The Potential of Using Liquid Hot Water Pretreated Rice Straw to Produce Environment Friendly Particleboard

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The high extractives content in rice straw severely hinders surface adhesion, resulting in poor strength and dimensional stability of rice straw particleboard bonded with castor oil-based polyurethane (CPUR) resin. In this study, rice straw was pretreated with liquid hot water (LHW) at 150 °C for 20 min to reduce its extractives content for particleboard production with CPUR resin. The effects of LHW pretreatment on the chemical composition of the rice straws was evaluated. In addition, effects of CPUR resin dosage and density on mechanical properties and dimensional stability of the rice straw particleboards were investigated. The results indicated that LHW pretreatment significantly reduced the extractives and hemicellulose contents of the rice straw. The LHW pretreatment significantly improved the mechanical properties and dimensional stability of the rice straw particleboards. The overall performances of the rice straw particleboards were enhanced as the CPUR dosage increased. Increase of density led to upgraded mechanical properties but lowered dimensional stability of the rice straw particleboards.

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INTRODUCTION

Particleboard, a popular engineered wood-based panel, is widely used as a replacement of solid wood in the housebuilding, furniture, and interior decoration fields (Zhang and Hu 2014; Klimek *et al*. 2018). Global demand for particleboard has grown due to fast population increase and economic growth and development (Shi *et al*. 2024). Particleboard is generally made from wood particles bonded with synthetic adhesive or other binders, being pressed under heat (Luo *et al*. 2020). With the continuous increase of demand for particleboards, the particleboard sector has been facing a shortage in wood raw materials supply due to deforestation and forest degradation (Jonoobi *et al*. 2016). In this scenario, considerable research efforts have been directed toward searching for alternative lignocellulosic resources (Mahieu *et al.* 2021). A lot of studies have been utilizing agricultural residues as raw materials to replace wood for particleboard production in recent years (Han *et al.* 1999; Papadopoulos *et al.* 2002; Li *et al.* 2010; Li *et al.* 2013). Rice straw, one of the agricultural residues, is generated in large quantities each year. At present rice straw has not been effectively utilized. Most rice straw is landfilled or burned in China, causing serious environmental issues. The chemical composition of rice straw, cellulose, hemicellulose, and lignin is similar to wood (Luo *et al*. 2020). Furthermore, rice straw can be easily crushed into particles, which may be used as raw materials for particleboard production. Therefore, rice straw has potential application in particleboard production as an alternative to wood particles.

Urea–formaldehyde (UF) resin is predominately used for particleboard production (Stoeckel *et al*. 2013; Frihart 2015). However, the utilization of UF resin may endanger human health and the environment due to the carcinogenic formaldehyde release from the particleboards (Aisyah *et al*. 2021). Hence, research and development of formaldehyde-free adhesives from natural renewable resources has great significance to address these issues (Espinosa *et al*. 2022). Castor oil-based polyurethane can be used as a binder for particleboard production (Garzón-Barrero *et al*. 2016). Several studies have been carried out on the substitute of UF resin by castor oil-based polyurethane to produce particleboards with various kinds of raw materials, and improved physical and mechanical properties were achieved (Fiorelli *et al.* 2012; Gava *et al.* 2015; Garzón-Barrero *et al*. 2016; Calegari *et al.* 2017; Sugahara *et al.* 2019; Seibel *et al*. 2021; de Oliveira *et al*. 2023; Faria *et al.* 2024). Castor oil-based polyurethane resin (CPUR) is derived from a renewable and natural resource and has a low degree of toxicity (Garzón-Barrero *et al*. 2016). To date, information about utilizing rice straw with CPUR in particleboard production is unknown. The extractives inhibit the reactivity of the lignocellulosic raw material with the CPUR (Gava *et al.* 2015; Martins *et al*. 2018; Faria *et al.* 2024). The extractives content in rice straw is much higher than that in wood particles (Li *et al.* 2013; Luo *et al.* 2020). To enhance the bondability between the rice straw particles and CPUR, it is necessary to pretreat rice straw to decrease its extractives content. Liquid hot water (LHW) pretreatment, utilizing pressure to maintain the water in a liquid state at elevated temperatures for several seconds to several minutes in order for the water to serve as both promoter and solvent, can effectively destroy the lignocellulosic structure and decrease the extractives content of lignocellulosic raw material (Li *et al.* 2017; Luo *et al.* 2020). LHW pretreatment, which has no chemical requirement, is regarded as an environmentally friendly process (González *et al.* 2014; Luo *et al.* 2020). No information is available in LHW pretreated rice straw particleboard bonded by CPUR. This study determined the technical feasibility of LHW pretreated rice straw in production of particleboard bonded with CPUR.

EXPERIMENTAL

The rice straw was obtained locally. Its moisture content was approximately 8.8%. The rice straw was cut into small particles by a fodder grinder. The rice straw particles were screened through a mesh with 0.3-mm aperture to remove undersized particles and dusts. The commercial CPUR adhesive used in this study was bi-component type in a ratio of 1:1 (50% polyol and 50% pre-polymer) purchased from Jinan Huakai Resin Corporation (Jinan, China). The CPUR is free of solvents, with a solid content of 100%.

The rice straw was pretreated using a custom-built 15-L batch rotary stainless steel cylindrical autoclave fitted with an electrical heater, a motor actuator, a safe valve, a steam releasing valve, a pressure gauge, and a temperature gauge (Luo *et al.* 2020). The rice straw was pretreated under the previously established optimum LHW pretreatment conditions: 150 ℃ pretreatment temperature, 20 min residence time, and 1:7 solid to water ratio (g/mL, dry weight) (Luo *et al.* 2020). At the end of the pretreatment time, the heating was stopped, and steam was released gradually. The pretreated rice straw was collected from the autoclave, subjecting to filtering and pressing to remove the excess water. The pretreated samples were oven dried at 100 ± 3 ℃ to 8% moisture content and bagged and used for later particleboard fabrication (Yano *et al.* 2020).

The native and pretreated rice straw were analyzed for moisture, cellulose, hemicellulose, lignin, and ethanol/benzene extractives contents according to the procedures of Liu and Zhang (Liu and Zhang 2020).

Table 1. Experimental Design

	Target Density (g/m^3)	Resin Dosage (%)	Board Type
Native Rice Straw	700	10	A1
		15	A2
		20	A3
	800	10	B1
		15	B2
		20	B3
LHW Pretreated Rice Straw	700	10	C1
		15	C2
		20	C3
	800	10	D1
		15	D2
		20	D3

Rice straw particleboards were produced with CPUR resin as the binder. Three levels of resin dosage, 10%, 15%, and 20% based on the oven-dried weight of the rice straw particles that were used. The CPUR was homogenized with the rice straw particles in a blender for 6 min. After mixing, the resinated rice straw particles were manually placed in an aluminum forming mold. The mats were cold pressed under 1.5 MPa press pressure for 30 s. Then, the mats were hot-pressed according to a three-phase pressing schedule at 110 °C to release gases that can cause blowing or blistering (Sugahara *et al.* 2019). During the first phase, the mat was pressed at 5 MPa for 180 s, and during the second and third phases, the mat was pressed under 0.3 MPa for 60 s and 4 MPa for 120 s, respectively. The particleboard size was 500 × 500 × 6 mm with target densities of 700 and 800 kg/m^3 for each condition. Three replicate panels were produced for each manufacturing condition. The particleboard made with native rice straw was used as control. The particleboard types made with various densities and resin dosages are given in Table 1. After fabrication, the panels were conditioned at 20 °C and 65% relative humidity for about two weeks prior to being cut into test specimens.

The panels were cut into test specimens and tested according to the China National Test Standard GB/T 17657 (1999) for density, internal bonding (IB), modulus of rupture (MOR), modulus of elasticity (MOE), and thickness swelling (TS) after 24 h water soaking. Analysis of variance (ANOVA) was utilized to statistically analyze the data obtained with SPSS software (SPSS Inc., Version 19, Chicago, IL, USA). Comparison of the means was conducted using Duncan's mean separation tests, with a 95% confidence level.

RESULTS AND DISCUSSION

Table 1 shows that the LHW pretreatment altered the chemical composition of the rice straw. The cellulose content increased from 38.5% in the native rice straw to 49.3% in the pretreated rice straw. The lignin content slightly increased from 15.9% in the native straw to 16.6% in the pretreated samples while hemicellulose content decreased from 23.8% in the native straw to 12.7% in the pretreated samples. It is noted that the ash and ethanol/toluene extractives content in the pretreated rice straw lowered significantly in comparison to the native rice straw. These results indicated that the LHW pretreatment could effectively degrade hemicellulose, ash and extractives of the rice straw. As extractives inhibit the curing of CPUR resin (Martins *et al*. 2018; Faria *et al.* 2024), the removal of extractives from rice straw is expected to improve the bondability between the rice straw and CPUR resin. Also, reduction of hemicellulose content contributes to improvement of internal bond and water resistance of the particleboard (Li *et al.* 2011).

Table 2. Chemical Composition of Rice Straw Before and After LHW Pretreatment

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Ethanol/toluene extractives (%)
Native	38.5	23.8	15.9	15.1	6.7
Pretreated	49.3	12.7	16.6	9.2	2.9

The test results of rice straw particleboards made with various resin dosages and densities are shown in Table 3. The overall performance of particleboards made with LHW pretreated rice straw was significantly better than that of particleboards made with native rice straw at every density and resin dosage level. The results indicated that LHW pretreatment is effective in improving the physical and mechanical properties of rice straw particleboards bonded with CPUR resin.

The IB is the most important strength property for particleboard. The particleboards made with LHW pretreated rice straw had much higher IB than particleboards produced with native rice straw at every density and resin dosage level, demonstrating that reducing ash and extractives contents by LHW pretreatment is a viable way to improve the bondability of rice straw with the CPUR resin. It is noted that the IB of particleboards made with LHW pretreated rice straw at 700 kg/m^3 density level with 15% CPUR resin dosage was significantly higher than that of particleboards made with native rice straw at 800 kg/m^3 density level with 20% CPUR resin dosage. Higher density level means requiring more raw material and higher CPUR resin dosage means consuming more CPUR resin, which increases the production cost. This finding indicated that LHW pretreatment of rice straw was capable of reducing the needed CPUR resin dosage and density of rice straw particleboard and therefore reducing the production cost. Resin dosage plays an important role in particleboard properties. As CPUR resin dosage increased, the IB of rice straw particleboards increased at every density level. Density is an important factor affecting properties of particleboard. As density increased, the IB of rice straw particleboards increased at every resin dosage level. The LHW pretreated rice straw particleboards bonded with 20% CPUR resin dosage at the 800 kg/m^3 density level yielded the highest IB, 0.52 MPa. The minimal IB requirements for general purpose and furniture and interior fitments are 0.31 and 0.45 MPa reported in the Chinese standards GB/T 4897.2 (2003) and GB/T 4897.3 (2003), respectively. It is noted that the IB of the 10% CPUR bonded panels at every density level failed to meet the minimum requirement by the Chinese standards. This phenomenon can be explained by the fact that rice straw particle has a lower resin coverage and less bonding ability due to its larger surface area. 10% CPUR resin dosage was too low to cover the surfaces of the rice straw particles. As a result, poor internal bond developed.

Increasing CPUR resin dosage from 10% to 15% and to 20% led to a significant increase of IB at every density level. The particleboard types B3, C2, and D2 met the minimum requirement for general purpose whereas particleboards types C3 and D3 satisfied the requirements for general purpose and furniture and interior fitments (including furniture) boards.

Table 3. Properties of Rice Straw Particleboards as Affected by Resin Dosage and Density

Board Type	Actual Density (g/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)	24 h TS (%)
A1	681	7.7±0.8a	1226.8±121.6a	0.08±0.006a	64.3±6.4a
A2	673	8.7±1.0ab	1437.5±155.5ab	0.16±0.025b	62.2±5.3a
A3	659	10.5±1.2bc	1725.7±182.6bc	0.29±0.032cd	57.5±6.2ab
B1	782	8.7±1.0ab	1682.4±170.0bc	0.17±0.015b	61.7±6.3a
B2	772	10.3±1.2bc	1769.3±216.6bc	0.28±0.035cd	53.2±5.7bc
B3	765	12.3±1.3cd	1898.6±182.2cd	0.32±0.031de	48.3±5.2cd
C1	677	12.2±1.3cd	1932.7±189.5cd	0.24±0.025c	40.1±4.7d
C2	671	14.8±1.4e	2044.2±249.6cd	0.36±0.035ef	16.8±1.5ef
C3	658	15.1±1.6e	2172.3±205.8d	0.47±0.045g	10.2±1.3f
D1	778	14.0±1.6de	1988.6±204.8cd	0.26±0.030c	41.9±4.5d
D2	771	15.5±1.4e	2059.2±228.6cd	0.39±0.045f	19.5±2.1e
D3	756	15.9±1.5e	2198.7±224.6d	0.52±0.05g	13.3±1.4ef

Data shown are mean ± standard deviation; different letters in the same row indicate significant different at $P < 0.01$

The particleboards made with LHW pretreated rice straw had significantly higher MOR and MOE values than the particleboards made with native rice straw at every density and resin dosage level. These findings indicated that diminishing ash and extractives contents by LHW pretreatment is effective in improving the static bending properties of rice straw particleboard bonded with the CPUR resin. The MOR and MOE values increased with increasing CPUR resin dosage at every density level. Also, increasing density level from 700 to 800 kg/m^3 resulted in significant increase of IB value at every resin dosage level. The improvement in the bending properties reflected a good correlation with the trend of IB betterment. The particleboard type C2 met the minimum MOR requirement for general purpose, whereas particleboard types C3, D2 and D3 satisfied the MOR requirements for general purpose and furniture and interior fitments (including furniture) boards stipulated in the Chinese standards GB/T 4897.2 (2003) and GB/T 4897.3 (2003), respectively.

The particleboards made with LHW pretreated rice straw particles had lower 24 h TS than particleboards made with native rice straw particles. The reason for this lowered 24 TS was undoubtedly due to the removal of substantial ash and extractives contents by LHW pretreatment. In addition, hydrolysis of hemicellulose by LHW pretreatment also contributed to improved dimensional stability of the panels. Enhancing the CPUR resin dosage in the particleboards led to a decreased 24 h TS value. These results were consistent with the findings from the studies by Seibel *et al.* (2021) and de Oliveira *et al.* (2023). They mentioned that increase of CPUR resin dosage led to decreased 24 h TS of wood composite panel. The hydrophobic nature of CPUR resin was responsible for the decreased 24 h TS (Faria *et al.* 2024). Enhancing density from 700 to 800 kg/m^3 resulted in increased 24 h TS. This result is explained by the fact that higher density caused increased compaction of rice straw particles in particleboards. After 24 h water immersion, the particleboards fully absorbed water, resulting in a higher extent of springback of particles. Therefore, the extent of thickness swelling grew.

CONCLUSIONS

1. Liquid hot water (LHW) pretreatment was found to be an efficacious way to lower the extractives contents and hemicellulose of rice straw. The decreased extractives contents improved the bondability between rice straw particles and castor oil-based polyurethane (CPUR) resin. The mechanical properties and dimensional stability of particleboards made with LHW pretreated rice straw were significantly upgraded.
2. The CPUR resin dosage significantly influenced the mechanical properties and dimensional stability of the rice straw particleboard. Increase of the CPUR resin dosage led to increased mechanical properties and dimensional stability of the rice straw particleboard.
3. The density significantly affected the strength properties and water resistance of rice straw particleboards. With a rise in density, the mechanical properties of the rice straw particleboard improved. However, the increase of density led to declined dimensional stability of the rice straw particleboard bonded with CPUR resin.

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