Determining Optimum Material Mixture Ratio and Hot-pressing Parameters for New Hybrid Fiber-reinforced Composites: Modeling and Optimization by Response Surface Methodology

Wei Song,[a,b,c] Minghao Zhu,[a] Wei Lin,[a] and Shuangbao Zhang [a,b,c,]*

As a bamboo processing residue, bamboo green (B) was evaluated as an additive to wood fiber (W) for developing composite panels. According to a Box-Behnken design, urea-formaldehyde resin-glued panels were fabricated from blends of B and W, with three preparation variables: B weight percentage in fibrous material (20%, 40%, and 60%), hot-pressing temperature (160 °C, 180 °C, and 200 °C), and hot-pressing duration (60, 120, and 180 s). The panels were tested for water uptake, thickness expansion, bending strength, and bending modulus. The results showed that the physical-mechanical properties of panels satisfied the strictest requirements of GB/T 11718 (2009). Four quadratic models were established to predict the four properties using the three variables. All models were statistically significant, with coefficients of variation below 5% and coefficients of determination beyond 0.96. An analysis of variance revealed that all variables significantly influenced panel properties. Their effect mechanisms were discussed. A response surface analysis demonstrated that, for different properties, the optimum B percentage, hot-pressing temperature, and hot-pressing duration ranged from 35% to 49%, 173 °C to 198 °C, and 111 s to 134 s, respectively. When all four properties were simultaneously optimized, the optimum preparation conditions were 42%, 179 °C, and 119 s, respectively.

Keywords: Hybrid fiber-reinforced composites; Material mixture ratio; Hot-pressing parameters; Physical-mechanical properties; Response surface methodology

*Contact information: a: Beijing Key Laboratory of Wood Science and Engineering, Beijing Forestry University, Beijing 100083, China; b: MOE Key Laboratory of Wooden Material Science and Application, Beijing Forestry University, Beijing 100083, China; c: MOE Engineering Research Center of Forestry Biomass Materials and Bioenergy, Beijing Forestry University, Beijing 100083, China; *Corresponding author: shuangbaozhangj5@163.com*

INTRODUCTION

Wood fiber-reinforced composite panels, such as particleboard and fiberboard glued by urea-formaldehyde resin binder, have been extensively employed in the furniture, construction, packaging, and transportation industries (Chen *et al*. 2017; Guan *et al*. 2017; Zhu *et al*. 2017). Medium-density fiberboard, for example, is composed of 10% to 20% binder and 80% to 90% wood fiber (Tang *et al*. 2017). With an increasing population, there is an increasing demand worldwide for these products (Kusumah *et al*. 2017). However, a scarcity of timber resources inevitably presents a challenge that restrains the development of wood-based panels (Klímek *et al*. 2018). Therefore, some potential lignocellulosic resources, such as straw and grass, have been studied for supporting panel production in the future (de Almeida *et al*. 2017; Jin *et al*. 2017; Zhang *et al*. 2017).

To date, many fibrous materials have been employed to replace or partially replace wood for developing formaldehyde-based resin-bonded composite panels. For example, Belini *et al*. (2012) described urea-formaldehyde resin-bonded fiberboard from a blend of *Saccharum* spp. sugarcane bagasse and *Eucalyptus grandis* eucalyptus wood. Buyuksari *et al*. (2010) prepared urea-formaldehyde resin-bonded particleboard from a blend of *Pinus pinea* cones, *Pinus nigra* wood, and *Fagus orientalis* wood. Barros Filho *et al*. (2011) manufactured urea-formaldehyde resin-bonded chipboard from a blend of industrial sugarcane bagasse and eucalyptus wood. Holt *et al*. (2014) produced melamine-modified urea-formaldehyde resin-bonded and phenol-formaldehyde resin-bonded fiberboard from a blend of cotton carpel and southern yellow pine. Lü *et al*. (2015) evaluated isocyanate/urea-formaldehyde compound-resin-bonded particleboard from a blend of corn stalk skin and poplar wood. Nayeri *et al*. (2014) obtained urea-formaldehyde resin-bonded fiberboard from *Hibiscus cannabinus* L. kenaf stem and rubber wood. Park *et al*. (2012) fabricated phenol-formaldehyde resin-bonded particleboard from a blend of *Miscanthus sacchariflorus* straw and Douglas fir wood. Paridah *et al*. (2014) assessed urea-formaldehyde resin-bonded particleboard from a blend of kenaf whole stem and rubber wood. Yang *et al*. (2003) made urea-formaldehyde resin-bonded particleboard from a blend of rice straw and wood. The above-mentioned reports have demonstrated that, for composite panels from blends of wood and other fibrous materials, there is an optimum material mixture ratio for different fibrous materials, which optimizes the panels' physical-mechanical properties.

Bamboo is a widely distributed and fast-growing woody grass that has been used in food, furniture, textiles, and household goods (Fan *et al*. 2015; Deng *et al*. 2017). Typically, the timber part of bamboo is divided into three layers: The outer layer, with a higher vascular bundle density, is called bamboo green; the inner layer, with a lower vascular bundle density, is called bamboo yellow; and the layer between them is called bamboo meat (Xin *et al*. 2015; Wang *et al*. 2016). Compared with bamboo meat, bamboo green and bamboo yellow possess very different physicochemical properties, which can produce some negative effects on bamboo processing (Li *et al*. 2014b). For example, bamboo green and bamboo yellow contain abundant wax and silica (Zhang *et al*. 2013). When manufacturing bamboo panels, the adhesion of bamboo timber can be deteriorated due to these hydrophobic substances (Zhou *et al*. 2017). In a pulping process, the lime kiln, recovery furnace, causticization, and evaporator operations can also be disturbed by the abundant silica in bamboo timber (Xu *et al*. 2016). Therefore, bamboo green and bamboo yellow are always cut from bamboo timber and become processing residues (Li *et al*. 2014b; Pan *et al*. 2017). For example, China, known as the "bamboo kingdom," has an annual production of these bamboo processing residues of up to 46 million tons (Song *et al*. 2015; Huang *et al*. 2016).

During the past few years, bamboo green has been utilized as a biomass feedstock for producing some chemicals and fuels. For example, Huang *et al*. (2015, 2016) extracted xylan and phenolic acid from bamboo green cell wall. Li *et al*. (2014b), Li *et al.* (2015), and Xin *et al*. (2015) evaluated the saccharification of bamboo green under different treatment methods (sulfuric acid, aqueous ammonia, sodium hydroxide, or sulfite) and additive types (polyethylene glycol, polysorbate, or bovine serum albumin). Yang *et al.* (2016) assessed the digestibility of bamboo green by proposing a rapid technique based on spectroscopy. In addition to these reports, some researchers have investigated the behavior of bamboo green in bamboo panel fabrication. For example, Deng *et al*. (2015) analyzed the impact of bamboo green retention ratio on the physical-mechanical data of laminated bamboo-bundle veneer lumber bonded with phenol-formaldehyde resin. Zhang *et al*. (2015) measured the effect of phosphoric acid/γ-aminopropyltriethoxysilane and corona treatments on the surface wettability and chemistry of bamboo green. Zhang *et al*. (2013) surveyed the influence of sodium hydroxide treatment on the bonding properties of bamboo green strips with isocyanate. Nevertheless, a systematic study of the preparation and properties of urea-formaldehyde resin-glued composite panels made from bamboo green has not yet been found. Because the surface of bamboo green is coated with abundant wax and silica, there is a difficulty in bonding bamboo green with commonly used wood adhesives such as urea-formaldehyde resin (Lü *et al*. 2015). Hence, incorporating wood fiber into bamboo green may be an approach to promote adhesion quality for this kind of panel (Park *et al*. 2012).

To open a gateway for the value-added utilization of bamboo green, a preliminary study has been conducted by the authors, in which bamboo green/wood fiber-reinforced composite panels bonded with urea-formaldehyde resin were developed. For composite panels made from blends of different fibrous materials, the material mixture ratio is often a very important preparation variable that must be considered in panel production (Yang *et al*. 2003; Buyuksari *et al*. 2010; Barros Filho *et al*. 2011; Belini *et al*. 2012; Park *et al*. 2012; Holt *et al*. 2014; Paridah *et al*. 2014; Lü *et al*. 2015; de Almeida *et al*. 2017). In addition, the physical-mechanical properties of lignocellulosic board are also strongly influenced by its hot-pressing parameters, such as temperature and duration (Nazerian *et al*. 2015). Considering that in the above-mentioned preliminary study, a series of single-factor experiments were employed to observe the effects of material mixture ratio (bamboo green weight percentage in fibrous material, including 0%, 20%, 40%, 60%, 80%, and 100%), hot-pressing temperature (140 °C, 160 °C, 180 °C, and 200 °C), and hot-pressing duration (60 s, 120 s, 180 s, 240 s, 300 s, and 360 s) on the physical-mechanical properties of bamboo green/wood fiber-reinforced composite panels. It was found that the optimum ranges for the three preparation variables were 20% to 60%, 160 °C to 200 °C, and 60 s to 180 s, respectively.

To further understand the preparation and properties of bamboo green/wood fiber-reinforced composites, the present study was performed. First, in accordance with a Box-Behnken design, panels were prepared under different material mixture ratios (20% to 60%), hot-pressing temperatures (160 °C to 200 °C), and hot-pressing durations (60 s to 180 s). To characterize the panels' physical-mechanical properties, water uptake, thickness expansion, bending strength, and bending modulus were evaluated. Secondly, based on these experimental data, mathematical models were developed to correlate the four properties with the three preparation variables, and the quality of these models was assessed. By virtue of a response surface analysis, the effects of the three variables on the four properties were elucidated, and their effect mechanisms were also discussed. Finally, for different optimization goals, the optimal values of the three variables were determined. This work will provide useful information for utilizing bamboo green to develop new wood-based composites.

EXPERIMENTAL

Materials

Bamboo green was bought from the Chitianhua Group (Guiyang, Guizhou, China). Its species was *Neosinocalamus affinis*, and its main particle size was 20-mesh to 40-mesh.

Wood fiber was bought from Krono Wood-based Panels Co., Ltd. (Beijing, China). Its species was *Populus tomentosa*, and its main particle size was 20-mesh to 40-mesh. Urea-formaldehyde resin was also bought from Krono. It had a solid weight percentage of 52%, a viscosity of 40 mPa·s, a formaldehyde/urea molar ratio of 1.1, a pH of 8.5, and an ammonium chloride hardener weight percentage of 1% based on solid resin.

Panel preparation

Fibrous material was kiln dried to a moisture weight percentage of 3% and then blended with resin (17% by weight in total material) by a laboratory mixer (Belini *et al*. 2012; Holt *et al*. 2014; Paridah *et al*. 2014; Lü *et al*. 2015). Subsequently, a mat was manually assembled from the resinated fibrous material, with a target density of 0.75 g/cm^3, a target dimension of 400 × 400 × 10 mm^3, and a moisture weight percentage of 12%. The pre-pressed mat was finally hot-pressed under 2 MPa pressure to harvest panel. Table 1 shows the Box-Behnken design for preparing the composite panels (Song *et al*. 2017). The three preparation variables were material mixture ratio (bamboo green weight percentage in fibrous material), hot-pressing temperature, and hot-pressing duration.

Table 1. Box-Behnken Design for Preparing Composite Panels and Levels of Preparation Variables

Panel Number Sorted by Randomized Run Order	Material Mixture Ratio Level	Hot-pressing Temperature Level	Hot-pressing Duration Level
1	3 (60%)	1 (160 °C)	2 (120 s)
2	2 (40%)	3 (200 °C)	3 (180 s)
3	2	2 (180 °C)	2
4	1 (20%)	1	2
5	2	2	2
6	2	1	3
7	1	3	2
8	2	2	2
9	2	2	2
10	2	1	1 (60 s)
11	1	2	3
12	3	2	3
13	3	3	2
14	2	2	2
15	2	3	1
16	3	2	1
17	1	2	1

Methods

Analytical

The water uptake of the panels was tested in accordance with Chinese national standard GB/T 17657 (2013). The thickness expansion, bending strength, and bending modulus of the panels were tested in accordance with Chinese national standard GB/T 11718 (2009). Water uptake and thickness expansion were tested after the panels were submerged in 20 °C water for 24 h. The bending properties were tested using a three-point bending method. The water absorption experiment was duplicated three times. The bending experiment was duplicated six times. The mechanical experiments were conducted on an MWW-50 universal mechanical testing machine (Tayasaf Corporation, Beijing, China).

The data were analyzed with Design-Expert 8.0.6 software (Stat-Ease, Inc., Minneapolis, MN, USA).

RESULTS AND DISCUSSION

Box-Behnken Design Experimental Data

Data distribution

Figure 1 shows the Box-Behnken design experimental data. As illustrated, in different groups, the water uptake, thickness expansion, bending strength, and bending modulus of the panels changed noticeably. The averages of the four properties were 23.7%, 4.1%, 33.4 MPa, and 2.6 GPa, respectively. The coefficients of variation for the four properties were 23.3%, 12.3%, 13.8%, and 15.7%, respectively. The thickness expansion, bending strength, and bending modulus of the panels were tested in accordance with Chinese fiberboard national standard GB/T 11718 (2009).

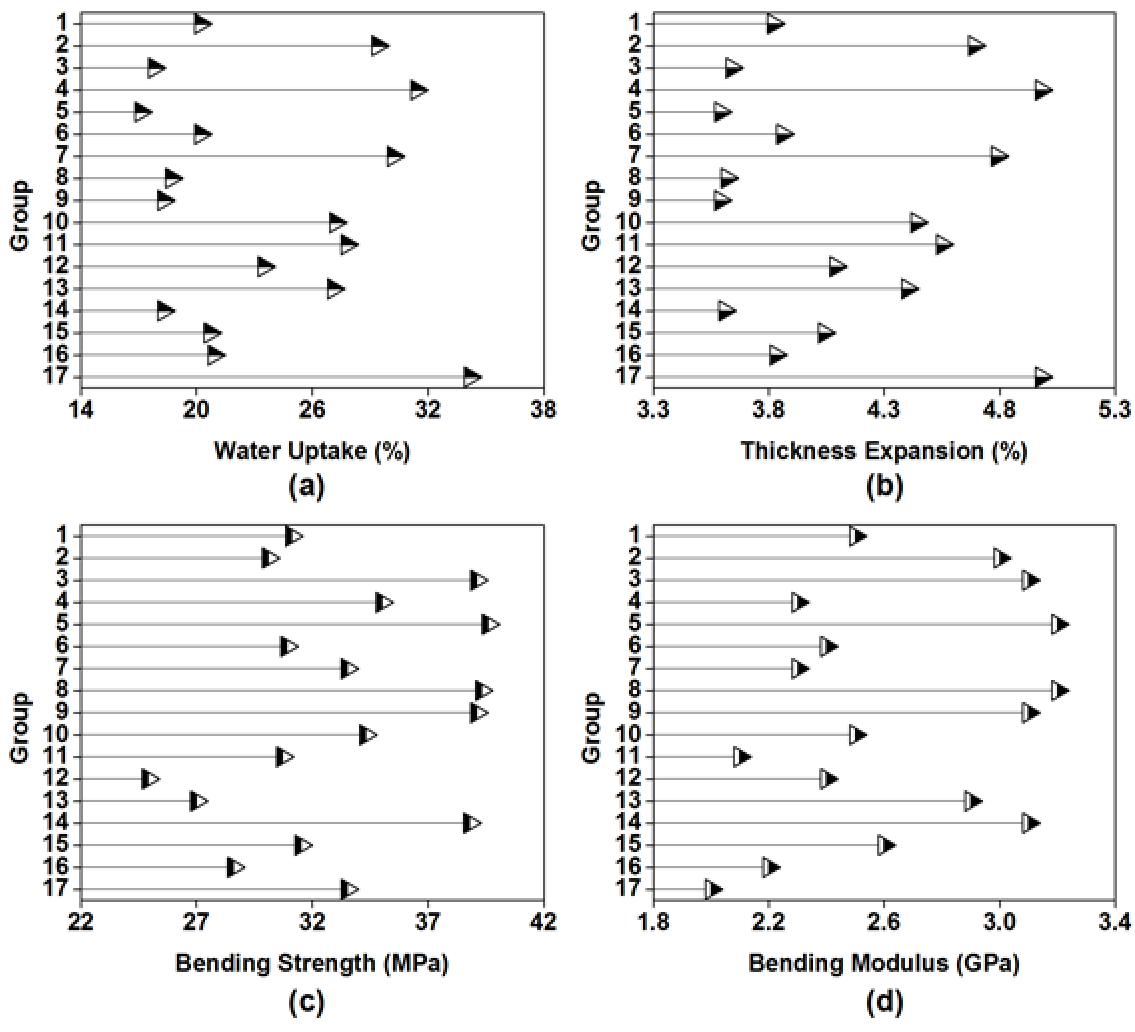

Fig. 1. Box-Behnken design experimental data for water uptake, thickness expansion, bending strength, and bending modulus of composite panels

In this standard, for panels with a thickness of 9 mm to 13 mm, the strictest requirements for bending modulus and strength are 2.80 GPa and 32.0 MPa, respectively, which are assigned as MDF-LB HMR (load-bearing panel for high-humidity application); furthermore, the strictest requirement for thickness expansion is 7.0%, which is assigned as MDF-FN EXT (furniture-grade panel for exterior application). Compared with these requirements, all groups in Fig. 1 exhibited lower thickness expansion, and some groups in Fig. 1 displayed higher bending strength and bending modulus.

Data correlation

Table 2 shows the linear correlations for the Fig. 1 data. As illustrated, there was a positive correlation between the two physical properties and between the two mechanical properties. However, there was a negative correlation between the physical properties and mechanical properties. For the six correlations L1 to L6, their coefficients of determination R^2 ranged from 0.15 to 0.98. The correlation L3 exhibited the highest R^2 (0.98), reflecting a very high correlation between water uptake and thickness expansion (Wang *et al*. 2015). In contrast, the other five correlations only displayed an R^2 of 0.15 to 0.39. This indicated that, for bamboo green/wood fiber-reinforced composite panels, the interaction between water uptake and thickness expansion was strong, but those among other properties were not very noticeable (Paridah *et al*. 2014).

Table 2. Linear Correlations for Fig. 1 Data Calculated by Model $y = \alpha \cdot x + \beta$

Correlation	Dependent Variable (y)	Independent Variable (x)	Slope (α)	Intercept (β)	Coefficient of Determination (R^2)
L1	Water uptake	Bending strength	-0.47	39.47	0.16
L2	Thickness expansion	Bending strength	-0.04	5.58	0.15
L3	Water uptake	Thickness expansion	10.72	-20.76	0.98
L4	Bending strength	Bending modulus	6.38	16.50	0.33
L5	Water uptake	Bending modulus	-8.30	45.64	0.39
L6	Thickness expansion	Bending modulus	-0.77	6.18	0.39

Modeling Analysis Based on Box-Behnken Design Experimental Data

Model development

Based on the Fig. 1 data, quadratic regression models (Eqs. 1 to 4) were fitted by the Design-Expert software, as shown in Table 3. When material mixture ratio, hot-pressing temperature, and hot-pressing duration vary in the ranges of 20% to 60%, 160 °C to 200 °C, and 60 s to 180 s, respectively, the four models can be used to predict the water uptake, thickness expansion, bending strength, and bending modulus of panels according to the three preparation variables.

Table 3. Quadratic Regression Models Fitted Based on Fig. 1 Data

Model	Equation *
Eq. 1	$Y_1 = 449.31 - 2.48\ X_1 - 3.67\ X_2 - 8.58 \times 10^{-1}\ X_3 + 5.06 \times 10^{-3}\ X_1X_2 + 1.88 \times 10^{-3}\ X_1X_3 + 3.27 \times 10^{-3}\ X_2X_3 + 1.43 \times 10^{-2}\ X_1^2 + 8.70 \times 10^{-3}\ X_2^2 + 7.93 \times 10^{-4}\ X_3^2$
Eq. 2	$Y_2 = 47.89 - 2.23 \times 10^{-1}\ X_1 - 3.97 \times 10^{-1}\ X_2 - 6.92 \times 10^{-2}\ X_3 + 4.81 \times 10^{-4}\ X_1X_2 + 1.44 \times 10^{-4}\ X_1X_3 + 2.56 \times 10^{-4}\ X_2X_3 + 1.24 \times 10^{-3}\ X_1^2 + 9.78 \times 10^{-4}\ X_2^2 + 7.12 \times 10^{-5}\ X_3^2$
Eq. 3	$Y_3 = -197.82 + 1.16\ X_1 + 2.32\ X_2 + 2.32 \times 10^{-1}\ X_3 - 1.63 \times 10^{-3}\ X_1X_2 - 1.88 \times 10^{-4}\ X_1X_3 + 4.17 \times 10^{-4}\ X_2X_3 - 1.23 \times 10^{-2}\ X_1^2 - 6.57 \times 10^{-3}\ X_2^2 - 1.35 \times 10^{-3}\ X_3^2$
Eq. 4	$Y_4 = -5.98 + 6.96 \times 10^{-2}\ X_1 + 6.99 \times 10^{-2}\ X_2 + 9.67 \times 10^{-3}\ X_3 + 2.50 \times 10^{-4}\ X_1X_2 + 2.08 \times 10^{-5}\ X_1X_3 + 1.04 \times 10^{-4}\ X_2X_3 - 1.36 \times 10^{-3}\ X_1^2 - 2.38 \times 10^{-4}\ X_2^2 - 1.17 \times 10^{-4}\ X_3^2$
* Y_1, Y_2, Y_3, and Y_4 represent water uptake (%), thickness expansion (%), bending strength (MPa), and bending modulus (GPa), respectively, and X_1, X_2, and X_3 represent material mixture ratio (%), hot-pressing temperature (°C), and hot-pressing duration (s), respectively	

Table 4 shows some evaluation parameters for Eqs. 1 through 4. As illustrated, the coefficient of variation ranged from 0.90% to 4.45%, R^2 ranged from 0.9841 to 0.9977, adjusted R^2 ranged from 0.9636 to 0.9947, and adequate precision ranged from 18.626 to 48.197. Generally, a coefficient of variation under 10% reflects low error for a model, R^2 higher than 0.9 and adjusted R^2 higher than 0.7 reflect high correlation between the predicted value and measured value, and adequate precision greater than 4 reflects a high signal-to-noise ratio (Nazerian *et al*. 2015; Wang *et al*. 2015). Therefore, the results in Table 4 indicated that the fitting for Eqs. 1 through 4 was favorable.

Table 4. Evaluation Parameters for Eqs. 1 to 4

Model	Coefficient of Variation (%)	R^2	Adjusted R^2	Adequate Precision
Eq. 1	4.45	0.9841	0.9636	18.626
Eq. 2	0.90	0.9977	0.9947	48.197
Eq. 3	1.25	0.9964	0.9918	43.809
Eq. 4	2.66	0.9874	0.9712	21.869

Analysis of variance

Table 5 shows the analysis of variance for Eqs. 1 to 4. As illustrated, all four models exhibited a p-value below 0.0001, while lack of fit for all displayed a p-value beyond 0.06.

Table 5. Analysis of Variance for Eqs. 1 to 4

Source *	p-value for Eq. 1	p-value for Eq. 2	p-value for Eq. 3	p-value for Eq. 4
Model	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Lack of fit	0.0661	0.0610	0.1371	0.1985
X_1	< 0.0001	< 0.0001	< 0.0001	0.0003
X_2	0.0259	0.0001	0.0001	0.0009
X_3	0.5040	0.3727	< 0.0001	0.0193
X_1X_2	0.0064	< 0.0001	0.0170	0.0247
X_1X_3	0.0037	< 0.0001	0.3169	0.4994
X_2X_3	0.0001	< 0.0001	0.0478	0.0092
X_1^2	< 0.0001	< 0.0001	< 0.0001	< 0.0001
X_2^2	0.0003	< 0.0001	< 0.0001	0.0274
X_3^2	0.0009	< 0.0001	< 0.0001	< 0.0001
* X_1, X_2, and X_3 represent material mixture ratio (%), hot-pressing temperature (°C), and hot-pressing duration (s), respectively				

A model p-value below 0.05 and a lack of fit p-value beyond 0.05 indicate a significant model and an insignificant lack of fit (Chen *et al*. 2018). Consequently, Eqs. 1 to 4 were found to be sufficiently accurate to correlate the four physical-mechanical properties of the panels with the three preparation variables (Wang *et al*. 2015).

Table 5 also shows the effect significance of the nine model terms on the dependent variables. Typically, a p-value below 0.05, 0.01, or 0.001 indicates a significant, highly significant, or remarkably significant effect, respectively, but a p-value beyond 0.05 indicates an insignificant effect (Chen *et al*. 2018).

The p-value results for Eq. 1 indicated that X_1, X_2X_3, X_1^2, X_2^2, and X_3^2 had remarkably significant effects on the water uptake of the composite panels, while X_1X_2 and X_1X_3 had highly significant effects, and X_2 had a significant effect. Only X_3 had an insignificant effect.

The p-value results for Eq. 2 indicated that only X_3 had an insignificant effect on the thickness expansion of the composite panels, while the other eight terms all had remarkably significant effects.

The p-value results for Eq. 3 indicated that X_1, X_2, X_3, X_1^2, X_2^2, and X_3^2 had remarkably significant effects on the bending strength of the composite panels, while X_1X_2 and X_2X_3 had significant effects. Only X_1X_3 had an insignificant effect.

The p-value results for Eq. 4 indicated that X_1, X_2, X_1^2, and X_3^2 had remarkably significant effects on the bending modulus of the composite panels, while X_2X_3 had a highly significant effect, and X_3, X_1X_2, and X_2^2 had significant effects. Only X_1X_3 had an insignificant effect.

Response Surface Analysis Based on Regression Models

Water uptake

The water uptake of the composite panels was simulated by Eq. 1. The 3D surfaces of water uptake as the function of different preparation variables are displayed in Figs. 2(a), 2(c), and 2(e).

As illustrated, the water uptake data gave a concave surface in a rough range of 15% to 35%. The corresponding contour graphs are displayed in Figs. 2(b), 2(d), and 2(f). As indicated, the minimum water uptake corresponded to a material mixture ratio of 40% to 50%, a hot-pressing temperature of 170 °C to 180 °C, and a hot-pressing duration of 120 s to 150 s.

When the three preparation variables were below these values, raising their levels led to lower water uptake, thus improving the hygroscopic resistance of the panels. However, when the three preparation variables were beyond these values, raising their levels resulted in higher water uptake, thus deteriorating the hygroscopic resistance of the panels.

Thickness expansion

The thickness expansion of the composite panels was simulated by Eq. 2. The 3D surfaces of thickness expansion as the function of different preparation variables are displayed in Figs. 3(a), 3(c), and 3(e). Similar to the water uptake data, the thickness expansion data also exhibited a concave surface in an approximate range of 3.5% to 5%. The corresponding contour graphs are displayed in Figs. 3(b), 3(d), and 3(f).

As indicated, the minimum thickness expansion corresponded to a material mixture ratio of 40% to 50%, a hot-pressing temperature of 170 °C to 180 °C, and a hot-pressing duration of 120 s to 150 s.

When the three preparation variables were less than these values, raising their levels caused lower thickness expansion, thus improving the dimensional stability of the panels after soaking in water. Nevertheless, when the three preparation variables were over these values, raising their levels yielded higher thickness expansion, thus deteriorating the dimensional stability of the panels.

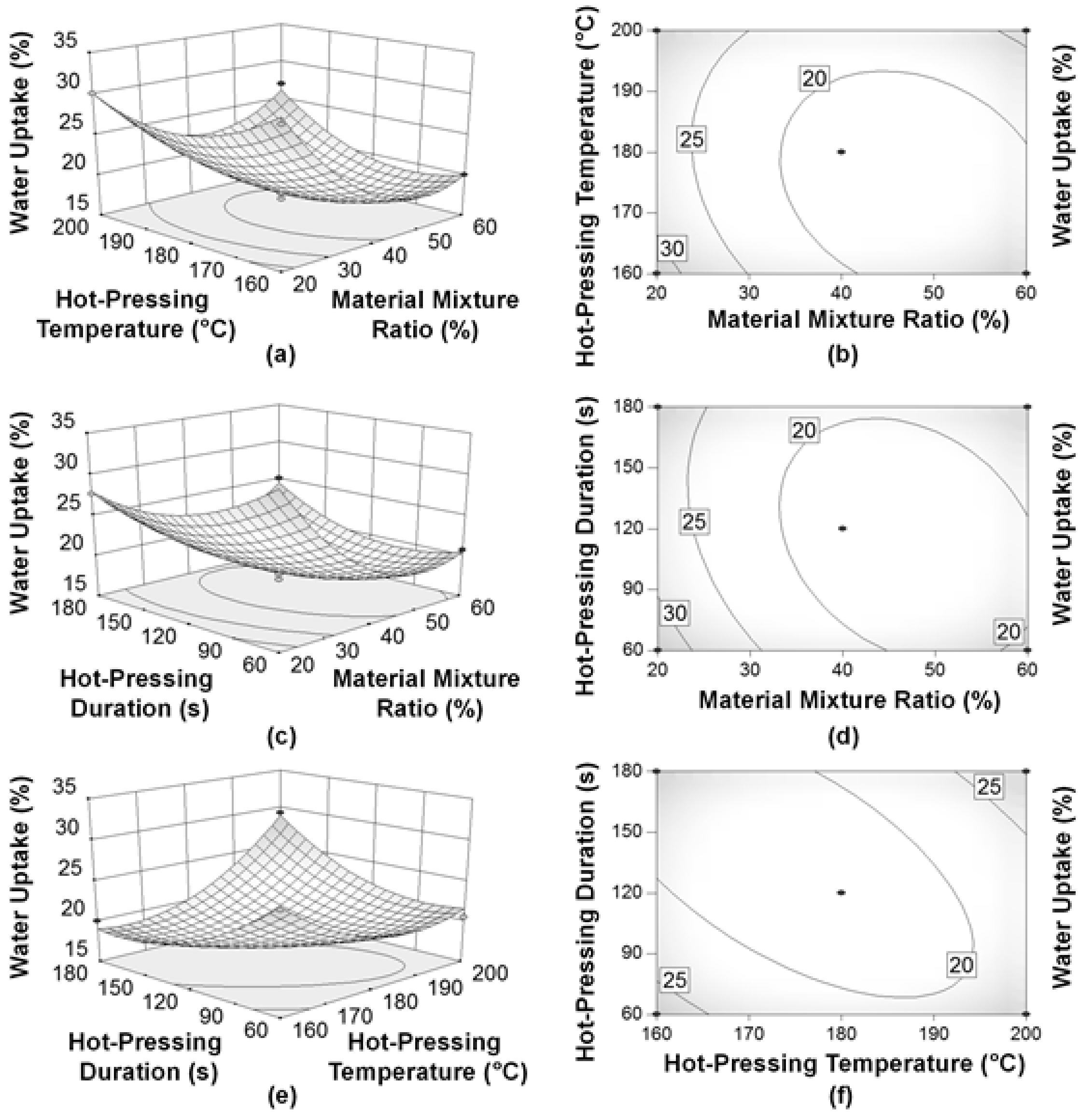

Fig. 2. Water uptake of composite panels simulated by Eq. 1: effects of material mixture ratio and hot-pressing temperature ((a) and (b)), material mixture ratio and hot-pressing duration ((c) and (d)), and hot-pressing temperature and hot-pressing duration ((e) and (f)). When showing the interactive effect of any two preparation variables, the third preparation variable is fixed at level 2.

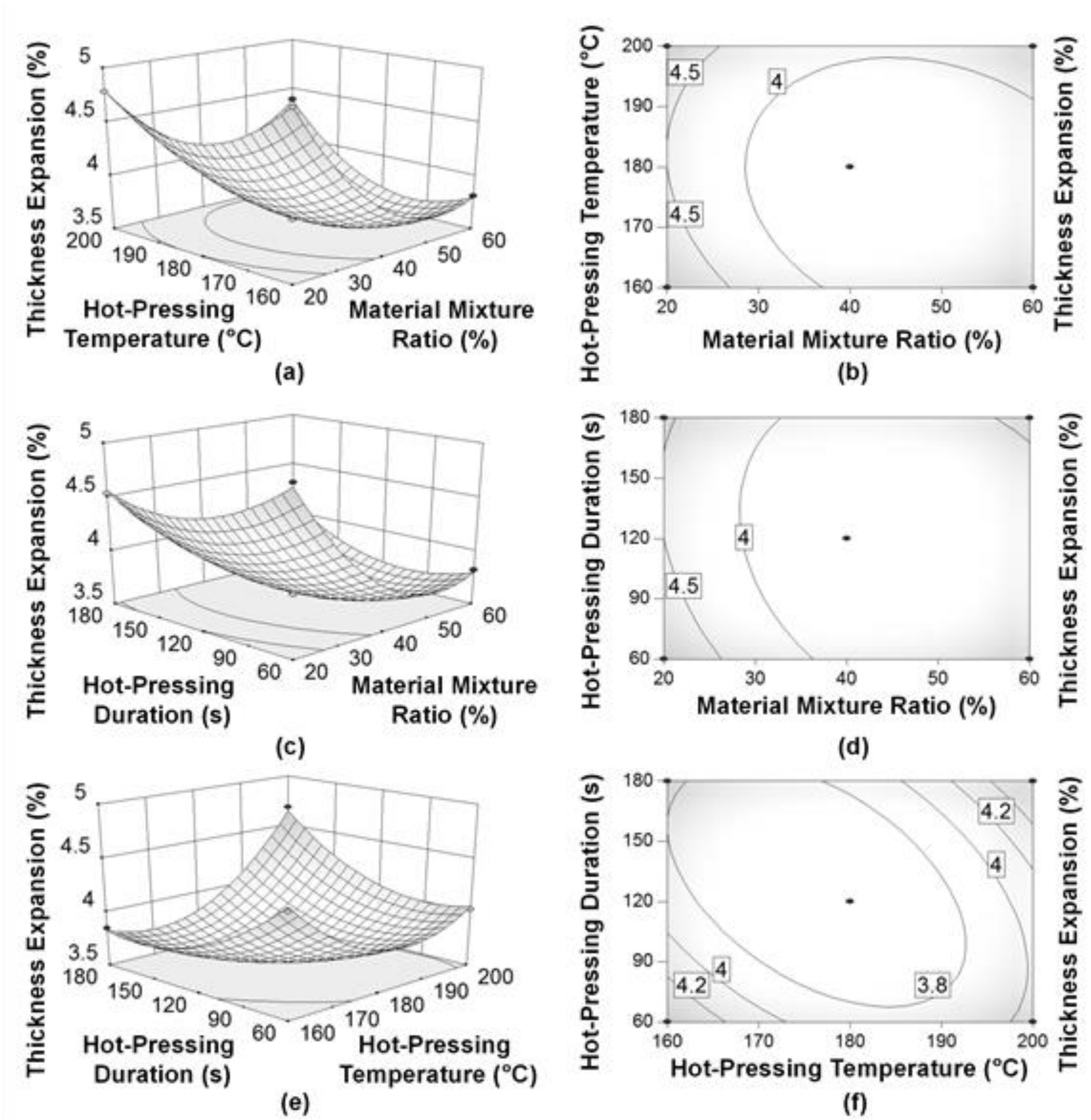

Fig. 3. Thickness expansion of composite panels simulated by Eq. 2: effects of material mixture ratio and hot-pressing temperature ((a) and (b)), material mixture ratio and hot-pressing duration ((c) and (d)), and hot-pressing temperature and hot-pressing duration ((e) and (f)). When showing the interactive effect of any two preparation variables, the third preparation variable is fixed at level 2.

Bending strength

The bending strength of the composite panels was simulated by Eq. 3. The 3D surfaces of bending strength as the function of different preparation variables are displayed in Figs. 4(a), 4(c), and 4(e). As illustrated, the bending strength data created a convex surface in a rough range of 24 MPa to 40 MPa. The corresponding contour graphs are displayed in Figs. 4(b), 4(d), and 4(f). As indicated, the maximum bending strength corresponded to a material mixture ratio of 30% to 40%, a hot-pressing temperature of 170 °C to 180 °C, and a hot-pressing duration of 90 s to 120 s. When the three preparation variables were below these values, raising their levels led to a higher bending strength, thus enhancing the resistance of the panels to bending fracture. However, when the three preparation variables exceeded these values, raising their levels produced a lower bending strength, thus reducing the fracture resistance of the panels.

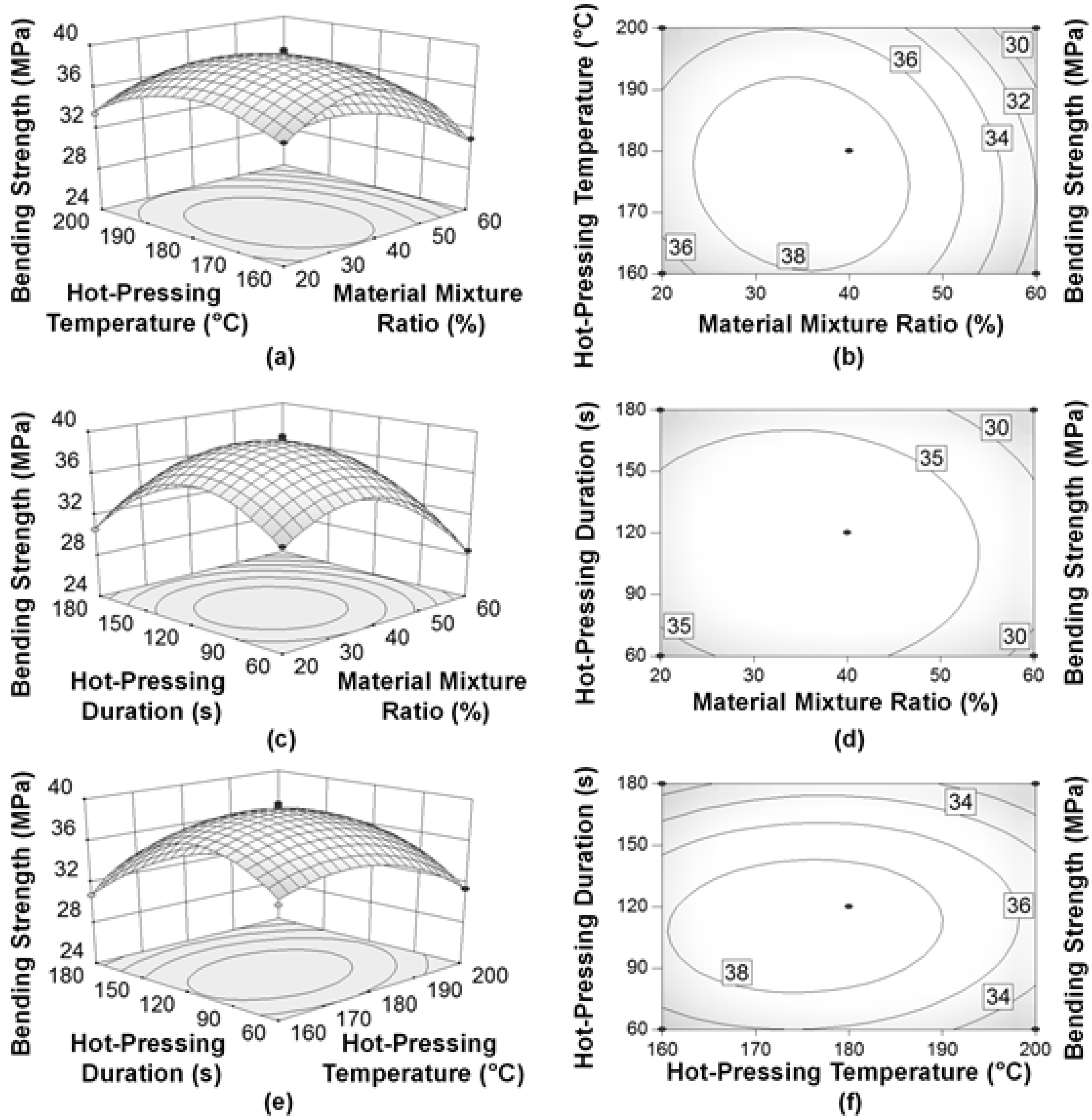

Fig. 4. Bending strength of composite panels simulated by Eq. 3: effects of material mixture ratio and hot-pressing temperature ((a) and (b)), material mixture ratio and hot-pressing duration ((c) and (d)), and hot-pressing temperature and hot-pressing duration ((e) and (f)). When showing the interactive effect of any two preparation variables, the third preparation variable is fixed at level 2.

Bending modulus

The bending modulus of the composite panels was simulated by Eq. 4. The 3D surfaces of bending modulus as the function of different preparation variables are displayed in Figs. 5(a), 5(c), and 5(e). Similar to the bending strength data, the bending modulus data also formed a convex surface in an approximate range of 1.8 GPa to 3.4 GPa. The corresponding contour graphs are displayed in Figs. 5(b), 5(d), and 5(f). As indicated, the maximum bending modulus corresponded to a material mixture ratio of 40% to 50%, a hot-pressing temperature of 190 °C to 200 °C, and a hot-pressing duration of 120 s to 150 s.

When the three preparation variables were less than these values, raising their levels yielded a higher bending modulus, thus enhancing the resistance of the panels to bending deformation. Nevertheless, when the three preparation variables were greater than these values, raising their levels resulted in a lower bending modulus, thus reducing the deformation resistance of the panels.

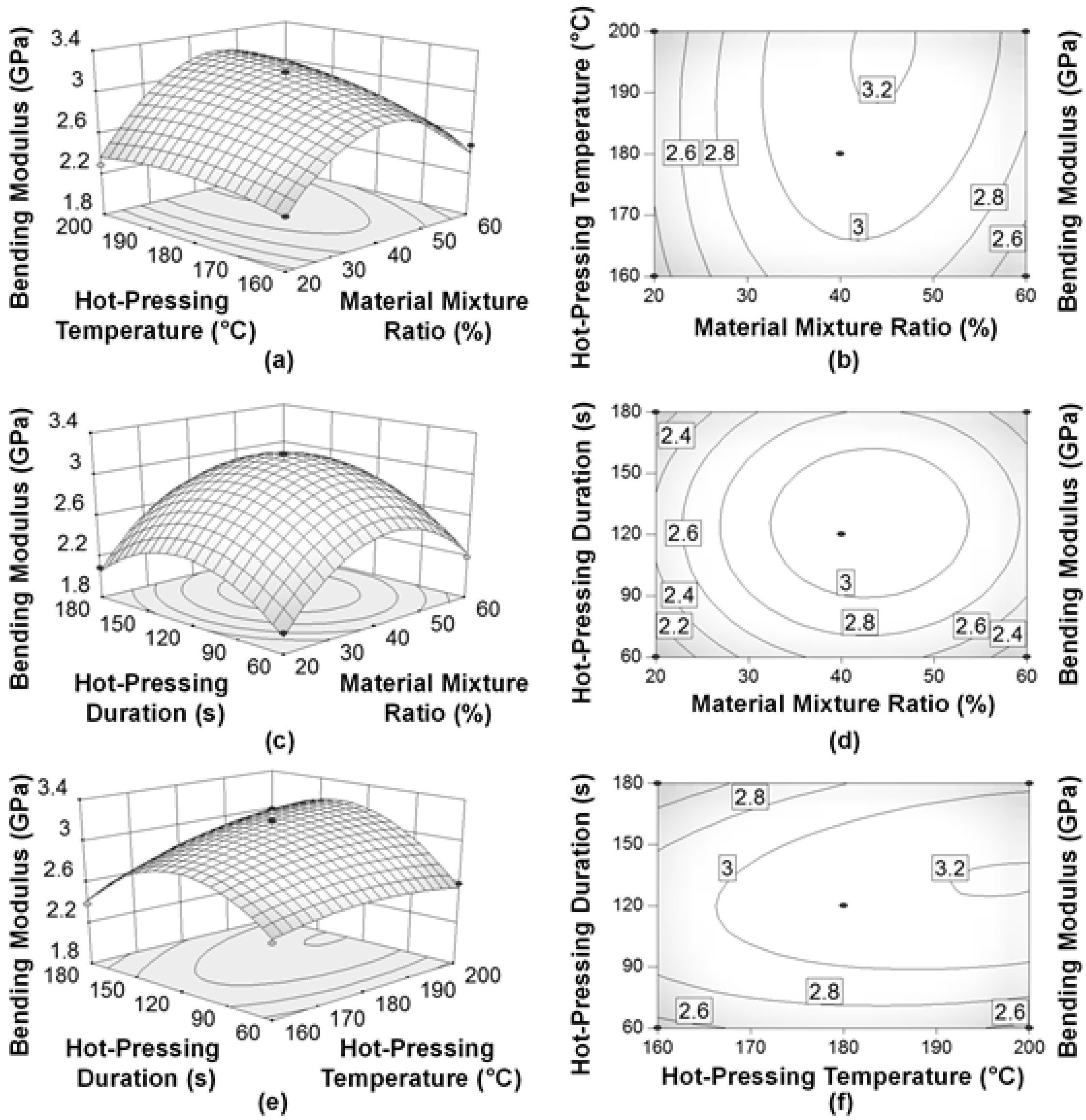

Fig. 5. Bending modulus of composite panels simulated by Eq. 4: effects of material mixture ratio and hot-pressing temperature ((a) and (b)), material mixture ratio and hot-pressing duration ((c) and (d)), and hot-pressing temperature and hot-pressing duration ((e) and (f)). When showing the interactive effect of any two preparation variables, the third preparation variable is fixed at level 2.

Discussion of Preparation Variables' Effects on Composites' Physical-mechanical Properties

Effect of material mixture ratio

The analysis of Figs. 2 through 5 demonstrated that the optimum material mixture ratio for the four physical-mechanical properties of the composite panels was in the range of 30% to 50%. When the material mixture ratio was lower than the optimum level, raising its value improved the properties of the panels. This result was explained by the physicochemical properties of bamboo green. For example, bamboo green contains abundant wax and silica (Zhang *et al*. 2013).

Firstly, these hydrophobic substances can make bamboo green exhibit a lower hydrophilicity (Deng *et al*. 2015). Therefore, adding bamboo green in fibrous material can reduce the probability of agglomeration and cause better dispersion (Li and Wang 2017; Xu and Fu 2017). With good dispersion, fibrous material can be well encapsulated with resin, leading to better interfacial adhesion in the panel (Ren *et al*. 2014). When a panel is soaked in water, good interfacial bonding can decrease the amount of water that enters the panel and inhibit deformation after water intake, thus giving the panel high hygroscopic resistance and dimensional stability (Song *et al*. 2017). When a panel is under load, good interfacial bonding can achieve an efficient stress transfer from resin to fibrous material, thus giving the panel high stiffness and strength (Lu *et al*. 2014). Similar results have been observed by Nordin *et al*. (2017), who reported that a heat treatment gave oil palm mesocarp fiber a lower hydrophilicity, which promoted its dispersion and boosted the properties of its composite panels.

Secondly, the abundance of wax and silica in bamboo green can decrease its hygroscopicity, so integrating bamboo green into wood fiber can decrease the hygroscopicity of the fibrous material, making panels absorb less water during water submersion (Kurokochi and Sato 2015). With reduced water uptake, the thickness expansion of panels can also be diminished (Chang *et al*. 2018). Similar results were observed by Kurokochi and Sato (2015), who reported that increased wax and silica content in rice straw reduced its fiberboard's water uptake and thickness expansion.

Thirdly, it has been pointed out that silica can strengthen the molecular structure of material, thus enhancing its water resistance and mechanical properties (Wang *et al*. 2011). With high silica content, bamboo green can be considered as a reinforcement material, so blending bamboo green in fibrous material can improve panel performance. Similar results were observed by Salari *et al*. (2013), who reported that introducing silica into oriented strand board from paulownia wood decreased its water uptake and thickness expansion and increased its bending strength and bending modulus.

For the proposed bamboo green/wood fiber-reinforced composites, when the material mixture ratio was over the optimum level, raising its value negatively impacted the physical-mechanical properties of the panel. Similar to the positive effects of bamboo green on the panel, its negative effects were also connected with the wax and silica in bamboo green, as these hydrophobic substances adversely can influence the wettability and gluability of fibrous material, thus being not good for interfacial adhesion in the panels (Zhang *et al*. 2013). Similar results have been observed by Deng *et al*. (2015), who manufactured laminated bamboo-bundle veneer lumber from bamboo bundle sheets with different bamboo green retention ratios. They found that, after an aging treatment, the product containing more bamboo green showed higher thickness expansion, as well as lower bending strength, bending modulus, and horizontal shear strength. Moreover, Zhang *et al*. (2013) found that a sodium hydroxide treatment removed the wax and silica in bamboo green strips, and the plywood made from the treated strips exhibited lower thickness expansion and dip peel, and higher bending strength and bending modulus. Cao *et al*. (2017) also employed a sodium hydroxide treatment to dissolve the wax and silica in wheat straw. They found that the particleboard made from the treated straw had lower thickness expansion and higher bending strength and bending modulus.

In some previous studies on composite panels made from blends of wood and other fibrous materials, different optimum levels for material mixture ratio have been reported. For example, Belini *et al*. (2012) manufactured fiberboard from blends of *Saccharum* spp. sugarcane bagasse and *Eucalyptus grandis* eucalyptus wood. In the blends, bagasse weight percentage was increased from 0% to 25%, 50%, 75%, and 100%. The optimum percentages for water uptake, thickness expansion, bending strength, and bending modulus of the panel were 0%, 50%, 25%, and 25%, respectively.

Barros Filho *et al*. (2011) produced chipboard from blends of industrial sugarcane bagasse and eucalyptus wood. In the blends, bagasse weight percentage was increased from 50% to 100%. The optimum percentages for water uptake, thickness expansion, bending strength, and bending modulus of the panel were 100%, 50%, 50%, and 100%, respectively.

Holt *et al*. (2014) made fiberboard from blends of cotton bur and southern yellow pine. In the blends, bur weight percentage was increased from 0% to 50% and 100%. The optimum percentages for water uptake, thickness expansion, bending strength, and bending modulus of the panel were 0%, 100%, 0%, and 0%, respectively.

Lü *et al*. (2015) obtained particleboard from blends of corn stalk skin and poplar wood. In the blends, stalk weight percentage increased from 30% to 50% and 70%. The optimum percentages for the thickness expansion, bending strength, and bending modulus of the panel were 50%, 30%, and 30%, respectively.

Park *et al*. (2012) measured particleboard from blends of *Miscanthus sacchariflorus* straw and Douglas fir wood. In the blends, straw weight percentage was increased from 0% to 20%, 40%, 60%, 80%, and 100%. The optimum percentages for thickness expansion, bending strength, and bending modulus of the panel were 0%, 0%, and 20%, respectively.

Paridah *et al*. (2014) prepared particleboard from blends of kenaf whole stem and rubber wood. In the blends, kenaf weight percentage was increased from 0% to 30%, 50%, and 100%. The optimum percentages for water uptake, thickness expansion, bending strength, and bending modulus of the panel were 30%, 30%, 50%, and 30%, respectively.

Yang *et al*. (2003) fabricated particleboard from blends of rice straw and wood. In the blends, straw weight percentage increased from 10% to 20% and 30%. The optimum percentage for the bending strength of the panel was 10%.

Effect of hot-pressing temperature and hot-pressing duration

The analysis of Figs. 2 through 5 showed that the optimum hot-pressing temperature and hot-pressing duration for the four physical-mechanical properties of the composite panels were in the ranges of 170 °C to 200 °C and 90 s to 150 s, respectively. When the two variables were below their optimum levels, raising their values positively influenced the properties of the panels. This result was because increasing these parameters allowed greater heat transfer into the mat, which can not only make resin cure more sufficiently but also boost the plasticization of fibrous materials during hot-pressing and improve contact between them, thus enhancing interfacial bonding in the panel and promoting its performance (Lü *et al*. 2015; Nazerian *et al*. 2015). Similar results were observed by Li *et al*. (2014a), who reported that the surface layer of poplar plywood showed a greater wet shear strength than the core layer. They found that, compared with the core layer, the surface layer reached the resin solidification temperature earlier, giving the resin in the surface layer more time to solidify completely.

For the proposed bamboo green/wood fiber-reinforced composites, when the hot-pressing temperature and hot-pressing duration exceeded the optimum levels, raising their values deteriorated the physical-mechanical properties of the panel. This result was because increasing these hot-pressing parameters can embrittle and induce pyrolysis in materials, which not only can make materials have a loose structure that admits water but also weaken their mechanical properties, thus negatively affecting panel performance (Sun *et al*. 2017; Song *et al*. 2018). Similar results have been observed by, for example, Chu *et al*. (2016), who reported that a high-temperature treatment remarkably increased pore number and pore size in poplar wood; additionally, the treated group exhibited greater surface brittleness and mechanical decline, such as lower surface hardness, smoothness, and abrasion resistance.

In some previous studies on the hot-pressing parameters of lignocellulosic board, different optimum levels for hot-pressing temperature and hot-pressing duration have been reported. For example, Boon *et al*. (2013) manufactured particleboard from oil palm trunk. In their study, hot-pressing temperatures included 160 °C, 180 °C, and 200 °C; hot-pressing durations included 900 s and 1200 s. The optimum temperature and duration for thickness expansion and bending strength of the panel were 200 °C and 1200 s, respectively.

Iswanto *et al*. (2013) fabricated particleboard from jatropha fruit hull. In their study, hot-pressing temperatures included 110 °C, 120 °C, and 130 °C; hot-pressing durations included 480 s and 600 s. The optimum temperatures for water uptake, thickness expansion, bending strength, and bending modulus of the panel were 120 °C, 130 °C, 130 °C, and 130 °C, respectively. The optimum duration for the four properties was 600 s.

Kargarfard and Jahan-Latibari (2014) produced fiberboard from *Eucalyptus camaldulensis* wood. In their study, hot-pressing temperatures included 170 °C, 180 °C, and 190 °C; hot-pressing durations included 180 s and 240 s. The optimum temperatures for thickness expansion, bending strength, and bending modulus of the panel were 170 °C, 190 °C, and 180 °C, respectively. The optimum duration for bending modulus was 180 s.

Lü *et al*. (2015) made particleboard from blends of corn stalk skin and poplar wood. In their study, hot-pressing temperatures included 130 °C, 150 °C, and 170 °C; hot-pressing durations included 180 s, 270 s, and 360 s. The optimum temperature and duration for thickness expansion, bending strength, and bending modulus of the panel were determined as 150 °C and 270 s, respectively.

Nasir *et al*. (2013) obtained fiberboard from *Hevea brasiliensis* rubber wood. In their study, hot-pressing temperatures included 180 °C, 190 °C, 200 °C, and 210 °C; hot-pressing durations included 240 s, 360 s, 480 s, and 600 s. The optimum temperature and duration for bending strength and bending modulus of the panel were 200 °C and 360 s, respectively.

Kusumah *et al*. (2017) measured particleboard from *Sorghum bicolor* (L.) Moench sweet sorghum bagasse. In their study, hot-pressing temperatures included 140 °C, 160 °C, 180 °C, 200 °C, and 220 °C; hot-pressing durations included 120 s, 300 s, 420 s, 600 s, and 900 s. The optimum temperatures for water uptake, thickness expansion, bending strength, and bending modulus of the panel were 220 °C, 220 °C, 200 °C, and 200 °C, respectively. The optimum durations for the four properties were 900 s, 900 s, 600 s, and 600 s, respectively.

Nazerian *et al*. (2015) prepared fiberboard from bagasse. In their study, hot-pressing temperatures included 145 °C, 155 °C, 165 °C, 175 °C, and 185 °C; hot-pressing durations included 300 s, 360 s, 420 s, 480 s, and 540 s. Using a response surface methodology, the optimum temperature and duration for thickness expansion and bending strength of the panel were determined as 158 °C and 385.8 s, respectively.

Optimization of Preparation Variables Based on Regression Models

Based on Eqs. 1 through 4, the material mixture ratio, hot-pressing temperature, and hot-pressing duration for fabricating the proposed composite panels were optimized. As shown in Table 6, when varying the optimization goal, the optimal values of the three preparation variables also varied. For example, the optimum material mixture ratio for bending strength was 35%, but for all other optimization goals it was over 40%. Similarly, the optimum hot-pressing temperature for bending modulus was near 200 °C, but for all other optimization goals it was below 180 °C. As for hot-pressing duration, its optimum value for bending modulus was over 130 s, but for bending strength it was only 111 s.

Table 6. Optimum Values of Preparation Variables for Different Optimization Goals

Group	Optimization Goal	Material Mixture Ratio (%)	Hot-pressing Temperature (°C)	Hot-pressing Duration (s)
G1	Water uptake	48	173	127
G2	Thickness expansion	49	175	122
G3	Bending strength	35	176	111
G4	Bending modulus	43	198	134
G5	All four properties	42	179	119

Table 7 shows the predicted physical-mechanical properties of composite panels under the different optimization goals. Among groups G1 to G4, the optimal water uptake, thickness expansion, bending strength, and bending modulus were 17.1%, 3.5%, 39.7 MPa, and 3.20 GPa, respectively. The fifth group, G5, was an optimization for all four properties. As seen, the water uptake, thickness expansion, bending strength, and bending modulus in group G5 were comparable to their optimal values in groups G1 to G4. Group G5 was experimentally validated. The coefficients of variation between the measured and predicted water uptakes, thickness expansions, bending strengths, and bending moduli were all under 5%.

Table 7. Predicted Physical-mechanical Properties of Composite Panels under Different Optimization Goals

Optimization Group in Table 6	Water Uptake (%)	Thickness Expansion (%)	Bending Strength (MPa)	Bending Modulus (GPa)
G1	17.1	3.5	37.3	3.07
G2	17.1	3.5	37.3	3.08
G3	19.8	3.8	39.7	3.01
G4	22.6	4.1	34.9	3.20
G5	17.6	3.6	38.9	3.14

This research determined the optimum material mixture ratio, hot-pressing temperature, and hot-pressing duration for preparing bamboo green/wood fiber-reinforced composite panels glued with urea-formaldehyde resin. In the future, the effects of resin type and content on the physical-mechanical properties of panel can be investigated (Holt *et al*. 2014; Nayeri *et al*. 2014). Additionally, a comparison of the properties of bamboo green and wood fiber will be made to further understand the effects of material mixture ratio on panel performance.

CONCLUSIONS

1. Bamboo green/wood fiber-reinforced composites were prepared according to a Box-Behnken design with variable material mixture ratio (20% to 60%), hot-pressing temperature (160 °C to 200 °C), and hot-pressing duration (60 s to 180 s). The water uptake, thickness expansion, bending strength, and bending modulus of the panels were observed. The physical-mechanical properties of the panels fulfilled the strictest requirements of GB/T 11718 (2009).
2. Four quadratic models were developed to predict the four physical-mechanical properties of the panels based on the three preparation variables. These models all exhibited a coefficient of variation under 5%, a coefficient of determination R^2 beyond 0.96, and an adequate precision over 18. An analysis of variance confirmed that the four models were statistically significant, and the three preparation variables significantly affected the four properties.
3. Response surface analysis found that the optimum levels of material mixture ratio, hot-pressing temperature, and hot-pressing duration were in the ranges of 35% to 49%, 173 °C to 198 °C, and 111 s to 134 s, respectively. For different physical-mechanical properties of panel, the optimum values of the three preparation variables were different. The effect mechanisms of these variables were discussed.
4. Based on the obtained models, the optimum material mixture ratios, hot-pressing temperatures, and hot-pressing durations for panel fabrication were determined as follows: 48%, 173 °C, and 127 s for the lowest water uptake; 49%, 175 °C, and 122 s for the lowest thickness expansion; 35%, 176 °C, and 111 s for the highest bending strength; 43%, 198 °C, and 134 s for the highest bending modulus; and 42%, 179 °C, and 119 s for the simultaneous optimization of all four properties.

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REFERENCES CITED

Barros Filho, R. M., Mendes, L. M., Novack, K. M., Aprelini, L. O., and Botaro, V. R. (2011). "Hybrid chipboard panels based on sugarcane bagasse, urea formaldehyde and melamine formaldehyde resin," *Industrial Crops and Products* 33(2), 369-373. DOI: 10.1016/j.indcrop.2010.11.007

Belini, U. L., Filho, M. T., Louzada, J. L. P. C., Rodrigues, J. C. C., and Astolphi, J. R. S. (2012). "Pilot study for MDF manufacture from sugarcane bagasse and eucalyptus fibers," *European Journal of Wood and Wood Products* 70(4), 537-539. DOI:

10.1007/s00107-011-0577-4

Boon, J. G., Hashim, R., Sulaiman, O., Hiziroglu, S., Sugimoto, T., and Sato, M. (2013). "Influence of processing parameters on some properties of oil palm trunk binderless particleboard," *European Journal of Wood and Wood Products* 71(5), 583-589. DOI: 10.1007/s00107-013-0712-5

Buyuksari, U., Avci, E., Ayrilmis, N., and Akkilic, H. (2010). "Effect of pine cone ratio on the wettability and surface roughness of particleboard," *BioResources* 5(3), 1824-1833. DOI: 10.15376/biores.5.3.1824-1833

Cao, Y., Song, W., Yang, Z., Chen, Z., and Zhang, S. (2017). "The properties of particleboard made from alkaline-treated wheat straw and methylene diphenyl diisocyanate binder," *BioResources* 12(2), 3265-3276. DOI: 10.15376/biores.12.2.3265-3276

Chang, L., Tang, Q., Gao, L., Fang, L., Wang, Z., and Guo, W. (2018). "Fabrication and characterization of HDPE resins as adhesives in plywood," *European Journal of Wood and Wood Products* 76(1), 325-335. DOI: 10.1007/s00107-016-1117-z

Chen, S., Zeng, Z., Hu, N., Bai, B., Wang, H., and Suo, Y. (2018). "Simultaneous optimization of the ultrasound-assisted extraction for phenolic compounds content and antioxidant activity of *Lycium ruthenicum* Murr. fruit using response surface methodology," *Food Chemistry* 242, 1-8. DOI: 10.1016/j.foodchem.2017.08.105

Chen, Y., Li, J., Liu, F., Xie, L., and Xiao, H. (2017). "Effects of temperature and solid content on the pre-curing behavior of urea-formaldehyde resin," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(3), 145-150. DOI: 10.3969/j.issn.1000-2006.200607036

Chu, D., Xue, L., Zhang, Y., Kang, L., and Mu, J. (2016). "Surface characteristics of poplar wood with high-temperature heat treatment: Wettability and surface brittleness," *BioResources* 11(3), 6948-6967. DOI: 10.15376/biores.11.3.6948-6967

de Almeida, A. C., de Araujo, V. A., Morales, E. A. M., Gava, M., Munis, R. A., Garcia, J. N., and Cortez-Barbosa, J. (2017). "Wood-bamboo particleboard: Mechanical properties," *BioResources* 12(4), 7784-7792. DOI: 10.15376/biores.12.4.7784-7792

Deng, J., Li, H., Wang, G., Chen, F., and Zhang, W. (2015). "Effect of removing extent of bamboo green on physical and mechanical properties of laminated bamboo-bundle veneer lumber (BLVL)," *European Journal of Wood and Wood Products* 73(4), 499-506. DOI: 10.1007/s00107-015-0897-x

Deng, L., Zhan, H., He, W., Zhao, J., and Wang, S. (2017). "Developmental changes of fiber wall of *Fargesia fungosa*," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(4), 147-152. DOI: 10.3969/j.issn.1000-2006.201701001

Fan, L., Ruan, R., Liu, Y., Wang, Y., and Tu, C. (2015). "Effects of extraction conditions on the characteristics of ethanol organosolv lignin from bamboo (*Phyllostachys pubescens* Mazel)," *BioResources* 10(4), 7998-8013. DOI: 10.15376/biores.10.4.7998-8013

GB/T 11718 (2009). "Medium density fibreboard," Standardization Administration of China, Beijing, China.

GB/T 17657 (2013). "Test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels," Standardization Administration of China, Beijing, China.

Guan, C., Zhang, H., Miao, H., and Zhou, L. (2017). "Non-destructive determination of modulus of elasticity and in-plane shear modulus of full-size wood composite panels," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(4),

153-159. DOI: 10.3969/j.issn.1000-2006.201609020
Holt, G. A., Chow, P., Wanjura, J. D., Pelletier, M. G., and Wedegaertner, T. C. (2014). "Evaluation of thermal treatments to improve physical and mechanical properties of bio-composites made from cotton byproducts and other agricultural fibers," *Industrial Crops and Products* 52, 627-632. DOI: 10.1016/j.indcrop.2013.11.003
Huang, C.-X., He, J., Min, D.-Y., Li, X., and Yong, Q. (2015). "Isolation and characterization of hemicellulose from moso bamboo green and bamboo yellow," *Chemistry and Industry of Forest Products* 35(5), 29-36. DOI: 10.3969/j.issn.0253-2417.2015.05.006
Huang, C.-X., He, J., Min, D.-Y., Li, X., Du, L.-T., and Yong, Q. (2016). "Quantitative determination of ferulic and *p*-coumaric acids in cell wall of moso bamboo green and bamboo yellow," *Chemistry and Industry of Forest Products* 36(3), 16-22. DOI: 10.3969/j.issn.0253-2417.2016.03.003
Iswanto, A., Febrianto, F., Hadi, Y., Ruhendi, S., and Hermawan, D. (2013). "The effect of pressing temperature and time on the quality of particle board made from jatropha fruit hulls treated in acidic condition," *Makara Journal of Technology* 17(3), 145-151. DOI: 10.7454/mst.v17i3.2930
Jin, X., Wu, G., Sun, E., Tang, W., Huang, H., and Chen, L. (2017). "Improving processability of rice straw by fermentation using *Streptomyces rochei*," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(2), 122-128. DOI: 10.3969/j.issn.1000-2006.2017.02.018
Kargarfard, A., and Jahan-Latibari, A. (2014). "The effect of press temperature on properties of medium density fiberboard produced from *Eucalyptus camaldulensis* fibers," *International Journal of Lignocellulosic Products* 1(2), 142-150.
Klímek, P., Wimmer, R., Meinlschmidt, P., and Kúdela, J. (2018). "Utilizing *Miscanthus* stalks as raw material for particleboards," *Industrial Crops and Products* 111, 270-276. DOI: 10.1016/j.indcrop.2017.10.032
Kurokochi, Y., and Sato, M., (2015). "Effect of surface structure, wax and silica on the properties of binderless board made from rice straw," *Industrial Crops and Products* 77, 949-953. DOI: 10.1016/j.indcrop.2015.10.007
Kusumah, S. S., Umemura, K., Guswenrivo, I., Yoshimura, T., and Kanayama, K. (2017). "Utilization of sweet sorghum bagasse and citric acid for manufacturing of particleboard II: Influences of pressing temperature and time on particleboard properties," *Journal of Wood Science* 63(2), 161-172. DOI: 10.1007/s10086-016-1605-0
Li, H., Li, C., Chen, H., Zhang, D., Zhang, S., and Li, J. (2014a). "Effects of hot-pressing parameters on shear strength of plywood bonded with modified soy protein adhesives," *BioResources* 9(4), 5858-5870. DOI: 10.15376/biores.9.4.5858-5870
Li, K., Wang, X., Wang, J., and Zhang, J. (2015). "Benefits from additives and xylanase during enzymatic hydrolysis of bamboo shoot and mature bamboo," *Bioresource Technology* 192, 424-431. DOI: 10.1016/j.biortech.2015.05.100
Li, Z., and Wang, W. (2017). "Preparation and properties of polypropylene based composites with high wood fibers content," *Journal of Forestry Engineering* 2(2), 9-15. DOI: 10.13360/j.issn.2096-1359.2017.02.002
Li, Z., Jiang, Z., Fei, B., Cai, Z., and Pan, X. (2014b). "Comparison of bamboo green, timber and yellow in sulfite, sulfuric acid and sodium hydroxide pretreatments for enzymatic saccharification," *Bioresource Technology* 151, 91-99. DOI: 10.1016/j.biortech.2013.10.060

Lü, H., Zhang, X., and Yu, B. (2015). "Optimization of corn-stalk skin flake-wood shaving composite technology," *Journal of Forestry Research* 26(3), 759-763. DOI: 10.1007/s11676-015-0054-8

Lu, T., Liu, S., Jiang, M., Xu, X., Wang, Y., Wang, Z., Gou, J., Hui, D., and Zhou, Z. (2014). "Effects of modifications of bamboo cellulose fibers on the improved mechanical properties of cellulose reinforced poly(lactic acid) composites," *Composites Part B: Engineering* 62, 191-197. DOI: 10.1016/j.compositesb.2014.02.030

Nasir, M., Gupta, A., Beg, M. D. H., Chua, G. K., Jawaid, M., Kumar, A., and Khan, T. A. (2013). "Fabricating eco-friendly binderless fiberboard from laccase-treated rubber wood fiber," *BioResources* 8(3), 3599-3608. DOI: 10.15376/biores.8.3.3599-3608

Nayeri, M. D., Tahir, P. M., Jawaid, M., Harun, J., Abdullah, L. C., Bakar, E. S., Keshani, S., and Namvar, F. (2014). "Effect of resin content and pressure on the performance properties of rubberwood-kenaf composite board panel," *Fibers and Polymers* 15(6), 1263-1269. DOI: 10.1007/s12221-014-1263-z

Nazerian, M., Dalirzadeh, A., and Farrokhpayam, S. R. (2015). "Use of almond shell powder in modification of the physical and mechanical properties of medium density fiberboard," *BioResources* 10(1), 169-181. DOI: 10.15376/biores.10.1.169-181

Nordin, N. I. A. A., Ariffin, H., Hassan, M. A., Shirai, Y., Ando, Y., Ibrahim, N. A., and Yunus, W. M. Z. W. (2017). "Superheated steam treatment of oil palm mesocarp fiber improved the properties of fiber-polypropylene biocomposite," *BioResources* 12(1), 68-81. DOI: 10.15376/biores.12.1.68-81

Pan, H., Tu, Q., Lin, S., and Liu, Y. (2017). "Design and simulation of a combined cutting tool for inner section and tabaxir cutting from the natural bamboo section," *Journal of Forestry Engineering* 2(2), 127-132. DOI: 10.13360/j.issn.2096-1359.2017.02.021

Paridah, M. T., Juliana, A. H., El-Shekeil, Y. A., Jawaid, M., and Alothman, O. Y. (2014). "Measurement of mechanical and physical properties of particleboard by hybridization of kenaf with rubberwood particles," *Measurement* 56, 70-80. DOI: 10.1016/j.measurement.2014.06.019

Park, H.-J., Oh, S.-W., and Wen, M.-Y. (2012). "Manufacture and properties of *Miscanthus*–wood particle composite boards," *Journal of Wood Science* 58(5), 459-464. DOI: 10.1007/s10086-012-1262-x

Ren, W., Zhang, D., Wang, G., and Cheng, H. (2014). "Mechanical and thermal properties of bamboo pulp fiber reinforced polyethylene composites," *BioResources* 9(3), 4117-4127. DOI: 10.15376/biores.9.3.4117-4127

Salari, A., Tabarsa, T., Khazaeian, A., and Saraeian, A. (2013). "Improving some of applied properties of oriented strand board (OSB) made from underutilized low quality paulownia (*Paulownia fortunie*) wood employing nano-SiO_2," *Industrial Crops and Products* 42, 1-9. DOI: 10.1016/j.indcrop.2012.05.010

Song, W., Wei, W., Wang, D., and Zhang, S. (2017). "Preparation and properties of new plywood composites made from surface modified veneers and polyvinyl chloride films," *BioResources* 12(4), 8320-8339. DOI: 10.15376/biores.12.4.8320-8339

Song, W., Xu, Z., and Zhang, S. (2018). "Using surface modified E-glass fiber cloths to enhance poplar laminated veneer lumber composites: Effects of modification conditions, gluing processes, hot-pressing parameters, and assembly patterns on physical-mechanical and interfacial properties," *BioResources* 13(1), 597-631. DOI: 10.15376/biores.13.1.597-631

Song, W., Zhao, F., Yu, X., Wang, C., Wei, W., and Zhang, S. (2015). "Interfacial characterization and optimal preparation of novel bamboo plastic composite engineering materials," *BioResources* 10(3), 5049-5070. DOI: 10.15376/biores.10.3.5049-5070

Sun, Y., You, L., Yu, C., Jiang, B., Han, J., and Xu, X. (2017). "Manufacturing of wood/rubber/HDPE composites by hot pressing," *Journal of Forestry Engineering* 2(3), 38-43. DOI: 10.13360/j.issn.2096-1359.2017.03.007

Tang, Q., Fang, L., and Guo, W. (2017). "Investigation into mechanical, thermal, flame-retardant properties of wood fiber reinforced ultra-high-density fiberboards," *BioResources* 12(3), 6749-6762. DOI: 10.15376/biores.12.3.6749-6762

Wang, C., Song, W., Cheng, H., Yu, X., Li, W., and Zhang, S. (2016). "Dipping modification with nano-$CaCO_3$ to improve tensile properties of individual bamboo fiber for developing bamboo–plastic composite," *Journal of Natural Fibers* 13(6), 737-748. DOI: 10.1080/15440478.2015.1137526

Wang, S., You, T., Xu, F., Chen, J., and Yang, G. (2015). "Optimization of [Amim]Cl pretreatment conditions for maximum glucose recovery from hybrid *Pennisetum* by response surface methodology," *BioResources* 10(4), 7021-7037. DOI: 10.15376/biores.10.4.7021-7037

Wang, Z., Gu, Z., Hong, Y., Cheng, L., and Li, Z. (2011). "Bonding strength and water resistance of starch-based wood adhesive improved by silica nanoparticles," *Carbohydrate Polymers* 86(1), 72-76. DOI: 10.1016/j.carbpol.2011.04.003

Xin, D., Yang, Z., Liu, F., Xu, X., and Zhang, J. (2015). "Comparison of aqueous ammonia and dilute acid pretreatment of bamboo fractions: Structure properties and enzymatic hydrolysis," *Bioresource Technology* 175, 529-536. DOI: 10.1016/j.biortech.2014.10.160

Xu, M., and Fu, X. (2017). "Study on application of modified wood powder/alkali lignin in wood/rubber composite," *Journal of Forestry Engineering* 2(4), 84-89. DOI: 10.13360/j.issn.2096-1359.2017.04.014

Xu, Y., Zhang, W., Yue, X., and Zhang, D. (2016). "Determination of aluminum in bamboo pulp black liquor by ICP-AES," *BioResources* 11(2), 3964-3971. DOI: 10.15376/biores.11.2.3964-3971

Yang, H.-S., Kim, D.-J., and Kim, H.-J. (2003). "Rice straw–wood particle composite for sound absorbing wooden construction materials," *Bioresource Technology* 86(2), 117-121. DOI: 10.1016/S0960-8524(02)00163-3

Yang, Z., Li, K., Zhang, M., Xin, D., and Zhang, J. (2016). "Rapid determination of chemical composition and classification of bamboo fractions using visible–near infrared spectroscopy coupled with multivariate data analysis," *Biotechnology for Biofuels* 9(1), 1-18. DOI: 10.1186/s13068-016-0443-z

Zhang, F., Sun, H., Zhang, X.-C., Qian, J., Yang, X.-L., and Yu, C. (2015). "Replacement of the wood substitute packaging materials with modified bamboo timber," *Packaging Engineering* 36(15), 55-61. DOI: 10.19554/j.cnki.1001-3563.2015.15.012

Zhang, X., Cheng, X., Lin, L., Tang, Y., and Wu, H. (2013). "Effect on bonding performance of bamboo skin and bamboo pith through chemical processing," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 37(4), 171-174. DOI: 10.3969/j.issn.1000-2006.2013.04.033

Zhang, Z., Guan, M., and Liu, Y. (2017). "Degradability of bamboo shoot shell/UF modified starch adhesive composites," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(4), 160-166. DOI: 10.3969/j.issn.1000-

2006.201610029
Zhou, X., Chen, M., and Du, G. (2017). "Research progress on surface modification of agriculture and forestry biomass materials by plasma treatment," *Journal of Forestry Engineering* 2(1), 1-7. DOI: 10.13360/j.issn.2096-1359.2017.01.001
Zhu, X., Han, S., Liu, Y., and Chen, G. (2017). "Effects of laccase incubated from white rot fungi on the mechanical properties of fiberboard," *Journal of Forestry Research* 28(6), 1293-1300. DOI: 10.1007/s11676-017-0398-3

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