.90	0.93	23.08	24.16	-1.08	14.10	14.14	-0.04	0.131	0.111	0.02
9	0.458	15	20	55.59	56.52	-0.94	25.00	23.92	1.08	17.83	17.78	0.04	0.089	0.108	-0.02
10	0.458	25	20	56.76	56.50	0.25	22.86	24.29	-1.42	17.96	18.24	-0.28	0.085	0.072	0.01
11	0.841	20	0	65.54	66.46	-0.93	28.85	29.10	-0.24	13.88	14.15	-0.27	0.071	0.086	-0.02
12	0.458	20	10	57.25	57.25	0.00	22.95	22.95	0.00	15.22	15.22	0.00	0.069	0.069	0.00
13	0.074	25	10	55.42	56.60	-1.18	22.67	21.49	1.18	16.04	16.03	0.00	0.071	0.098	-0.03
14	0.841	15	10	66.05	64.87	1.18	31.22	32.40	-1.18	17.85	17.85	0.00	0.078	0.050	0.03
15	0.458	15	0	58.72	58.97	-0.25	29.70	28.27	1.42	13.73	13.44	0.28	0.110	0.122	-0.01
16	0.841	20	20	65.12	65.36	-0.24	29.63	29.53	0.09	18.89	18.92	-0.03	0.067	0.075	-0.01
17	0.458	20	10	57.25	57.25	0.00	22.95	22.95	0.00	15.22	15.22	0.00	0.069	0.069	0.00

Note: X_1 – particle size (mm), X_2 – press duration (min.), X_3 – ramie fiber ratio (%), Y_1 – water absorption (%), Y_2 – thickness swelling (%), Y_3 – MOR (MPa), Y_4 – thermal conductivity (W/mK), *A* – actual value; *P*, predicted value; *R*, residu value.

Table 5. Regression coefficients

Regression coefficients	*WA* (%)	*TS* (%)	*MOR* (MPa)	*K* (W/mK)
Intercept	57.250	22.950	15.220	0.069
X_1 - Particle size	4.613	4.524	1.198	-0.036
X_2 - Press duration	0.478	-0.934	0.288	-0.012
X_3 - Ramie fiber ratio	-1.710	-1.058	2.110	-0.013
$X_1 X_2$	-0.168	-0.793	-0.300	0.029
$X_1 X_3$	1.158	1.275	0.275	0.007
$X_2 X_3$	-0.488	1.120	-0.060	-0.006
X_1^2	3.196	1.416	0.433	0.024
X_2^2	0.121	1.786	0.993	0.011
X_3^2	0.856	0.424	-0.308	0.024
R^2	0.975	0.944	0.990	0.873

differences between the actual and predicted or theoretically calculated values.

The ANOVA was used to evaluate the model's quality, adequacy of the BBD model, and the significance level for coefficients of the quadratic polynomial model. The results showed that a quadratic polynomial model can properly describe the experimental data, where the coefficients of determination (R^2) values for water absorption (Y_1), thickness swelling (Y_2) and MOR (Y_3), and thermal conductivity (Y_4) obtained are 0.975, 0.944, 0.990 and 0.873, respectively (Table 5).

The total R^2 values of responses were closer to 1; when this value approaches unity, it shows a more accurate model fitting the actual data used. Meanwhile, lower values indicate that the response variables used to explain the variation in behavior were inappropriate [Myers, Montgomery, & Anderson-Cook, 2016]. According to the R^2 values, the fitted model explained 2.5% only of the total variables for water absorption, 5.6% thickness swelling, 1% MOR, and 12.7% thermal conductivity.

Effects of independent variables on the response

The RSM analysis can interpret the interaction among the variables by generating three-dimensional (3D) response surface plots [Danish, Hashim, Ibrahim, & Sulaiman, 2014]. Figures 2 to 5 show the 3D response surface plots of the effect of interaction between independent and dependent variables formed from hybrid bio panels.

Water absorption

The 3D response surface plots for water absorption of hybrid bio panels were generated (Figure 1) to explore the effect of OPT particle size, ramie ratio, and press duration. Figure 1a shows that increased OPT particle size can significantly improve the water absorption performance of hybrid bio panels. This indicated that the larger particle size absorbs more water than the smaller ones. Increasing the press duration during hybrid bio panels manufacturing did not affect the water absorption properties (Figure 1b). However, an increase in the quantity of ramie fiber affected the decrease in water absorption.

The presence of ramie fiber and a higher quantity also led to an increase in water absorption resistance. Hybrid bio panels with OPT particle sizes of 0.074 mm and 20% of ramie fiber showed the lowest range of water absorption value compared to other bio boards. A slight decrease in water absorption was noticed by increasing the ramie fiber ratio (Figure 1c). Hybridization of ramie fiber can increase compactness consequence or densities of hybrid bio panels. This is indicated by the 20% hybridization which showed a lower range value for water absorption properties than others. Highly densified hybrid bio panels had lower water absorption capability compared to those with low compaction ratios. Meanwhile, panels with lower compactness had more void spaces between fibers, which leads to easy absorption of water. The addition of co-reinforcement has reduced water absorption due to suitable characteristics of the mixed material, decreasing the void and surface area exposed to water.

Thickness swelling

The interaction plots between OPT particle size, ramie fiber ratio, and press duration for thickness swelling of hybrid bio panels are shown in Figure 2. These plots were similar trends as shown in Figure 2, where a decrease in particle size and increase in ramie fiber ratio, reduce the thickness swelling values of hybrid bio panels.

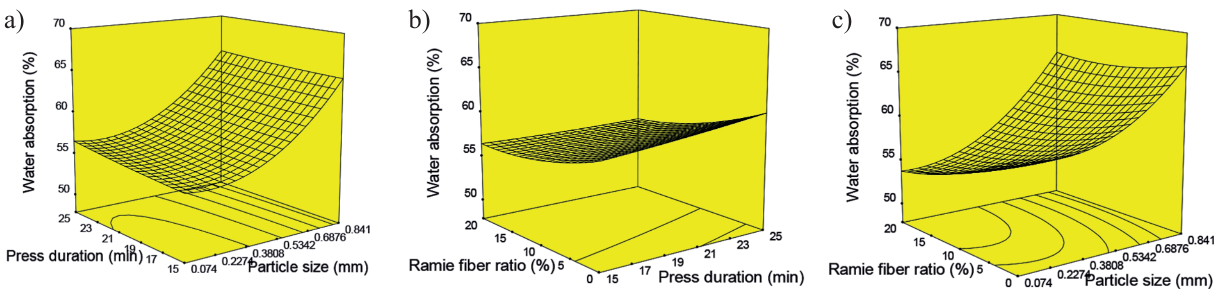

Figure 1. Response surface 3D plots on water absorption of hybrid bio panels (a) particle size and press durations, (b) ramie fiber ratio and press durations, and (c) ramie fiber ratio and particle size

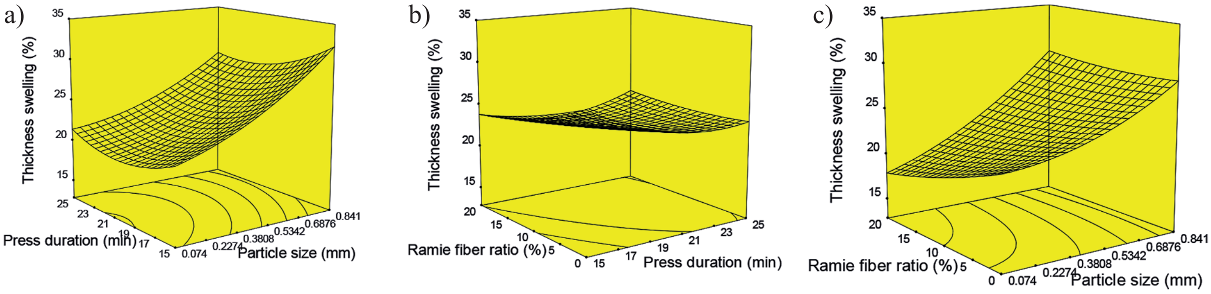

Figure 2. Response surface 3D plots on thickness swelling of hybrid bio panels (a) particle size and press durations, (b) ramie fiber ratio and press durations, and (c) ramie fiber ratio and particle size

On the basis of Figure 2a which showed the lowest value at a particle size of 0.074 mm and press duration ranging from 19 to 21 minutes, higher particle size increases the thickness swelling of the hybrid bio panels. Although these properties were not significantly affected by press duration, there was a slight improvement in their performance as the amount of ramie fiber increased (Figure 2b), which was observed when the panels' OPT particle size was reduced (Figure 2c). This showed that the thickness swelling properties of hybrid bio panels influenced OPT particle size and ramie fiber ratio. However, the press duration only marginally affected the properties. On the basis of the results, the thickness swelling of the bio panel was affected by the water absorption performance.

Modulus of rupture

Figure 3 showed the 3D relationship between OPT particle size, ramie fiber ratio, and press duration on MOR properties of hybrid bio panels. From Figure 3a, the OPT particle size significantly influenced the modulus of rupture compared to the press duration, where MOR increased with higher OPT particle size. The bio panel of 0.841 mm seems to have higher MOR properties than the samples with a size of 0.074 mm. This is due to larger particle size, leading to a more comprehensive interfacial bonding, or higher glue lines, which increases the flexural strength of panels. This was also discovered in the interaction between ramie fiber and press duration on MOR response, as shown in Figure 3b. A decrease in the quantity of ramie fiber resulted in a strong reduction in MOR strength. Figure 3c shows the interaction between OPT particle size and ramie fiber ratio for MOR properties of hybrid bio panels. The 3D response surface plots indicated that the ramie fiber and OPT particle size significantly influence the modulus of rupture, which is increased with higher OPT particle size. Moreover, an improvement in the MOR was also observed when there was an increase in the ratio of ramie fiber in the bio panels.

On the basis of the results, it can be concluded that MOR of hybrid bio panels was influenced by OPT particle size and ramie fiber ratio, but not by press duration for bio panels manufacturing. Moreover, bio panels with large OPT particle size and the hybridization of ramie fiber as co-reinforcement require a greater load to make them rupture. Previous studies observed a similar tendency with different reinforcements such as wood, bamboo, and rice straw using natural resin as a binder [Nguyen, Grillet, Bui, Diep, & Woloszyn, 2018; Viel, Collet, & Lanos, 2019].

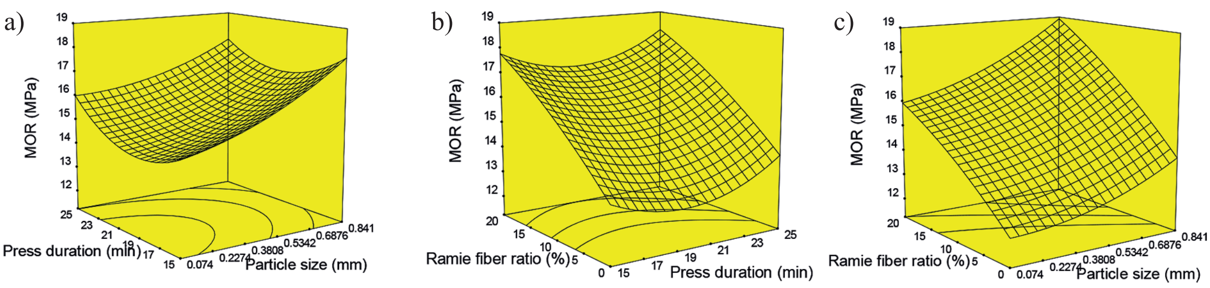

Figure 3. Response surface 3D plots on MOR of hybrid bio panels (a) particle size and press durations, (b) ramie fiber ratio and press durations, and (c) ramie fiber ratio and particle size

The decrease in particle size led to a reduction in porosity, which indicated that a low porosity will improve the density of bio panels and reduces the MOR value.

Thermal conductivity

The 3D response surface plot between OPT particle size, ramie fiber ratio, and press duration on thermal conductivity is shown in Figure 4. On the basis of the results, there is a significant relationship between the particle size, co-reinforcement ramie fiber ratio composition, and thermal conductivity coefficient of bio panels. When the ramie fiber ratio is the highest and the particle size is the largest, the thermal conductivity coefficient of bio panels is lowest. The thermal conductivity coefficient increases with the smaller the particle size, which improves density and decreases the porosity. An increase in porosity can affect the thermal conductivity susceptibility of the material. This finding is similar to the research studied by [Pundiene, Vitola, Pranckeviciene, & Bajare, 2022] and [Dębska, Lichołai, & Krasoń, 2017]. However, larger particle size indicated a positive effect on thermal resistance (Figure 4a). Figure 4b shows that the interaction between the quantity of ramie fiber and the press duration has little effect on the thermal conductivity value of the bio panels. The addition of ramie fiber to OPT particles in the bio panels reduced the thermal conductivity coefficient (Figure 4c).

The pores formed contain gas and became the center of thermal scattering, reducing the heat passing through bio panel. The increase in the thermal resistance of the hybrid bio panel with higher ramie fiber ratio and particle size of OPT led to a decrease in physical properties and an improvement in the MOR properties. The results showed that the thermal conductivity of hybrid bio panels is influenced by several parameters such as the type of the material, the thermal stability, the density associated with the compactness level, the number of pores formed, and the adhesive.

Optimization of variables

The optimization process was carried out using the desirability function, which ranges from 0 to 1 and combines multiple responses into one part. A very good value is 1, which indicates that the model can use the suggested variables. Table 6 shows an optimum hybrid bio panel manufacturing condition selected from variables with various OPT particle sizes, ramie fiber ratios, and press duration. The optimum variables for manufacturing were determined using Equations (1)–(4). Since this study aimed to optimize OPT particle size, ramie fiber ratio, and press duration in the manufacturing hybrid bio panels as thermal insulation, the variables were adjusted to obtain the least values for the minimum thermal conductivity coefficient, water absorption, and thickness expansion, while bending strength

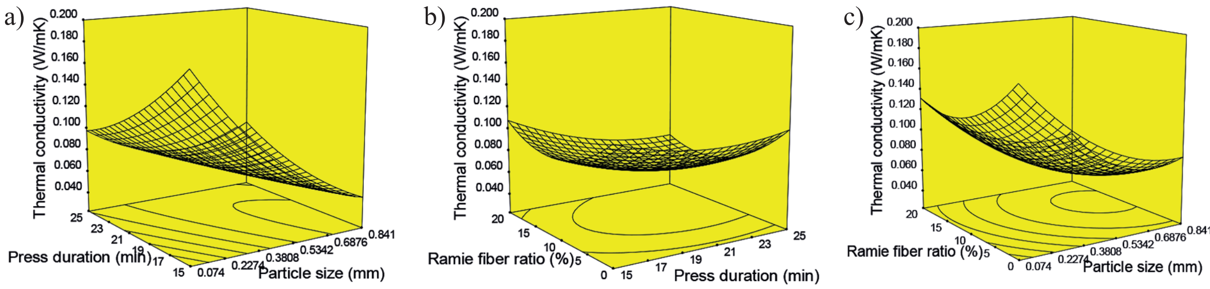

Figure 4. Response surface 3D plots on thermal conductivity of hybrid bio panels (a) particle size and press durations, (b) ramie fiber ratio and press durations, and (c) ramie fiber ratio and particle size

Table 6. Optimum conditions of manufacturing hybrid bio panel based on OPT

Optimum condition	Particle size (mm)	Press duration (min)	Ramie fiber ratio	*WA* (%)	*TS* (%)	*MOR* (MPa)	*TC* (W/mK)	Desirability
WA (min)	0.189	17.858	16.347	54.232	19.593	15.671	0.122	1.000
TS (min)	0.101	18.887	19.348	53.834	18.144	15.882	0.136	1.000
MOR (max)	0.074	25.000	20.000	54.101	20.699	17.502	0.096	0.860
TC (min)	0.248	25.000	19.775	54.428	21.974	17.702	0.079	0.850

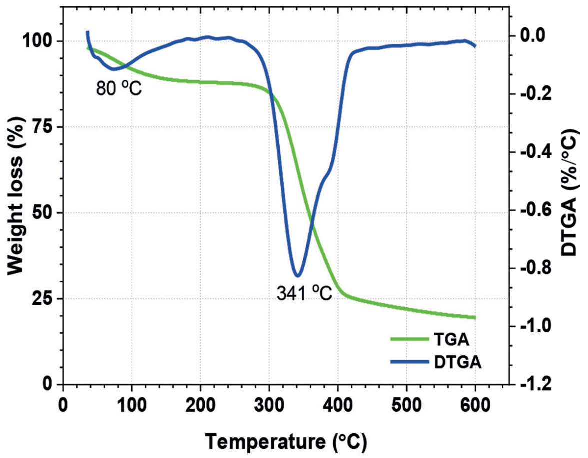

Figure 5. TGA and DTGA curve of hybrid bio-panels based on OPT

(MOR) was maximum. Furthermore, the hybrid bio panels with ideal thermal insulation properties suggested OPT particle size 0.248 mm, ramie fiber ratio 25, and press duration of 19.775 minutes press duration.

Thermal stability

The large OPT particle size and characteristics of ramie fiber, with good thermal stability, have promoted the thermal resistance properties on the hybrid bio panels. The thermal stability of the hybrid bio panel was evaluated using thermogravimetry by analyzing the degradation and decomposition of the panel's constituent elements. Figure 5 shows the TGA curve of thermal weight loss and derivative thermogravimetric analysis (DTGA) curve of hybrid bio panels as a function of temperature increase. The TGA curve is divided into three major sections, where the first degradation causes a slight loss of weight due to water evaporation at a temperature of 120 °C. It also shows the maximum decomposition of hybrid bio panels in the range of 310-405 °C, which causes partial oxidation of the starch and degradation of the fiber. In the final stage, the highest decomposition rate of the bio panel is observed above the 408 °C.

Figure 5 also shows the DTGA curve, indicating the thermal stability of bio panel, at peak degradation of 341 °C. This result is better than a bio-panel manufactured from oil palm trunk and treated with ammonium dihydrogen phosphate at 200 °C and 330 °C [Komariah et al., 2019]. The thermal stability is influenced by the good interfacial bonding between OPT, ramie fiber, and tapioca starch, leading to strong hydrogen bonds, thereby reducing weight loss in the sample. Furthermore, the thermal stability behavior of natural-fiber-reinforced panels is also affected by fiber types, treatment processes, and matrices.

CONCLUSIONS

The optimum manufacturing conditions of hybrid bio panels based on OPT as thermal insulation were determined using a BBD in response surface methodology software. A statistical study of mathematical model equations was built using ANOVA and experimental data. The results showed that the interaction between particle size OPT and ramie fiber ratio was the largest significant variable in optimizing hybrid bio panel production; however, the press duration is not a substantial variable. The result showed the lowest thermal conductivity of 0.079 W/mK with the modulus of rupture of 17.702 MPa, water absorption of 54.428 %, and thickness swelling of 21.974%. Furthermore, the optimized conditions of the manufacturing process variable at particle size OPT of 0.248 mm, ramie fiber ratio of 19.775, and press duration of 25 minutes. The DTGA analysis showed that the hybrid bio panel has thermal stability at temperature 341 °C.

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