Developing and Evaluating Composites Based on Plantation Eucalyptus Rotary-cut Veneer and High-density Polyethylene Film as Novel Building Materials

Wei Song,[a,b,c] Wenbang Wei,[a] Congrong Ren,[a] and Shuangbao Zhang [a,b,c,]*

To achieve value-added utilizations of plantation timbers, eucalyptus veneer/high-density polyethylene film composites were prepared, with process-factors (PF) (hot-pressing temperature, HT; hot-pressing duration, HD; hot-pressing pressure, HP; HDPE-film content, HC) and composite-properties (CP) (water-resistant bonding-strength, BS; modulus of rupture, MOR; modulus of elasticity, MOE) investigated. According to thermal analyses, 140 to 180 °C was appropriate for HT. Based on statistical analyses, HD was easier to affect CP, while MOE was easier to be affected by PF. Quantitative relationships between PF and CP were determined by the neural-network (ANN) modeling. In ANN simulation surveys, CP displayed Gaussian distributions ($R^2 > 0.9$) when PF changed in current ranges, with positive correlations between BS and MOR ($R^2 \approx 0.5$). Combining ANN and the genetic-algorithm, optimal processes (HT, 160 °C; HD, 50 s/mm; HP, 1.3 MPa; HC, 6 layers) were found, and optimal results (BS, 1.30 MPa; MOR, 86.94 MPa; MOE, 8.33 GPa) were comparable to various reported poplar-plywoods. Microscopic images demonstrated that composite interfaces were formed by the mechanical interlocking. The optimal BS attained Chinese standards for water-resistant plywoods, so proposed composites can serve as water-resistant and formaldehyde-free building materials for furniture and interior design.

Keywords: Plantation eucalyptus; High-density polyethylene; Wood plastic composite; Artificial neural network; Genetic algorithm

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

With diminishing petroleum-based resources and rising concerns towards environmental issues, the lignocellulose and thermoplastic are becoming more emphasized in the field of the material science (Matthews *et al.* 2015). To date, a wide range of plant units (*e.g.*, the flour, fiber, and particle of the wood, bamboo, flax, jute, and kenaf, *etc.*) have been considered for preparing polymer composites, while the polyolefin (*e.g.*, polyethylene and polypropylene, *etc.*) is the commonly-used matrix (Song *et al.* 2015).

Plywood is a value-added product in the forest product industry, which serves as important building materials in the fields of furniture and interior design (Fang *et al.* 2016; Yang *et al.* 2016). To develop novel plywoods combining the lignocellulose and thermoplastic materials, composites made of poplar veneers and polyethylene films (or called poplar/polyethylene plywoods) have been recently reported (Fang 2014). It was reported that certain conditions (a hot-pressing temperature of 160 °C, a hot-pressing duration of 1 min/mm, a hot-pressing pressure of 0.7 MPa, and a polyethylene-film dosage of 2 layers) can lead to water-resistant bonding strength values of poplar/polyethylene plywoods that exceed Chinese standards for water-resistant plywoods and are comparable to those of poplar/urea-formaldehyde (UF) resin plywoods (Fang *et al.* 2013a). Particularly, the hot-pressing temperature has a notable effect on the formation of adhesive bonded joints between porous veneers and molten films, where the wood plastic interface is formed through the mechanical interlocking (Fang *et al.* 2013a). When the polyethylene-film dosage between every two veneers increases from 61.6 g/m^2 to 246 g/m^2, various properties of poplar/polyethylene plywoods are positively affected (Fang *et al.* 2013b). Compared to poplar/UF resin plywoods, poplar/polyethylene plywoods present the lower 7-day water adsorption (by 23.5 %), thickness swelling (by 5.10 %), and almost the same dynamic mechanical properties under 100 °C; therefore poplar/polyethylene plywoods are applicable for the higher moisture and geothermal floors (Fang *et al.* 2013b). Moreover, the silane A-171 has been used to modify veneer surfaces, thus enhancing the affinity of hydrophilic poplar veneers with hydrophobic polyethylene films (Fang *et al.* 2014).

Like the poplar in the above reports, eucalyptus also serves as an important plantation tree species. It is a native species of Australia and has been widely cultivated in almost 100 countries and regions (McGavin *et al.* 2015a). Due to its high growth rate, eucalyptus has a great potential to serve the forest product industry; for example, eucalyptus has been applied in the pulp and paper industry (Zhang *et al.* 2015). However, in order to achieve the value-added utilization, the utilization of plantation eucalyptus rotary-cut veneers as raw materials in the fields of furniture and interior design should be more emphasized, such as to develop novel plywoods based on eucalyptus veneers and water-resistant, tough, and formaldehyde-free polyolefin films (McGavin *et al.* 2015b).

To focus on eucalyptus veneer/polyolefin film composites is very meaningful, especially for China. For one thing, like its counterparts poplar or pine in North China, eucalyptus is the most important plantation tree species in South China (Liu *et al.* 2015). On the other hand, China has become the largest producer and consumer of various wood-based panels, of which about 50% the plywood (Fang 2014). In this context, to develop eucalyptus veneer/polyolefin film composites is an interesting challenge. Since polyolefin films can be made from recycled plastics, novel composites also contribute to lessening the plastic waste, thus bringing huge economic, social and ecological benefits (Song *et al.* 2015).

This work presented the first effort to develop and evaluate composites based on plantation eucalyptus veneers and high-density polyethylene (HDPE) film: (1) A process for manufacturing novel composites was developed, in which the range of the hot-pressing temperature was estimated according to thermal analyses. (2) The interaction between process factors and composite properties was evaluated using statistical analyses. (3) By the artificial neural network (ANN) modeling, the quantitative relationship between process factors and composite properties was determined, based on which large scale simulation surveys on composite properties were performed. (4) Combining ANN and the genetic algorithm (GA), the optimal process was found, under which water-resistant, flexural, and micro-morphological properties of proposed composites were evaluated.

EXPERIMENTAL

Raw Materials

Eucalyptus veneers (*E. grandis* × *E. urophylla*) were purchased from a plantation in the Guangxi Region of China, with the dimension of 400 × 400 × 2 mm^3, and the moisture content of 8 to 9 wt%.

HDPE films were purchased from the Huadun Xuehua Plastic Group Co., Ltd. in the Beijing Region of China, with the thickness of 0.06 mm, and the density of 0.89 g/cm^3.

UF resins were synthesized according to a reference (Fang 2014), with the formaldehyde/urea molar ratio of 1.15, the solid content of 52.4wt%, the flour content of 20wt%, and the curing agent NH_4Cl content of 1wt%.

Thermal Characterizations of Raw Materials

Melting data of HDPE under a nitrogen atmosphere were collected using a DSC-60 calorimeter (Shimadzu, Kyoto, Japan), from room temperature to 170 °C at a heating rate of 10 °C/min. Weight-loss data of the eucalyptus, HDPE, and UF resin under a nitrogen atmosphere were collected by a DTG-60 analyzer (Shimadzu, Kyoto, Japan), from room temperature to 600 °C at a heating rate of 10 °C/min. Viscosity data of HDPE were collected by a CFT-500D/100D rheometer (Shimadzu, Kyoto, Japan), from 140 °C to 180 °C.

Orthogonal Experiments of Composite Preparations

According to the orthogonal design in Table 1, eucalyptus veneer/HDPE film composites were prepared, in which a BY302 × 2/15 150T presser (Xinxieli Group Co., Ltd., Suzhou, China) was employed.

In detail, the range of the hot-pressing temperature (HT) was estimated by thermal characterizations of raw materials, while the range of the hot-pressing duration (HD), hot-pressing pressure (HP), and HDPE-film content between every two veneers (HC) was estimated according to the process for conventional plywoods (Li *et al.* 2015).

Before performing various tests, specimens were conditioned at a temperature of 20 °C and a relative humidity of 65%, until a constant weight was reached.

Table 1. L_9 (3^4) Orthogonal Design

Level	HT (°C)	HD (s/mm)	HP (MPa)	HC (layer)
1	140	50	0.7	2
2	160	70	1.0	4
3	180	90	1.3	6
HT, hot-pressing temperature; HD, hot-pressing duration; HP, hot-pressing pressure; HC, HDPE-film content between every two veneers.				

Macroscopic and Microscopic Characterizations of Composites

According to the Chinese standard GB/T 17657 (2013), water-resistant and flexural properties of eucalyptus veneer/HDPE film composites were investigated, in which a MWW-50 tester (Tianhua Test Device Co., Ltd., Jinan, China) was employed.

Water-resistant properties were evaluated by the water-resistant bonding strength (BS) in a tensile shear test, with six replicates measured. Before the test, specimens were immersed in 63 °C water for 3 h, and cooled in air at room temperature for 10 min.

Flexural properties were evaluated by the modulus of rupture (MOR) and modulus of elasticity (MOE) in a 3-point bending test, with six replicates measured.

In addition, micro-morphological properties were evaluated by microscopic imaging under a S-3400N scanning electron microscope (Hitachi, Tokyo, Japan), at an accelerating voltage of 5.00 kV. Before the observation, specimens were sputter-coated with the platinum.

Data Analyses

To reveal the interaction between process factors (HT, HD, HP, and HC) and composite properties (BS, MOR, and MOE), results of orthogonal experiments were statistically evaluated *via* the variance analysis and the range analysis. To further determine the quantitative relationship between process factors and composite properties, the ANN modeling was performed by the Neural Network Toolbox of the MATLAB 7.0 (MathWorks, Natick, USA), based on which large scale simulation surveys on composite properties were further conducted. To harvest the optimal process, an optimization combining ANN and GA was performed by the Genetic Algorithm Optimization Toolbox for MATLAB (North Carolina State University, Raleigh, USA), while the optimal result of composite properties was evaluated according to Chinese plywood standards and reported results of various poplar plywoods.

In some figures, presented in this paper, that compare composite properties with different units together, experimental data were normalized by dividing the maximum value of the corresponding property.

RESULTS AND DISCUSSION

The Process Route of Eucalyptus Veneer/HDPE Film Composites

As illustrated in Fig. 1, a technical route for manufacturing proposed composites was obtained after trial and error. In detail, the assembly was carried out with three eucalyptus veneers, with some HDPE films added between every two veneers, in which these films were cut according to the dimension of veneers, causing a density of 60 g/m^2 for each piece of the HDPE film.

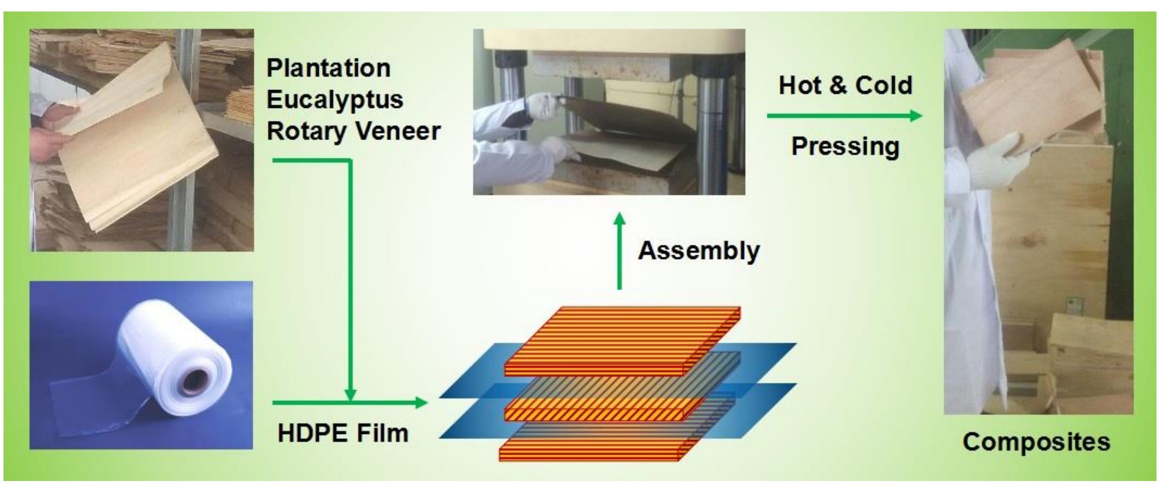

Fig. 1. The technical route for manufacturing proposed eucalyptus veneer/HDPE film composites

After the hot-pressing, a 1 MPa cold-pressing was further performed at room temperature for 5 min, which contributed to reducing the distortion and stress of composites.

The Estimation of the Hot-pressing Temperature (HT)

Considering the potential difference between the HDPE adhesive in proposed composites and formaldehyde resin adhesive in conventional plywoods, important thermal properties were investigated to estimate the range of HT.

As illustrated in Fig. 1(a), the eucalyptus and HDPE, respectively, gave the degradation temperatures of 230 °C and 400 °C, implying the value of the upper limit of HT. In this sense, HT must be below 230 °C, thus avoiding the pyrolysis of raw materials. On the other hand, the degradation temperature of the UF resin was also 230 °C, reflecting the similar upper limit of HT.

As illustrated in Fig. 1(b), the melting temperature of HDPE was 130 °C, implying the value of the lower limit of HT. In other words, HT must be over 130 °C, thus making HDPE flow and penetrate the eucalyptus veneers. By contrast, conventional plywoods made from the commercial UF resin are generally hot-pressed at around 100 °C (Fang *et al.* 2013a,b; Fang 2014).

Therefore, a range of 140 °C to 180 °C was considered for hot-pressing proposed composites. As illustrated in Fig. 1(c), the increase of HT in this range led to the decrease of the viscosity of HDPE, thus improving the mobility of HDPE, largely because the chain segment motion of HDPE was enhanced (Song *et al.* 2015). However, the optimal level of HT must be further discussed in following sections.

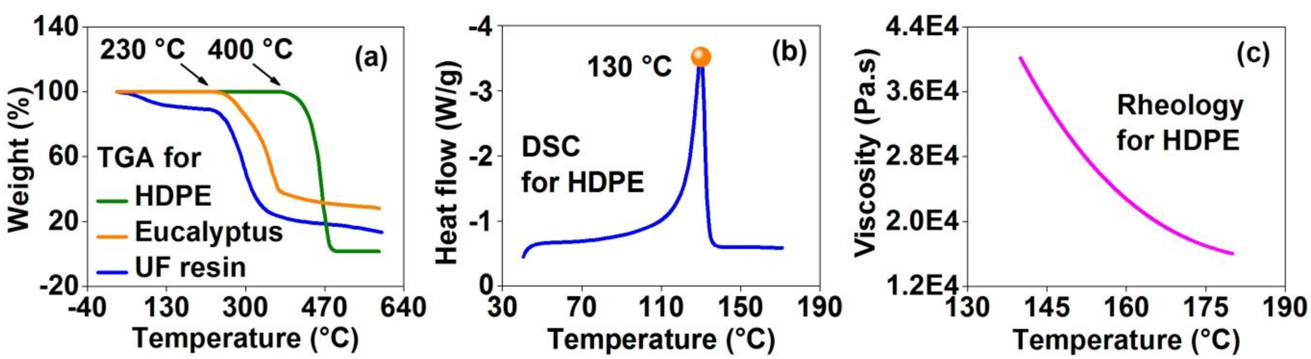

Fig. 2. Important thermal properties of raw materials for eucalyptus veneer/HDPE film composites

The Interaction between Process Factors and Composite Properties

As illustrated in Fig. 3, the manufacture of proposed eucalyptus veneer/HDPE film composites was statistically evaluated.

The influence of process factors on composite properties is exhibited in Fig. 3 (a) and (c). In the variance analysis (Fig. 3a), HD showed significant effects on all the composite properties, including one at the 0.01 level (on MOE) and two at the 0.05 level; HC showed two significant effects, both at the 0.01 level (on BS and MOE), while HT showed two significant effects respectively at the 0.01 level (on BS) and at the 0.05 level (on MOR); and HP only showed one significant effect at the 0.01 level (on MOE). In the range analysis (Fig. 3c), it seemed difficult to determine the order of the influence of process factors, but the arithmetic mean of the influence showed: HD (mean = 0.243) >

HC (mean = 0.234) > HP (mean = 0.198) > HT (mean = 0.180). Therefore, for the four process factors, HD was easier to affect composite properties.

The sensitivity of composite properties to process factors is exhibited in Fig. 3 (b) and (d). In the variance analysis (Fig. 3b), MOE showed the high sensitivity to all the process factors except HT; BS showed two high sensitivities (to HT and HC) and one medium sensitivity (to HD); and MOR only showed two medium sensitivities (to HT and HD). While in the range analysis (Fig. 3d), it was clear that MOE showed the higher sensitivity to process factors than others, and the arithmetic mean of the sensitivity showed: MOE (mean = 0.292) > BS (mean = 0.193) > MOR (mean = 0.155). Therefore, for the three composite properties, MOE was easier to be affected by process factors.

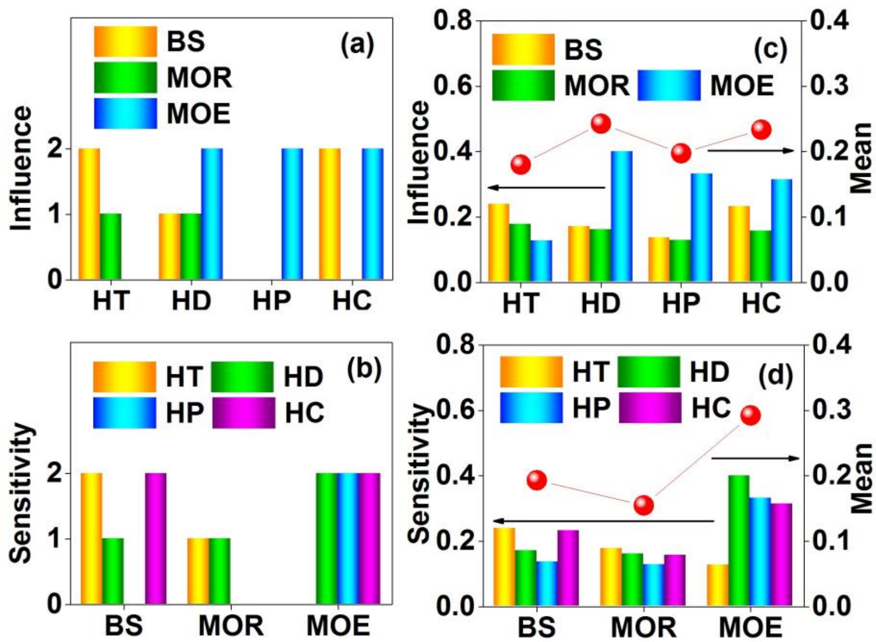

Fig. 3. The interaction between process factors and composite properties. (a) and (b) are the variance analysis, respectively, categorized by process factors and composite properties, in which the values 0, 1, and 2 for the "influence" (or "sensitivity"), respectively, represent the insignificant effect at 0.05 level (or called the low sensitivity), significant effect at 0.05 level (or called the medium sensitivity), and significant effect 0.01 level (or called the high sensitivity); (c) and (d) are the range analysis, respectively, categorized by process factors and composite properties, in which the values for the "influence" (or "sensitivity") represent the range normalized by dividing the maximum value of the corresponding property among the three levels of the orthogonal design. HT, hot-pressing temperature; HD, hot-pressing duration; HP, hot-pressing pressure; HC, HDPE-film content between every two veneers. BS, water-resistant bonding strength; MOR, modulus of rupture; MOE, modulus of elasticity

In addition, the change of the value of composite properties with the change of the level (*i.e.*, level 1, level 2, and level 3) of process factors is further exhibited in Fig. 4. As can be seen, when the level of process factors changed, the response of different composite properties was different, which was similar for all the four process factors.

Typically, in an optimal range of the level of a process factor, the optimal level of this process factor is included, which produces the optimal result of composite properties. When the level of this process factor rises in this range, the value of composite properties (*e.g.*, MOE) will first increase and then decrease, during which the optimal result of composite properties will occur at the optimal level of the process factor. But in some cases (like this research), the optimal range of the level of the process factor depends on the type of composite properties. Taking HT (Fig. 4a) as an example, with HT rising from 140 °C (level 1) to 180 °C (level 3), the value of BS and MOR always increased, while the value of MOE first increased and then decreased, during which the optimal result of MOE occurred at 160 °C (level 2); in this sense, the range of HT (140 °C to 180 °C) in this research was the optimal range for MOE, but it was not necessarily the optimal range for BS and MOR. Overall, it was difficult for all the four process factors in this research to find the optimal range of the level simultaneously applicable for all the three composite properties, causing the complicated phenomenon in Fig. 4. In previous reports, the similar phenomenon has been found for some wood composites (Song *et al.* 2015).

Despite the complicated phenomenon, the mechanism of the effect of process factors can be understandable as follows. Generally speaking, a higher HT and longer HD contribute to fully melting HDPE, thus boosting the interaction with veneers; however, the too high HT or too long HD can cause energy wastage and render the lignocellulose of eucalyptus veneers prone to degradation. On the other hand, the greater HP contributes to enhancing the penetration of HDPE into the wood tissue, thus forming composites with the more compact micro-structure; however, the too high HP can destroy the morphology of plant cells and diminish the density of wood-plastic interfaces due to pressing excess HDPE into veneers. Moreover, the larger HC contributes to providing adequate adhesive, thus creating stronger interfacial bonding; however, too high HC can decrease the composite strength due to the flexibility of HDPE and lead to the overflow of some HDPE as resource wastes (Li *et al.* 2014). Considering the complexity, the quantitative relationship between process factors and composite properties must be determined by the artificial intelligence in following sections.

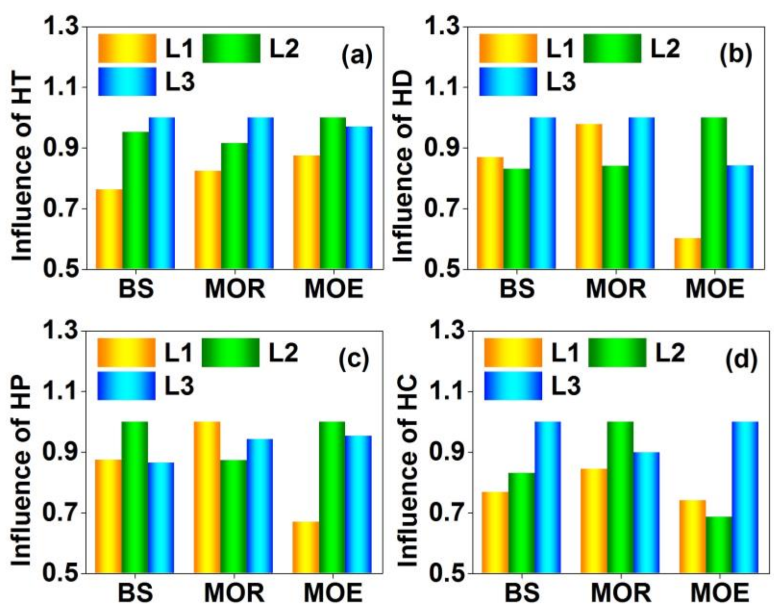

Fig. 4. Change of the value of composite properties with the change of the level of process factors, which is normalized by dividing the maximum value of the corresponding property among the three levels of the orthogonal design. HT, hot-pressing temperature; HD, hot-pressing duration; HP, hot-pressing pressure; HC, HDPE-film content between every two veneers; BS, water-resistant bonding strength; MOR, modulus of rupture; MOE, modulus of elasticity. L1 to L3, level 1 to level 3 in the orthogonal design

Modeling Based on the Artificial Neural Network (ANN)

Through simulating the behavior characteristic of biological neural systems, ANN has become an efficient and flexible modeling method for determine the general mapping rule between dependent and independent variables (Emeko *et al*. 2015). With the help of experimental data derived from some typical conditions, ANN can be trained and further used to predict experimental data under various unknown conditions included in the known range, which can be employed to conduct large-scale simulation surveys.

For proposed eucalyptus veneer/HDPE film composites in this research, a feed-forward back-propagation ANN was constructed to determine the quantitative relationship between process factors and composite properties. As shown in Fig. 5, this model consisted of three layers, in which neurons of input and output layers, respectively, represented the four process factors and the three composite properties; after the trial and error, 14 neurons were finally adopted in the hidden layer. For hidden and output layers, each neuron processed signals according to Eq. 1,

$$y_j = f(\sum_{i=1}^{k} x_i \cdot w_{i \to j} + \theta_j) \quad (1)$$

where x_i is the input signal from the neuron i in the former layer to the neuron j in the current layer, $w_{i \to j}$ is the weight between the two neurons, k is the number of neurons in the former layer, θ_j is the threshold for the neuron j, f is the transfer function between the two layers, and y_j is the output signal of the neuron j. In this research, TANSIG and PURELIN functions respectively served as the transfer function between the input layer and hidden layers, and between the hidden layer and output layer.

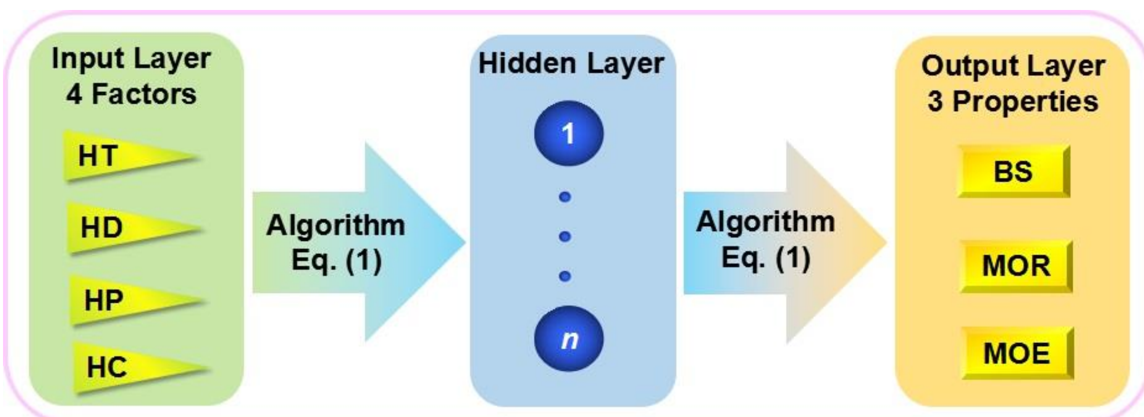

Fig. 5. The structure of the artificial neural network (ANN) for modeling the manufacture of proposed eucalyptus veneer/HDPE film composites. HT, hot-pressing temperature; HD, hot-pressing duration; HP, hot-pressing pressure; HC, HDPE-film content between every two veneers; BS, water-resistant bonding strength; MOR, modulus of rupture; MOE, modulus of elasticity

Due to the uniform dispersion and neat comparability, experimental data obtained according to the orthogonal design were very appropriate to train ANN with a Levenberg-Marquardt algorithm under given criteria (*i.e*., a EPOCHS of 3000 and a GOAL of 10^{-14}), thus not only making the model learn the general mapping rule between process factors and composite properties, but also avoiding over-fitting; to accelerate the convergence and reduce the error during the machine learning, the input signal was normalized using the PREMNMX function (Song *et al*. 2015).

To evaluate the trained ANN, both the reproductive and predictive capabilities were demonstrated as follows. For the former, ANN trained with nine conditions of the orthogonal design was employed to reproduce all data, which showed the relative deviation of -1% to 1%. While for the latter, conditions 1 to 4 and 6 to 9 of the orthogonal design, and the condition 5 of the orthogonal design respectively served as the training set and the testing set for ANN (*i.e.*, a cross validation), which showed the relative deviation of 5% (BS), 9% (MOR), and -10% (MOE) for the condition 5.

Simulation Surveys Based on the Artificial Neural Network (ANN)

By virtue of the trained ANN, a large scale numerical experiment was conducted to investigate composite properties, in which five levels were set by average for each process factor in the original range (*e.g.*, the five levels for HT were 140 °C, 150 °C, 160 °C, 170 °C, and 180 °C), resulting in 5^4 = 625 level-combinations of process factors (*i.e.*, five levels of each process factor multiplied by the four process factors). As illustrated in Fig. 6, maximum values of BS, MOR, and MOE of proposed eucalyptus veneer/HDPE film composites were respectively up to 1.4 MPa, 95 MPa, and 13 GPa. Overall, values of each composite property derived from the 625 conditions were unequally distributed and shaped like a bell curve. Considering the similarity to the Gaussian distribution, values of each composite property were fitted by Eq. 2,

$$f = \beta + \frac{\alpha}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{2}$$

where f is the probability density function of the Gaussian distribution, x is a random variable (*e.g.*, BS, or MOR, or MOE), μ and σ are respectively the arithmetic mean and standard deviation of x, and α and β are parameters of this model. As illustrated in Fig. 6, the three coefficients of determination (R^2) were all over 0.9. Presently, the Gaussian distribution is common in the field of the wood science; taking the property of wood composites as an example, the compressive strength of fiber-reinforced composites, and the density and ultimate strength of scrimbers have been recently reported to be normally distributed (Shangguan *et al.* 2014; Zhong *et al.* 2014), thus reflecting the reliability of the Gaussian distribution in this research.

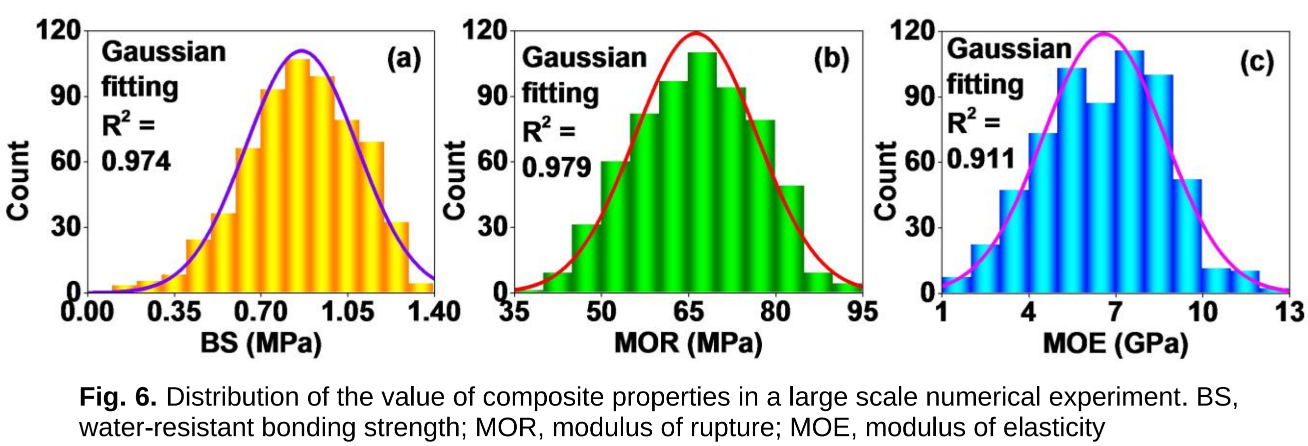

Fig. 6. Distribution of the value of composite properties in a large scale numerical experiment. BS, water-resistant bonding strength; MOR, modulus of rupture; MOE, modulus of elasticity

As illustrated in Fig. 7, data correlations between various composite properties in the large scale numerical experiment were established by the linear model. Overall, there was a positive correlation between BS and MOR (Fig. 7a, $R^2 \approx 0.5$), a positive correlation between BS and MOE (Fig. 7b, $R^2 \approx 0.1$), and a negative correlation between MOR and MOE (Fig. 7c, $R^2 \approx 0.01$). In this sense, a process that can produce higher BS and MOR might compromise MOE, thus highlighting the complexity in the manufacture of proposed eucalyptus veneer/HDPE film composites. Therefore, the balance among composite properties must be achieved by artificial intelligence, as described in the following sections.

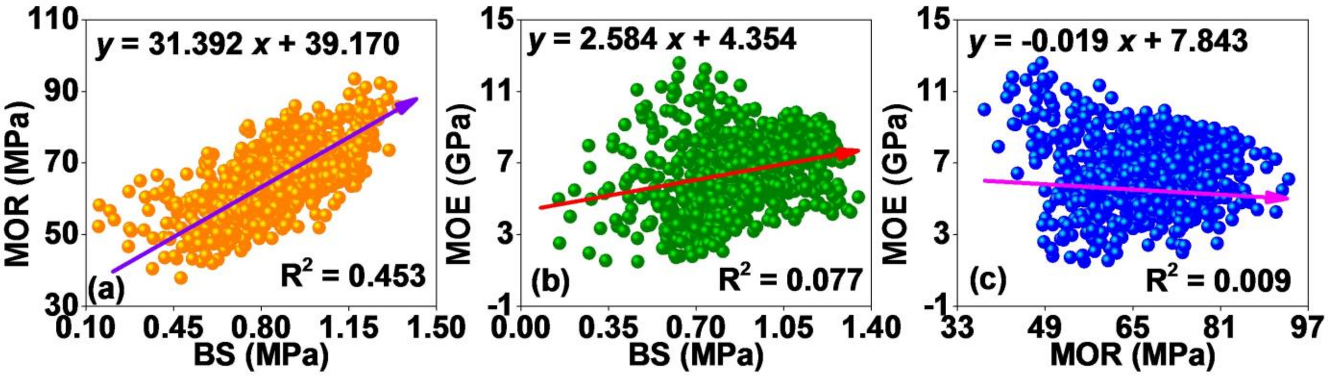

Fig. 7. Data correlations between various composite properties in the large scale numerical experiment. BS, water-resistant bonding strength; MOR, modulus of rupture; MOE, modulus of elasticity

Process Optimization based on the Genetic Algorithm (GA)

Through simulating the natural selection and heredity mechanism of biological evolution processes, GA has become an efficient and flexible searching method for determining the optimal solution of multi-parameter and multi-objective problems (Quirino *et al.* 2015). In a typical run, an initial population is randomly generated, whose fitness is then calculated according to a given function: if the fitness has been maximized, the current population is considered the optimal population; if the fitness has not yet been maximized, the current population is modified through the selection, crossover and mutation, thus yielding a new initial population to undergo a similar process again.

For proposed eucalyptus veneer/HDPE film composites in this research, the level-combination of process factors was considered the population in GA, so the optimal population corresponded to the optimal process. Therefore, the fitness was defined by Eq. (3), which can be regarded as a reciprocal of the distance between optimized results (BS, MOR, MOE) and a point (BS = 1.5 MPa, MOR = 150 MPa, MOE = 15 GPa). In detail, this point was chosen according to the potential optimal results observed in Fig. 6 (BS = 1.4 MPa, MOR = 95 MPa, MOE = 13 GPa), and a greater fitness indicated a smaller difference between optimized results and this point.

$$f = \left[\left(\frac{BS}{1.5} - 1\right)^2 + \left(\frac{MOR}{150} - 1\right)^2 + \left(\frac{MOE}{15} - 1\right)^2 \right]^{-\frac{1}{2}} \tag{3}$$

As illustrated in Fig. 8, the trained ANN was employed to generate the value of composite properties corresponding to a given level-combination of process factors, with which the fitness was calculated according to Eq. (3), thus achieving a GA-ANN optimization.

In detail, the optimization was performed with the setting of: population size = 20, terminal generation = 300, selection function = normGeomSelect, crossover function = arithXover, and mutation function = nonUnifMutation.

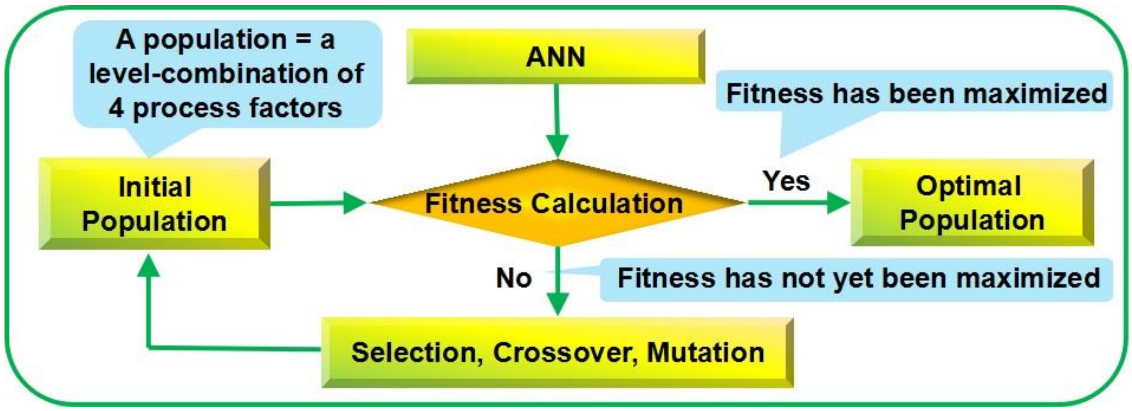

Fig. 8. The information flow in the genetic algorithm (GA) for optimizing the manufacture of proposed eucalyptus veneer/HDPE film composites. ANN, artificial neural network

The Evaluation of the Optimal Result of Composite Properties

After the GA-ANN optimization, the optimal process of proposed eucalyptus veneer/HDPE film composites was as follows: HT, 160 °C; HD, 50 s/mm; HP, 1.3 MPa; and HC, 6 layers, which was experimentally validated. In detail, the optimal BS was up to 1.30 MPa, which attained the required 0.7 MPa for water-resistant plywoods in Chinese standard GB/T 9846 (2015). As illustrated in Fig. 9(a), the optimal result of BS, MOR, and MOE of proposed composites was comparable to reported results for poplar/polyethylene plywoods and poplar/UF resin plywoods (Fang 2014).

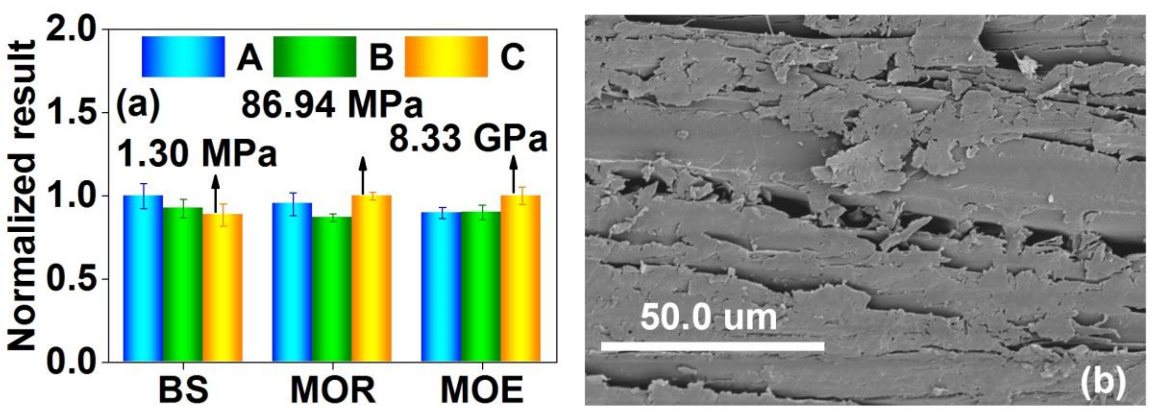

Fig. 9. Composite properties under the optimal process. (a) Comparison of macroscopic properties of proposed eucalyptus veneer/HDPE film composites (C) with reported poplar/polyethylene plywoods (A) and poplar/urea-formaldehyde resin plywoods (B) (Fang 2014), whose data are normalized by dividing the maximum value of the corresponding property. For the plywood (A) and (B): Thickness: veneer, 1.6 mm. Layers: five veneers. Species: *Populus × euramericana cv. '74/76'*. Bonding: hot-pressing temperature, 152 °C (A) and 115 °C (B); hot-pressing duration, 1.1 min/mm (A) and 1 min/mm (B); hot-pressing pressure, 1 MPa; adhesive content, 3 layers of the polyethylene film (A) and 300 g/m^2 resin (B). (b) Micro-morphological properties of proposed composites

As observed in Fig. 9(b), micro-morphological properties of proposed eucalyptus veneer/HDPE film composites under the optimal process showed that the hot-pressing allowed molten HDPE to penetrate the micro-structure of eucalyptus veneers, thus forming composite interfaces through the mechanical interlocking (Fang *et al.* 2013a). However, there were also evident gaps between the veneer and HDPE, largely due to the relatively poor affinity of hydrophobic HDPE films with hydrophilic eucalyptus veneers (Fang *et al.* 2014; Zhu *et al.* 2016). Therefore, to improve the interface compatibility will be a focus of the future research.

CONCLUSIONS

1. A process route for manufacturing plantation eucalyptus rotary-cut veneer/high-density polyethylene film composites were developed, in which a range of 140 to 180 °C was appropriate for the hot-pressing.
2. According to the statistical analysis, HD was easier to affect composite properties, while MOE was easier to be affected by process factors, while the optimal range of the level of process factors depended on the type of composite properties.
3. The quantitative relationship between process factors (HT, HD, HP, and HC) and composite properties (BS, MOR, and MOE) was determined by the artificial neural network (ANN) modeling, while reproductive and predictive capabilities of this model were experimentally validated.
4. In ANN simulation surveys, the value of each composite property displayed the Gaussian distribution ($R^2 > 0.9$) when the level-combination of process factors changed in current ranges; as for data correlations, there were a positive correlation between BS and MOR ($R^2 \approx 0.5$), a positive correlation between BS and MOE ($R^2 \approx 0.1$), and a negative correlation between MOR and MOE ($R^2 \approx 0.01$).
5. Combining ANN and the genetic algorithm (GA), the optimal process (HT, 160 °C; HD, 50 s/mm; HP, 1.3 MPa; and HC, 6 layers) was found, under which the optimal result (BS, 1.30 MPa; MOR, 86.94 MPa; MOE, 8.33 GPa) was comparable to reported results of poplar/polyethylene plywoods and poplar/UF resin plywoods.
6. Microscopic images demonstrated that composite interfaces were formed by a mechanical interlocking mechanism.
7. The optimal BS attained Chinese standards for water-resistant plywoods, thus indicating that proposed composites can serve as water-resistant and formaldehyde-free building materials in the fields of furniture and interior decoration.

ACKNOWLEDGMENTS

This work is supported by the Co-built Foundation with the Beijing Municipal Commission of Education, Beijing Natural Science Foundation (6162019) "Research on Mechanism in Bionic Compatibilization for Bamboo Plastic Interface Bioinspired by Super Adhesion of Marine Shellfish", Co-built Foundation with the Zhejiang Province (CZXC201410) "R & D on Natural Fiber Composites and Environmentally Friendly

Adhesives”, Forest Certification Foundation of the Chinese State Forestry Administration “Pilot Research on Chain of Custody Certification for Environmentally Friendly Bamboo Composites”, and the Fundamental Research Funds for the Central Universities of China. Furthermore, we are grateful for the technical support from the Chinese Academy of Forestry, Zhejiang Chengzhu Advanced Material Technology Co., Ltd., and Mr. Zaihua Shen.

REFERENCES CITED

Emeko, H. A., Olugbogi, A. O., and Betiku, E. (2015). "Appraisal of artificial neural network and response surface methodology in modeling and process variable optimization of oxalic acid production from cashew apple juice: A case of surface fermentation," *BioResources* 10(2), 2067-2082. DOI: 10.15376/biores.10.2.2067-2082

Fang, L. (2014). *Interfacial Modification Methods and Mechanism of High Density Polyethylene Film/Poplar Veneer Plywood*, Ph.D. Dissertation, Chinese Academy of Forestry, Beijing, China.

Fang, L., Chang, L., Guo, W., Chen, Y., and Wang, Z. (2013a). "Manufacture of environmentally friendly plywood bonded with plastic film," *Forest Prod. J*. 63(7), 283-287. DOI: 10.13073/FPJ-D-12-00062

Fang, L., Chang, L., Guo, W., Ren, Y., and Wang, Z. (2013b). "Preparation and characterization of wood-plastic plywood bonded with high density polyethylene film," *Eur. J. Wood Prod*. 71(6), 739-746. DOI: 10.1007/s00107-013-0733-0

Fang, L., Chang, L., Guo, W., Chen, Y., and Wang, Z. (2014). "Influence of silane surface modification of veneer on interfacial adhesion of wood–plastic plywood," *Appl. Surf. Sci*. 288(0), 682-689. DOI: 10.1016/j.apsusc.2013.10.098

Fang, L., Wang, X., Xiong, X., Zou, Y., and Wang, Z. (2016). "Effects of surface pretreatments on wet cycle resistance of wood-plastic plywood," *Journal of Forestry Engineering* 1(1), 37-41. DOI: 10.13360/j.issn.2096-1359.2016.01.007

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.

GB/T 9846. (2015). "Plywood for general use," Standardization Administration of China, Beijing, China.

Li, H., Li, C., Chen, H., Zhang, D., Zhang, S., and Li, J. (2014). "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, X., Li, J., Li, J., and Gao, Q. (2015). "Effect of sepiolite filler in malamine-urea-formaldehyde resin on the properties of three-ply plywood," *BioResources* 10(4), 6624-6634. DOI: 10.15376/biores.10.4.6624-6634

Liu, H., Gao, J., and Chen, Y. (2015). "Effects of pre-freezing prior to drying upon some physical and mechanical properties of *Eucalyptus urophylla x Eucalyptus grandis* wood," *BioResources* 10(4), 6417-6427. DOI: 10.15376/biores.10.4.6417-6427

Matthews, S., Toghyani, A. E., Eskelinen, H., Kärki, T., and Varis, J. (2015). "Manufacturability of wood plastic composite sheets on the basis of the post-processing cooling curve," *BioResources* 10(4), 7970-7984. DOI: 10.15376/biores.10.4.7970-7984

McGavin, R. L., Bailleres, H., Hamilton, M., Blackburn, D., Vega, M., and Ozarska, B. (2015a). "Variation in rotary veneer recovery from Australian plantation *Eucalyptus globulus* and *Eucalyptus nitens*," *BioResources* 10(1), 313-329. DOI: 10.15376/biores.10.1.313-329

McGavin, R. L., Bailleres, H., Fehrmann, J., and Ozarska, B. (2015b). "Stiffness and density analysis of rotary veneer recovered from six species of Australian plantation hardwoods," *BioResources* 10(4), 6395-6416. DOI: 10.15376/biores.10.4.6395-6416

Quirino, T. M., Souza, J. B., Amaral, J. L., Amaral, J. F., and de Oliveira, M. A. (2015). "Computation intelligent methods applied for modeling and adjustment of a thermal flow meter," *Int. J. Mech. Eng. Autom.* 2(3), 127-134.

Shangguan, W., Zhong, Y., Xing, X., Zhao, R., and Ren, H. (2014). "2D model of strength parameters for bamboo scrimber," *BioResources* 9(4), 7073-7085. DOI: 10.15376/biores.9.4.7073-7085

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

Yang, X., Xu, X., Lyv, J., and Zhan, X. (2016). "Surface properties of *Populus euramevicana* plywood painted with damping coating," *Journal of Forestry Engineering* 1(1), 25-30. DOI: 10.13360/j.issn.2096-1359.2016.01.005

Zhang, T., Tu, D., Peng, C., and Zhang, X. (2015), "Effects of heat treatment on physical-mechanical properties of *Eucalyptus regnans*," *BioResources* 10(2), 3531-3540. DOI: 10.15376/biores.10.2.3531-3540

Zhong, Y., Jiang, Z., Shangguan, W., and Ren, H. (2014). "Design value of the compressive strength for bamboo fiber-reinforced composite based on a reliability analysis," *BioResources* 9(4), 7737-7748. DOI: 10.15376/biores.9.4.7737-7748

Zhu, L., Huang, H., Lyv, Y., Mao, R., An, R., Zhan, X., and Wang, M. (2016). "Surface properties of poplar wood after vacuum coating," *Journal of Forestry Engineering* 1(1), 42-45. DOI: 10.13360/j.issn.2096-1359.2016.01.008

Article submitted: November 29, 2015; Peer review completed: January 31, 2016; Revised version received and accepted: February 10, 2016; Published: February 17, 2016.
DOI: 10.15376/biores.11.2.3318-3331