Development and Performance Evaluation of Rice Straw Particleboard Bonded with Chitosan

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Single-layer particleboards were fabricated from rice straw bonded with chitosan. The rice straw was pre-treated by steam explosion to reduce the extractives and ash contents. The obtained pulp was analyzed for chemical composition, which indicated that the steam explosion pretreatment effectively decreased the extractives and ash contents. The effects of steam explosion pretreatment and chitosan contents on mechanical properties and dimensional stability of rice straw particleboards were explored. The mechanical properties and dimensional stability of particleboards made of steam exploded rice straw showed significant improvement. Addition of chitosan increased the mechanical properties and dimensional stability of particleboards. The mechanical properties and dimensional stability of particleboards improved with the increase of chitosan content.

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INTRODUCTION

Energy conservation, resource substitution, environmental protection, and sustainable economic development have become the concept of survival in modern society (Pedzik *et al.* 2021). Adhesives widely used in the manufacturing of wood composite panels, such as phenol formaldehyde and urea formaldehyde resin, are derived from non-renewable petroleum resources. They release formaldehyde, which is harmful to human health and the environment during production and use (Wang *et al.* 2019; Jerman *et al.* 2022). Therefore, developing environmentally friendly biomass adhesives for wood composites production has significant ecological benefits and environmental significance.

Chitosan is one of the most abundant polysaccharides in nature, with advantages such as abundant sources, moderate cost, nontoxicity, simple preparation, biodegradability, and high biocompatibility (Talaei *et al.* 2022). There are a large number of free amino and hydroxyl groups on the framework of chitosan, which can form strong chemical and hydrogen bonds with cellulose and hemicellulose components of lignocellulosic biomass (Umemura *et al.* 2009; Mati-Baouche *et al.* 2014; Huang *et al.* 2021; Talaei *et al.* 2022; Xi *et al.* 2022). Hence, chitosan is an ideal raw material for making wood adhesives. In recent years, the use of chitosan to prepare environmentally friendly wood adhesives to replace traditional wood adhesives has gradually become a research hotspot. Wood-based panel boards bonded with chitosan-based adhesives showed good performance (Mati-Baouche *et al.* 2014; Huang *et al.* 2021), indicating that it is feasible to produce wood particleboard using chitosan adhesive.

Rice straw is most significant in China. China's annual rice straw production is around 210 million tons (Zheng *et al.* 2022), ranking the top in the world. However, rice straw resources have not been effectively utilized, not only causing serious waste of resources, but also bringing about environmental pollution problems (Luo *et al.* 2024; Zheng *et al.* 2022). Rice straw contains chemical components similar to wood, such as cellulose, hemicellulose, lignin, which suggests that rice straw can replace wood in the production of particleboards (El-Kassas and Elsheikh 2021). However, rice straws have high ash and extractives contents, and rice straws' surfaces are covered with hydrophobic wax layers that are expected to adversely affect bonding (Peng *et al.* 2019). Consequently, rice straw particleboard often have exhibited poor quality, failing to meet the requirements of commercial standards for particleboards (Luo *et al.* 2024). It is worth exploring whether chitosan can be used to produce qualified rice straw particleboard. So far, there have been no reports on the application of chitosan for production of rice straw particleboard. In order to facilitate the wetting, penetration, and diffusion of chitosan adhesive onto the surface of rice straw, it is necessary to pretreat the rice straw. Steam explosion (SE) pretreatment can destroy the wax layer on the surface of rice straw, reduce the ash and extractive contents of rice straw, and improve the adhesion properties of rice straw (Han *et al.* 2010). This study conducted steam explosion pretreatment on rice straw and prepared rice straw particleboard using chitosan as a binder. The effects of chitosan addition on the physical and mechanical properties of rice straw particleboard was investigated. The aim of this study is to assess the technical feasibility of producing rice straw particleboard with chitosan as adhesive.

EXPERIMENTAL

Raw Materials

Rice straw with moisture content about 8.3% was collected from farmland in the suburbs of Tianjin City. The rice straw was crushed using a fodder grinder and screened through a mesh with 0.3-mm aperture. Particles that remained on the sieves were collected and stored in plastic bags for subsequent experiments.

Acetic acid was purchased from China National Pharmaceutical Group Chemical Reagent Co., Ltd. (Shanghai, China). Chitosan with 90% deacetylation was purchased from Tianjin Kermel Chemical Reagent Co., Ltd., (Tianjin, China).

Steam Explosion Pretreatment

Steam explosion pretreatment was carried out in a custom-built batch equipment with a 15-L pressure vessel (with a maximum operating pressure of 4 MPa) equipped with a quick-opening ball valve. 1 kg (dry matter) of rice straw was placed in the pressure vessel. Saturated steam from the boiler then flowed into the vessel. The rice straw was thereby heated to 150 ℃ for 3 min. Then the steam pressure was immediately released. The exploded rice straw was recovered in a cyclone. After cooling to about 40 ℃, it was filtered for solid recovery. The solid fraction was pressed to remove excess liquid and then dried in an oven at 100 ℃ to 8% moisture content. The pretreatment condition selected was relatively mild, which had been optimized by the research group in a previous study. The purpose of choosing mild pretreatment condition was to disrupt the wax layer while avoiding excess hemicelluloses degradation.

Chemical Composition Analysis

The HNO_3–ethanol cellulose, hemicellulose, Klason's lignin, and ethanol/benzene extractives contents of the raw and steamed exploded rice straw were analyzed in accordance with the procedures of Liu and Zhang (2020).

Particleboard Fabrication

Chitosan was solubilized in acetic acid (1.3%, w/v) under stirring at ambient temperature, and a stable chitosan-acetic acid solution (4%, w/v) was prepared. The solution was sprayed onto rice straw particles in a mixer. The addition amount of chitosan solid was 4%, 6%, and 8% based on the rice straw's oven-dried weight.

The rice straw particles were then manually formed into a mat of 350 mm by 350 mm in an aluminum frame. The mat was hot pressed at 3 MPa for 12 min to 4 mm of the target thickness. The hot press temperature was 200 ℃, and the target density of particleboard was 800 kg/m^3.

Particleboard Properties Test

The particleboards were sawn into test specimens and tested for density, internal bonding (IB), modulus of rupture (MOR), modulus of elasticity (MOE), and thickness swelling (TS) after 2 h water soaking in accordance with the China National Test Standard GB/T 17657 (1999). Analysis of variance (ANOVA) and Duncan's multiple tests were performed to analyze the data obtained with SPSS software (SPSS Inc., Version 19, Chicago, IL, USA). The p-value level for statistical significance was $P < 0.05$.

RESULTS AND DISCUSSION

Table 1 shows the chemical composition of rice straw before and after steam explosion pretreatment. As expected, SE pretreatment changed the rice straw's chemical composition. The results suggest that SE pretreatment substantially reduced the ash and ethanol/benzene extractives contents. The hemicellulose content was reduced from 23.9% in the raw rice straw to 16.6% in the steam exploded samples. The SE pretreatment also resulted in slightly higher cellulose and lignin proportional contents, which were beneficial to mechanical properties of the produced particleboard. These data implied that the SE pretreatment led to a substantial degradation of hemicellulose, ash and extractives. As extractives impede the penetration, and diffusion of chitosan adhesive through the surface of rice straw to form chemical and hydrogen bonds with cellulose and hemicellulose (Mantanis *et al.* 2018), the disruption of extractives from rice straw surface is anticipated to enhance the bonding strength between the rice straw and chitosan adhesive.

Table 1. Chemical Composition of Native and Steam Exploded Rice Straw

Sample	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Ethanol/toluene extractives (%)
Native	38.4	23.9	15.8	15.2	6.8
Steamed	43.9	16.6	16.5	12.2	5.2

The effects of SE pretreatment and chitosan loading on mechanical properties and water resistance of the particleboards are shown in Figs. 1 through 4. As expected, SE pretreatment improved the mechanical properties and water resistance of rice straw particleboards bonded with chitosan at every chitosan content level. The mechanical properties and water resistance increased as chitosan loading was increased.

Figure 1 shows the relationships between IB and SE pretreatment and chitosan content levels. The IBs of the particleboards made with steam exploded rice straw ranged between 0.26 and 0.49 MPa, suggesting a statistically significant enhancement ($P < 0.05$) in comparison with the particleboards made with native rice straw ranging between 0.23 and 0.33 MPa. The enhancement of IB should be ascribed to the partial elimination of the extractives and ash via the SE pretreatment, leading to improved penetration and diffusion of chitosan through the surface of rice straw to form chemical and hydrogen bonds with cellulose and hemicellulose (Inglesby *et al.* 2005; Li *et al.* 2011). As expected, the IBs of particleboards with addition of chitosan were enhanced significantly ($P < 0.05$) compared to the particleboards without chitosan. For example, the IB of the steam exploded rice straw particleboards containing 4% chitosan were 0.32 MPa as compared to the steam exploded rice straw particleboards without chitosan which was 0.26 MPa, increasing the IB by 23.1%. Notably, the IB strength of both SE pretreated and native rice straw particleboards increased as the chitosan loading was increased. The improvements in IB could be due to better distribution of chitosan on the rice straw particles.

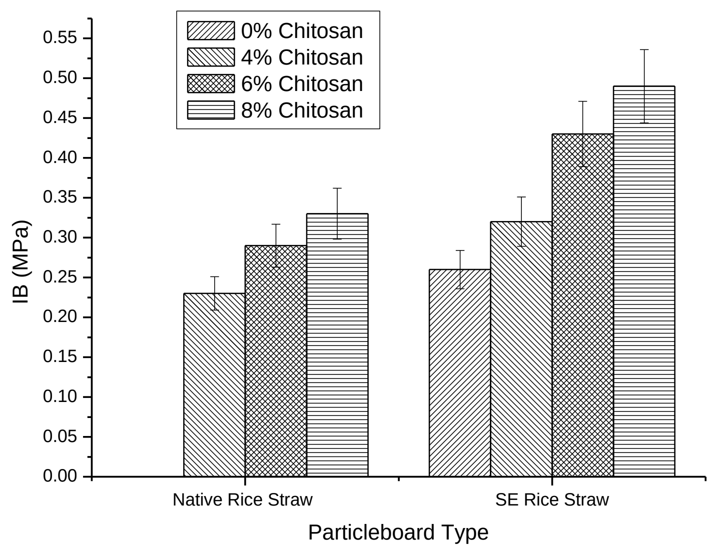

Fig. 1. Relationship between IB and SE pretreatment and chitosan content levels

Figures 2 and 3 present the relationships between MOR and MOE and SE pretreatment and chitosan content levels, respectively. The particleboards based on steam exploded rice straw had MOR values ranging from 4.73 to 18.3 MPa, whereas those made of native rice straw had the corresponding values ranging from 11.9 to 14.5 MPa. Similarly, the MOE for the steam exploded rice straw particleboards ranged from 826 to 2820 MPa and that of the particleboards with native rice straw was from 1430 to 2050 MPa. The statistically significant improvement ($P < 0.05$) of MOR and MOE could be attributed to enhanced amide linkages and hydrogen bonds between chitosan and SE pretreated rice straw particles. As can be observed, the addition of chitosan resulted in significantly improved MOR and MOE ($P < 0.05$). For example, the MOR and MOE values of the SE pretreated rice straw particleboards containing 4% chitosan were 14.3 MPa and 2170 MPa as compared to the particleboards without chitosan, which were 4.73 and 826 MPa, respectively. The MOR and MOE of both steam exploded rice straw and native rice straw particleboards bonded with chitosan were increased with the increase in the amount of chitosan.

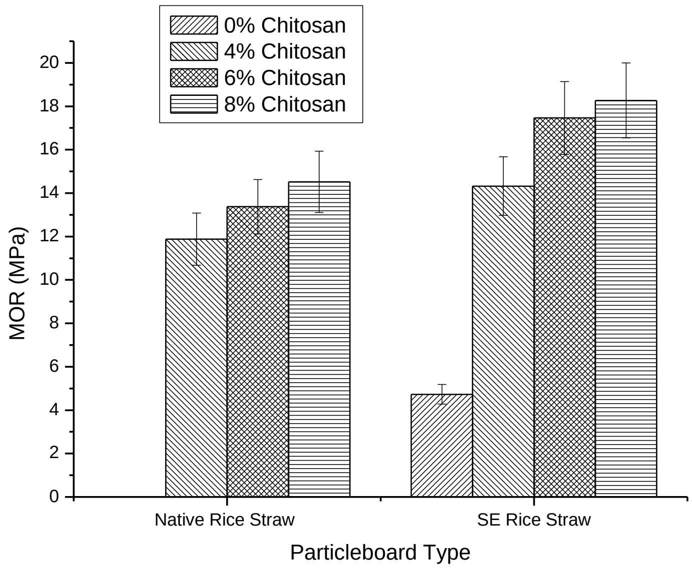

Fig. 2. Relationship between MOR and SE pretreatment and chitosan content levels

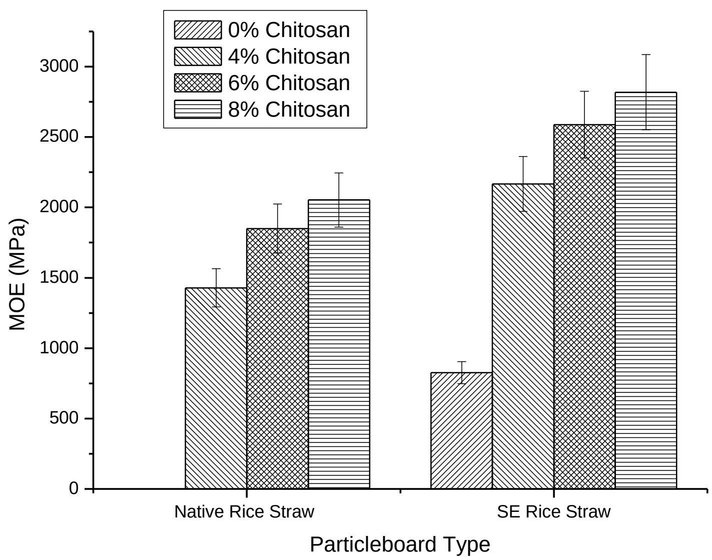

Fig. 3. Relationship between MOE and SE pretreatment and chitosan content levels

The relationships between 24 h TS and SE pretreatment and chitosan content levels are shown in Fig. 4. The 24 h TS values of the SE pretreated rice straw particleboards ranged from 13.3% to 48.6%, while those of the native rice straw particleboards ranged from 23.5% to 38.2%. The particleboards made with steam exploded rice straw exhibited statistically significant lower ($P < 0.05$) 24 h TS values compared with the particleboards made with native rice straw. The change was attributed to the partial removal of extractives and ash, thereby improving the compatibility between the rice straw and chitosan. Thus the water resistance and internal bonding strength improved. Compared with the steam exploded rice straw particleboards without chitosan, the 24 h TS of the steam exploded rice straw particleboards with chitosan were reduced significantly ($P < 0.05$). For example, the addition of 4% chitosan to the SE pretreated rice straw particleboards decreased the 24 h TS by 53.6%. The improvement of water resistance could be ascribed to the adhesiveness effect of chitosan which resulted in a tight structure, reducing the routes for water absorption (Huang *et al.* 2021). The 24 h TS of both SE pretreated and native rice straw particleboards bonded using chitosan decreased as the amount of chitosan are increased. An increase in chitosan content from 4 to 6 and to 8% led to a decrement of 24 h TS of the SE pretreated rice straw particleboards from 22.6 to 17.4 and to 13.3%, respectively, and decrease of 24 h TS of the native rice straw particleboards from 38.2 to 29.7 and to 23.5%, respectively. The observed results indicated that the water resistance of the particleboards was enhanced by increasing chitosan content.

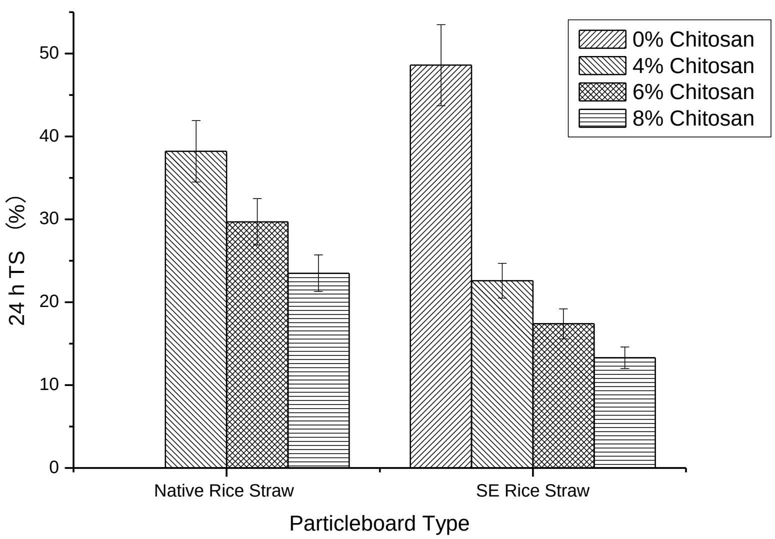

Fig. 4. Relationship between 24 h TS and SE pretreatment and chitosan content levels

CONCLUSIONS

1. Pretreating rice straw with steam explosion effectively reduced ash and extractives contents.
2. Single-layer particleboards from native and steam exploded rice straw bonded with chitosan were produced. A comparison of the mechanical properties and dimensional stability was conducted. The particleboards made of steam exploded rice straw showed significantly improved mechanical properties and dimensional stability compared to particleboards made of native rice straw.
3. Addition of chitosan led to remarkably enhanced mechanical properties and dimensional stability of rice straw particleboards. And the mechanical properties and dimensional stability of rice straw particleboards increased with increasing chitosan content

4. Future research should focus on the optimization of hot press technology, such as hot press temperature, time, pressure, and moisture content of raw material.

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