Surface Modification of Self-Adhesive Straw-Based Fiberboard *via* Alkali Treatment Combined with DES

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Self adhesion is a simple and effective bonding technique that can be used to produce environmentally friendly and green straw-based fiberboard (CLS) through deep eutectic-like solvent (DES) treatment. This article mainly introduces the use of DES composed of choline chloride and oxalic acid. DES is diluted with deionized water and straw is immersed in it, and finally dried into pretreated fiber raw materials. Fiber boards are prepared by adjusting the hot pressing parameters and the preset moisture content of straw itself for hot pressing solidification. The aim of this study was to investigate the effects of different processing parameters (hot pressing temperature and straw moisture content) on the microstructure, physical properties, and mechanical properties of CLS. Straw-based fiberboard heated at 180 ° C exhibited the best mechanical and water resistance performance. The fiberboard reached its highest mechanical performance at a moisture content of 50%. The bending performance of fiberboard produced at 180 °C reached 13.5 MPa, and compared with the board manufactured at 120 °C, the bending strength, tensile strength, and internal bonding strength increased by 320%, 224%, and 280%, respectively.

DOI: 10.15376/biores.19.4.9115-9130

Keywords: DES; Deep eutectic solvents; Surface treatment; Adhesive free; Fiberboard; Mechanical

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INTRODUCTION

The increase in global greenhouse gases and the depletion of fossil fuel resources have led to growing concerns over excessive fossil fuel consumption and global environmental issues. This has prompted efforts to seek sustainable carbon-neutral resources (Maiti *et al.* 2022). Extensive efforts have been made to develop and deploy renewable energy sources, with agricultural residues being rich and low-cost renewable raw materials available globally (Nasir *et al.* 2019). Converting renewable and bio-based straw into commercial chemicals is a promising strategy to reduce society's dependence on petrochemical production, thus significantly promoting sustainable development (Lou and Zhang 2022).

On the market, there are several types of adhesives, with the majority being based on formaldehyde resins such as phenol-formaldehyde or urea-formaldehyde resins. These synthetic materials have significant drawbacks, such as health or environmental issues, in addition to being non-biodegradable. Additionally, European Regulation 605/2014 classifies formaldehyde as a carcinogen, listing it under Category 1B (Domínguez-Robles *et al.* 2020). Deep eutectic-like solvents (DES) have unique advantages as green solvents for fiber surface treatment due to their low toxicity, biodegradability, and environmental friendliness. The term "eutectic-like" is used here in recognition of the fact that most such solvent mixtures are not used at their eutectic ratios. Different DES systems have significant differences in composition and effectiveness. The composition of DES typically includes hydrogen bond donors and hydrogen bond acceptors, such as the system composed of choline chloride and oxalic acid (Sert *et al.* 2018). The different components and ratios of DES will significantly affect the modification effect of fibers (Chen *et al.* 2023). In this study, the selection of an appropriate DES system was aimed at maximizing the mechanical properties and environmental benefits of straw fiberboard, while other DES systems may not be suitable for such applications (Vitrone *et al.* 2021). Therefore, exploring the potential of DES in straw fiberboard manufacturing may provide a new direction for green, efficient, and energy-saving non adhesive board manufacturing.

Nikvash *et al.* (2012) studied wheat protein as a bioadhesive and demonstrated that non-wood fiber materials can be used to produce adhesive free particleboard, which is superior to traditional plywood in all aspects. These fiberboards are superior to traditional plywood in terms of mechanical properties and water resistance, demonstrating the feasibility and superiority of self-adhesive technology. Jia *et al.* (2020) studied the method of preparing adhesive-free composite straw particleboard using straw and soybean as raw materials and inherent self-adhesiveness through cogrinding technology. Orthogonal experiments were conducted to investigate the effects of pressing time, temperature, and pretreatment time on the properties of these particle boards. The results showed that the optimal conditions included pressing time of 12 minutes/mm, temperature of 160 ° C, pretreatment time of 8 days, and addition of 30 to 50% by mass of sawdust, providing key parameters for the preparation of adhesive-free boards. Xia *et al.* (2021) used deep eutectic-like solvents (DES) to deconstruct the porous matrix of natural wood, dissolve lignin, and microfiber cellulose fibers into micro/nano fibers. This process has created a new type of lignocellulosic bioplastic with high tensile strength, water stability, UV resistance, biodegradability, and recyclability. This bioplastic not only can be naturally biodegraded, but it is also mechanically recycled to achieve material reuse. The study provides a theoretical basis for the treatment of straw materials through DES. Yang Yi *et al.* (2023) further demonstrated that DES treatment of straw materials with similar composition to wood fibers (lignin, cellulose, and hemicellulose) can effectively improve fiber reactivity and adhesive strength. The study demonstrated that DES treatment can achieve excellent physical and mechanical properties without the use of adhesives, providing key support for this research.

Therefore, it is hypothesized that biocomposite fiberboards prepared through a combination of alkali treatment and DES surface modification, followed by thermoforming, will exhibit enhanced mechanical properties due to the chemical modification of the fiber surfaces. The proposed mechanism is based on the ability of DES to disrupt the natural lignin-cellulose-hemicellulose matrix, increasing the exposure of hydroxyl (-OH) groups on the fiber surface. This increased availability of reactive sites promotes hydrogen bonding and other chemical interactions between fibers during thermoforming, contributing to improved bonding strength and overall mechanical performance (Liu *et al.* 2017). Different forms of raw materials (pretreatments) were used to demonstrate the effectiveness of the proposed method for manufacturing biocomposite fiberboards. The physical and chemical properties of fiberboards in different forms were analyzed. Finally, the mechanism underlying this preparation method was proposed. The findings of this study are significant for the efficient valorization of rice straw. Support for this hypothesis can be found in previous studies that have demonstrated the effectiveness of DES in modifying the surface chemistry of lignocellulosic materials (Sharma *et al.* 2022).

EXPERIMENTAL

Materials

The straw material was provided by Su Rui Agricultural Products (Lianyungang, China) through deep processing, with a size of about 20-mesh and a moisture content of 7%. It is a recycled material that is easily obtained during the post-processing stage of agricultural products. Choline chloride, oxalic acid, and sodium hydroxide used in this study were purchased from Macklin Biochemical Co., Ltd. (Shanghai, China).

Instrument

Equipment used in this research included a convection oven (PH-010A type), Shanghai Yiheng Scientific Instrument Co., Ltd., China; electronic balance (JM-A20001 Type), Chaoze Weighing Equipment Co., Ltd., Zhuji City, China; flat hot press machine (YLJ-HP300 type), Shenzhen Kejing Zhida Technology Co., Ltd., China; electronic universal testing machine (WCW-20 type), Jinan Tianchen Testing Machine Manufacturing Co., Ltd., China; scanning electron microscope (SEM, S-4800 model), Hitachi, Ltd., Japan; X-ray photoelectron spectroscopy (XPS, Nexsa), Thermo Fisher Scientific, USA; and Fourier transform infrared spectroscometer (FTIR, Nicolet iS20) from Thermo Fisher Scientific, USA.

Experimental Process

The procedure involved placing the straw in a 5% NaOH solution for 12 h and then rinsing with clean water. DES was prepared by mixing choline chloride and oxalic acid in a 1:1 molar ratio at 80 °C until the liquid became colorless uniformly. Next, the cleaned straw fibers were immersed in DES solution with stirring to ensure that the solution fully covered the fibers. Then, water was added with a volume 10 times that of DES solution, with continued stirring at 95 °C for 2 h (Xia *et al.* 2021). Subsequently, the fibers were thoroughly rinsed with running water to remove residual DES, and then the straw powder was dried in an oven.

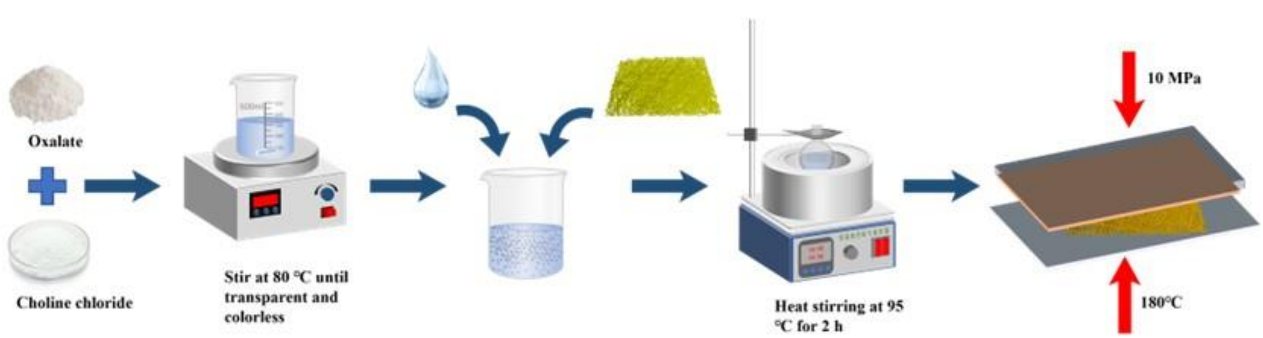

Fig. 1. Process flowchart for the preparation of straw-based fiberboard

Finally, the fiberboard was subjected to hot pressing at 120, 140, 160, 180, 200, and 220 °C for 10 min under a pressure of 10 MPa, maintaining a moisture content of 50%, to investigate the mechanical properties of the fiberboard at a constant moisture level. Optimal mechanical performance was found at 180 °C. Hence, subsequent experiments were conducted at this temperature. During hot-pressing, the mechanical properties of the fiberboards were evaluated under different moisture levels (30%, 40%, 50%, and 60%). Their water absorption measured, and characterized using techniques such as infrared spectroscopy (IR), scanning electron microscopy (SEM), and X-ray photoelectron spectroscopy (XPS).

Table 1. Sample Identification and Sequencing

Sample Number	Hot-Pressing Temperature (°C)	Preset Moisture Content (%)
CLS-T1	120	50
CLS-T2	140	50
CLS-T3	160	50
CLS-T4	180	50
CLS-T5	200	50
CLS-T6	220	50
CLS-H1	180	30
CLS-H2	180	40
CLS-H3	180	50
CLS-H4	180	60

Performance Testing

Mechanical properties testing

(1) Tensile testing was conducted according to GB/T 1040.4 (2006) using an electronic universal testing machine (WCW-20 electronic universal testing machine, Jinan Tianchen Testing Machine Manufacturing Co., Ltd., China) with a tensile speed of 2 mm/min. The tensile specimen had a length of 250 mm, a width of 25 mm, and a thickness of 4 mm. A minimum of 5 valid data points were recorded.

(2) The bending test was conducted according to ISO 178 (2010) using a controlled electronic universal testing machine (WCW-20 electronic universal testing machine, Jinan Tianchen Testing Machine Manufacturing Co., Ltd., China) to measure the three-point bending performance of the material. The specimen span ratio was 16:1, the width was 10 mm, and the specimen length was 20% longer than the span. The test speed was 2 mm/min, and a minimum of 5 valid data points are recorded.

Fourier transform infrared spectroscopy (FTIR)

Straw fibers and straw fibers treated with different methods were characterized by means of the KBr pellet method of FTIR. The test range was 400 to 4000 cm^{-1} with a resolution of 4 cm^{-1} and 32 scans.

Scanning electron microscopy (SEM)

In this experiment, the sample consisted of the fractured part after the tensile test. The experimental conditions were as follows: the fractured part was gold-plated twice using a Mini Coater (Supu Instrument Co., Ltd., Shenzhen, China), each time for 20 seconds. The SEM (scanning electron microscope SEM, S-4800 type, Hitachi, Japan) acceleration voltage was set to 5 kV and the magnification was 500 times.

Contact angle testing

A contact angle meter (Shengding Precision Instrument Co., Ltd, Dongwan City, China) was utilized to conduct static contact angle tests on fiberboards with various parameters. The testing process involves extruding tiny water droplets onto the board surface using a needle with an inner diameter of 0.03 mm. The contact angle was measured using the contact angle meter, and software fitting was used to obtain accurate water contact angles. The optimal contact angle of the board was studied by comparing the contact angles under different parameters.

X-ray photoelectron spectroscopy (XPS)

The XPS testing was performed using a Thermo Scientific K-Alpha X-ray photoelectron spectrometer. Samples were laid as thinly and flatly as possible on 1 cm × 1 cm adhesive tape, wrapped with aluminum foil, and pressed into a module. The excess aluminum foil around the sample was cut away, and the sample was affixed to the sample stage for testing. Al Kα radiation (1486.6 eV) was used to irradiate the sample, with the scanning ion beam spot size set to 400 µm. For full spectrum scans, the pass energy was 150 eV with a step size of 1 eV; for narrow spectrum scans, the pass energy was 50 eV with a step size of 0.1 eV. The C1s peak (284.8 eV) from surface contamination was used for calibration.

RESULTS AND DISCUSSION

Surface Morphology of Sheet Metal and its Testing Fixture

The surface of the board exhibited a pale yellow sheen, with a noticeable improvement in glossiness after DES treatment. The fiberboard, after being affected by water and hot-pressed, had a smooth and flat surface with no defects, making it less prone to processing issues and suitable for applications in fiber building materials such as facing panels and particle boards.

Fig. 2. Surface morphology of straw fiberboard (CLS)

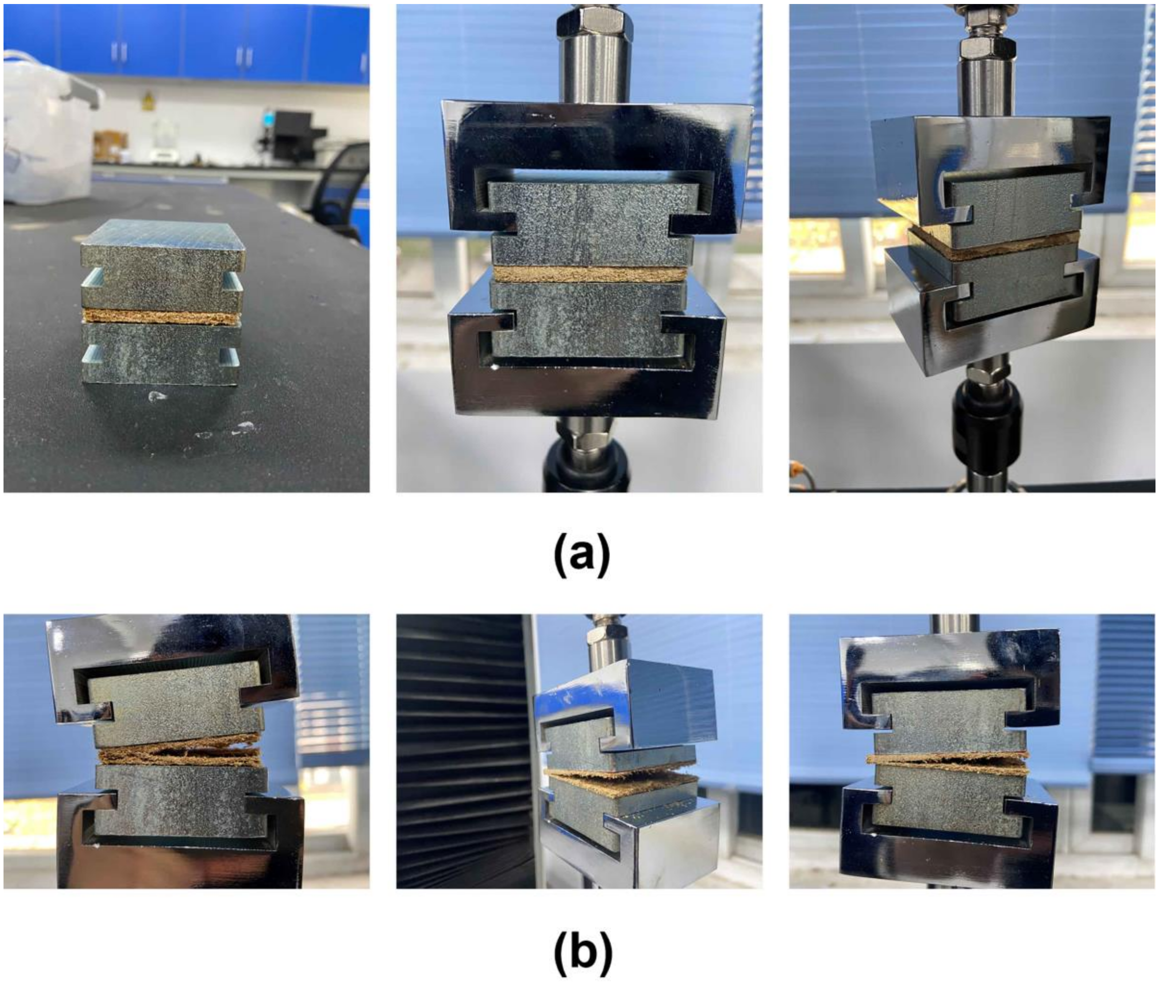

Fig. 3. Internal adhesive strength testing fixture and fracture morphology: (a) Internal bonding test fixture; (b) Fracture morphology of bonding inside fiberboard

The surface morphology of the board, influenced by the large amount of steam generated during hot pressing and the interaction with the straw surface, had undergone certain chemical reactions that enhance the mechanical properties of the fiberboard. Consequently, the board itself possessed good mechanical properties. Although this study did not conduct color measurements, the importance of quantitatively evaluating material color changes is recognized. Future research will consider using spectrophotometers to measure sample color, in order to better understand the effects of heat treatment on the surface chemical properties and appearance of materials. These data will provide support for further elucidating the properties of straw materials at different heat treatment temperatures.

Contact Angle

From Fig. 4(a), it is apparent that the contact angle decreased with increasing time after the sessile drop application. Figure 4(b) shows the variation in contact angle with time after the sessile drop application. The rate of change in contact angle slowed down as time passed, which indicates the hydrophobic nature of the composite material. Initially, the contact angle reached a maximum of 125° and decreases to 112° within 20 s. In Fig. 4(b), at hot-pressing temperatures of 180, 200, and 220 °C, the contact angle of the fiberboard was significantly higher compared to temperatures of 120, 140, and 160 °C. Temperatures above 180 °C induce reactions within the straw material, increasing the contact angle, which indicates enhanced surface hydrophobicity. This is related to the softening of lignin in straw materials at 180 °C, which is deposited on the surface of fibers through heating and pressure. The change in contact angle above 180 °C was slightly smaller than below 180 °C. It is speculated that temperatures above 180 ° C will promote the densification of the surface of straw materials, thereby enhancing their hydrophobic properties. As the moisture content increases, the contact angle initially increases and then decreases. At a moisture content of 50%, the water contact angle of straw fiberboard reached a maximum of 125.5 °. The experimental results show that when the moisture content of straw material was 50%, its mechanical properties reached an optimal state. This phenomenon may be due to the fact that at this moisture content, the moisture in the material was sufficient to promote good bonding between fibers, thereby increasing the density of the material. In addition, the increase in density also helps to improve the water resistance of the material surface.

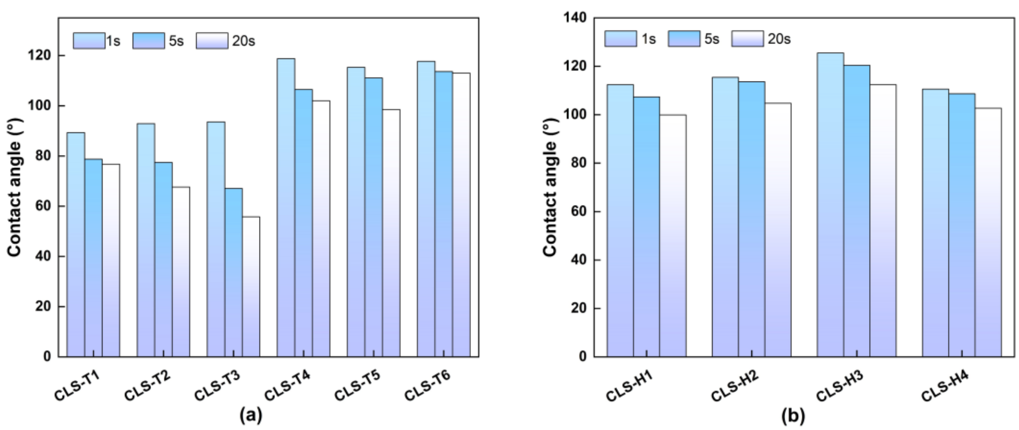

Fig. 4. The variation of contact angle over time under different preset parameters: (a) Changes in contact angle of fiberboard under temperature influence; (b) Changes in contact angle of fiberboard under the influence of moisture content

In addition to lignin softening and deposition, hydrophobicity may also be influenced by the migration of hydrophobic components, such as triglyceride fats, fatty acids, and waxes, to the material’s surface during the hot-pressing process. These hydrophobic monomers, which naturally exist in straw material, can migrate to the surface when exposed to high temperatures, further enhancing the surface’s hydrophobic properties. The temperature-induced migration of these materials, coupled with lignin deposition, may explain the increase in contact angle observed at higher pressing temperatures. These findings suggest that both temperature and moisture content significantly influence the surface characteristics and hydrophobicity of the straw fiberboard, with 180 °C being optimal for enhancing surface hydrophobicity due to lignin and cellulose melting and deposition.

Effect of Hot-pressing Temperature on the Mechanical Properties of the Plate

Figure 5 shows that the mechanical properties of fiberboard exhibited a trend of first increasing and then decreasing at different hot-pressing temperatures. However, considering the standard deviation in the experimental data, it was noticed that the change in tensile strength between 160 and 180 ° C did not show a simple increasing trend, but rather it exhibited a certain degree of dispersion. This indicates that changes in mechanical properties may not only be caused by reactions within straw fibers, but may also be influenced by other factors.

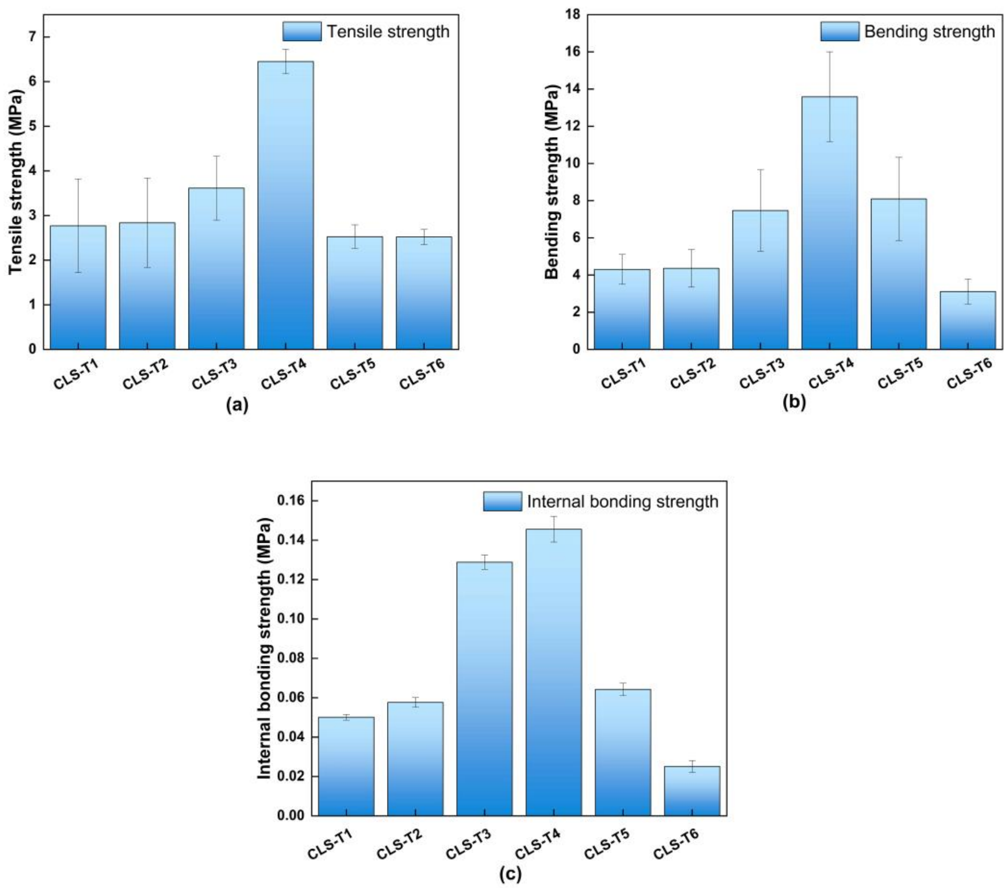

Fig. 5. Mechanical properties of fiberboard under temperature influence: (a) Changes in tensile strength of fiberboard; (b) Changes in bending strength of fiberboard; (c) Changes in internal bonding strength of fiberboard

At 180 ° C, although the tensile strength and internal bonding strength reached their maximum values, the performance improvement at this temperature may also be influenced by factors such as changes in fiber microstructure, internal stress distribution of the material, and external environmental conditions. These factors may have led to significant variability in the experimental results, resulting in a significant difference in tensile strength between 160 and 180 °C that is difficult to explain solely through the reaction of straw fibers. Nevertheless, it was observed that the bending strength of the sheet prepared at 180 °C still reached 13.5 MPa, which was significantly higher than the 4.2 MPa of the sheet prepared at 120 ° C, an increase of 3.2 times. This result may be related to the thermal decomposition and chemical reactions of lignin and hemicellulose during heating, which cause partial softening and flow of lignin and hemicellulose, filling the surface and cell walls of fibers, thereby forming chemical adhesion and physical mechanical entanglement between fibers. However, when the temperature exceeded 180 °C, the mechanical properties of the board significantly decreased, which may be due to the carbonization of straw based materials at high temperatures, resulting in a brown surface and partial collapse of the straw structure, ultimately reducing the overall mechanical properties of the board. Therefore, despite the significant difference between 160 °C and 180 °C, it was determined that 180 ° C was the optimal hot pressing temperature for preparing straw fiberboard. Further research is needed to better understand the underlying mechanisms behind the results in this range.

Effect of Moisture Content on Mechanical Properties of the Plate

As the moisture content of fiberboard increased from 30% to 60%, its mechanical properties exhibited a trend of initially increasing and then decreasing.

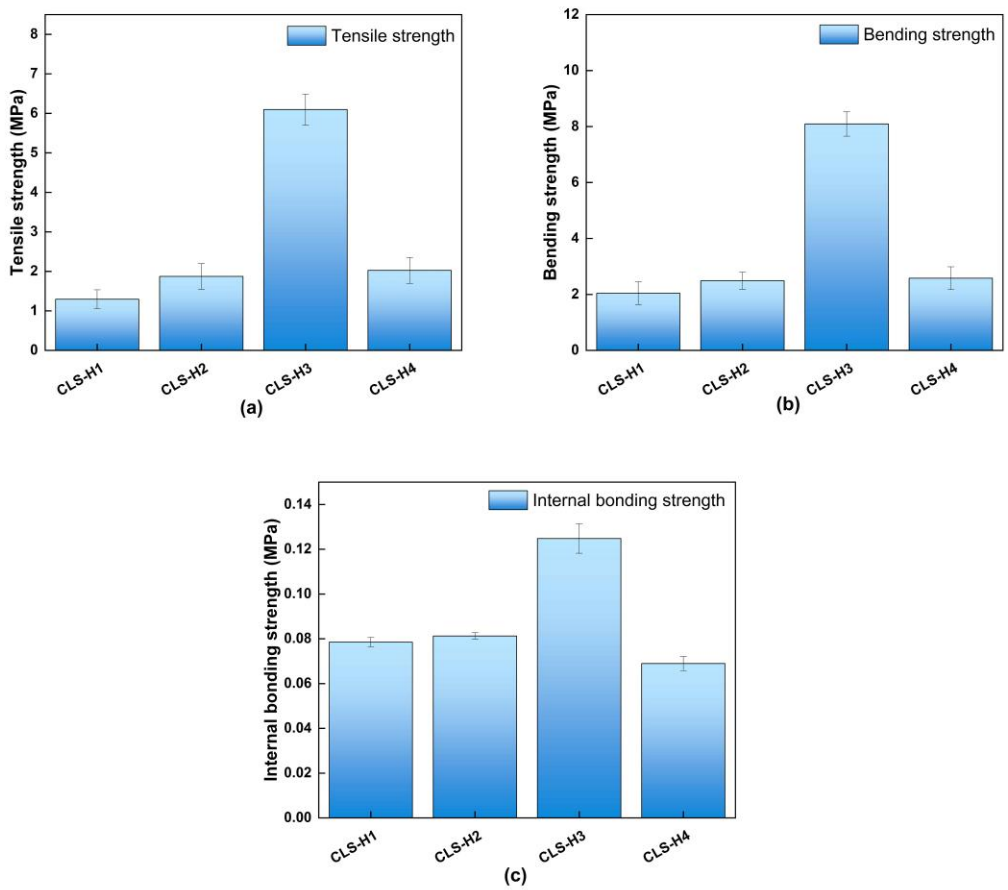

Fig. 6. The mechanical properties of fiberboard under the influence of moisture content: (a) Changes in tensile strength of fiberboard; (b) Changes in bending strength of fiberboard; (c) Changes in internal bonding strength of fiberboard

The tensile strength of the boards showed a significant increase, and the internal bonding strength also notably peaked when the moisture content was around 50%. This indicates that the mechanical performance of fiberboard was optimal after treatment at this moisture level. Under high temperature conditions, the moisture inside the board diffuses towards the surface and evaporates as it approaches the surface. This process significantly reduces the moisture content on the surface of the board, while the moisture content at the center of the internal particles is relatively high, forming a moisture gradient from the surface to the center. It is this gradient that triggers stress changes inside the sheet, leading to changes in mechanical properties.

As adsorption progresses and moisture content increases, enhanced diffusion of water molecules increases internal impregnation, intensifying chemical reactions during the hot-pressing reaction. This results in stronger adhesion. However, further increases in moisture content lead to internal vaporization during high-temperature hot pressing, creating internal voids in the boards. Therefore, beyond a certain moisture content threshold, the mechanical properties of the boards decline due to increased moisture content.

SEM Surface Appearance

Figure 7 shows the optical microscope and SEM morphology of fiberboard surfaces. Through optical microscopy, the surface of the fiberboard appeared smooth, even, and exhibited a certain gloss.

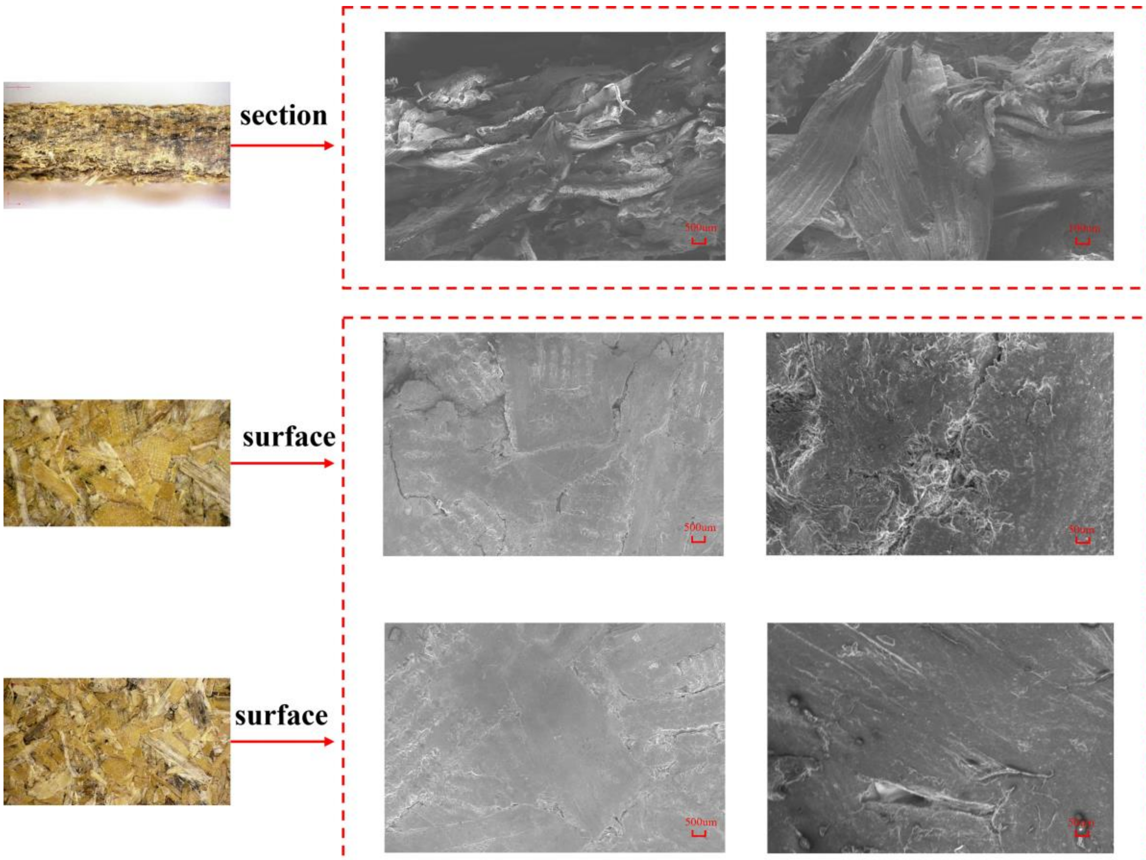

Fig. 7. Surface morphology of fracture and hot-pressing surface of straw-based fiberboard

After processing, straw fibers acquired a degree of hardness and underwent chemical adhesion reactions during hot-pressing. The SEM observation reveals that the hot-pressed surface of straw fibers was smooth and uniform. The smooth surface exhibited a random and highly anisotropic arrangement of straw fibers within the board, which contributed to enhanced strength and rigidity, advantageous for bearing loads and resisting bending. A smooth surface typically suggests good surface quality without significant pores or defects, enhancing the board's wear resistance and durability. The smooth and uniform surface of straw fiberboard reflected its good strength in tensile and internal bonding aspects. These attributes rendered it suitable for various load conditions due to its high rigidity, maintaining stable shape under stress without significant deformation. Smooth fiberboard surfaces also exhibited higher stability, being less prone to moisture-induced deformation. Mechanical grinding of straw fibers and DES pretreatment generate forces and friction, resulting in the layered structure of straw lignocellulose. Increased surface area of cellulose exposes more hydroxyl groups, facilitating molecular chain connections of cellulose, hemicellulose, and lignin in biomass nanocrystalline cellulose composites. Post-thermal pressing without adhesives reveals a dense layered structure in the cross-sections, with further water removal occurring after hot-pressing. As water evaporates, surface tension affects cellulose movement, bringing hydroxyl groups closer within cellulose molecules to less than 2.8 Å, ultimately forming hydrogen bonds (Yang *et al.* 2020), as shown in the cross-sectional view.

Infrared FTIR Analysis

The FTIR analysis was employed to analyze the chemical structure of the bio-composite materials. As shown in Fig. 8, the absorbance peak at 3430 cm^{-1} indicates the stretching vibration of -OH groups, while the peak at 2914 cm^{-1} corresponds to the stretching vibration of methyl and methylene (-CH_3 and -CH_2) groups. The absorbance peak at 1621 cm^{-1} represents the stretching vibration of C=O bonds in ketones and esters not conjugated with aromatic rings, and the peak at 1782 cm^{-1} indicates C=C stretching vibration conjugated with benzene rings.

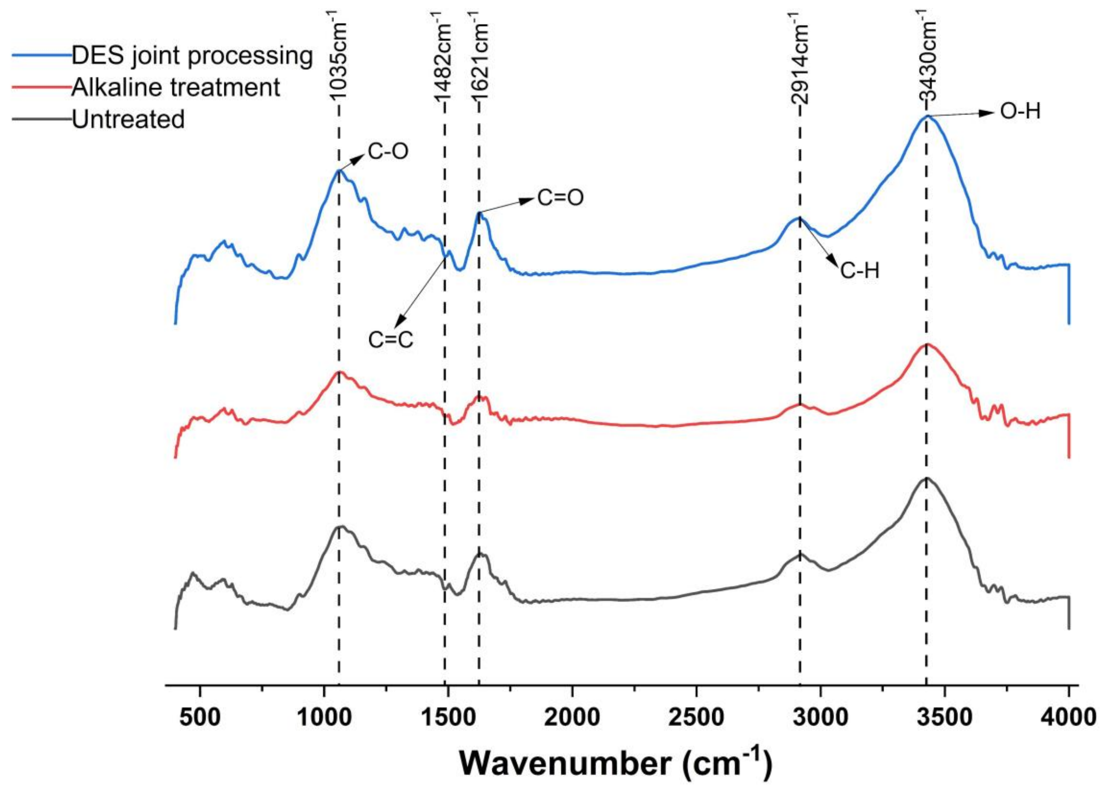

Fig. 8. FTIR analysis of straw fibers under different pretreatments

Table 2. Attribution of Absorbance Bands in the Infrared Spectrum of Wood Fibers

Wavelength (cm^{-1})	Band Attribution and Explanation
3650 to 3300	O-H stretching vibration
3000 to 2840	C-H stretching vibration (- CH3, - CH2)
1600	Carbon skeleton vibration of benzene ring (lignin) C-H bending vibration (- CH2 in lignin and polysaccharides)
1460	C-H bending vibration (- CH2 in lignin and polysaccharides) carbon skeleton vibration of benzene ring (lignin)
1373	C-H bending vibration (cellulose, hemicellulose)
1050 to 1030	C-O stretching vibration (cellulose, hemicellulose, lignin) stretching vibration of alkoxy bonds in acetyl groups (hemicellulose)
896	Glycoside bond vibration (cellulose)

Additionally, the peak at 1025 cm^{-1} corresponds to the stretching vibration of C-O-C bonds.The reduction of the C-H stretching vibration at 2914 cm^{-1} after alkali treatment can be attributed to the saponification reaction, which removes fatty acids from the surface of the fibers. This observation is consistent with the known effects of alkali treatment, where saponification leads to the removal of hydrophobic components such as fatty acids, resulting in a reduction of C-H bonds on the fiber surface.

On the other hand, DES treatment significantly enhanced the content of -OH groups compared to alkali treatment, and all chemical bond peaks showed enhancement, indicating an increase in chemical groups on the fiber surface and enhanced fiber reactivity as a result of DES treatment. This enhancement contributed to improved mechanical properties of adhesive-free fiberboard. The morphology and changes in peak shapes also reflect that green adhesive-free boards exhibited structural similarities and chemical functional groups similar to wood. During hot-pressing, the components of the cell wall undergo thermal softening and partial degradation under high temperature and pressure, causing the internal hemicellulose and lignin to migrate and deposit onto the outer layer of the biocomposite material. This results in the formation of a dense surface layer, which contributes to the enhanced mechanical properties and water resistance of the biocomposite material.

XPS Analysis

The XPS data were deconvoluted to show the contributions of different classes of carbon atoms, based on their covalent bonds. Based on Fig. 9, the surface analysis of original straw fibers shows that carbons of type A accounted for 43.1% of the peak area, type B for 41.45%, and type C for 15.41%. After DES treatment, the peak area percentages for types A, B, and C on the straw fiber surface changed to 48.2%, 29.9%, and 21.9%, respectively. From Table 3, it is evident that the combination of alkali treatment and heating decreased the contents of hemicelluloses and extractives, as these components were broken down and removed during the treatment process. Additionally, the DES treatment activated the straw fibers, leading to an increase in lignin and lignin derivatives, which enhanced the structural integrity and reactivity of the fibers. Qualitative FTIR analysis indicated that DES activation enhanced the number of active hydroxyl groups on the straw fiber surface. The oxygen atoms in these hydroxyl groups form not only covalent bonds with hydrogen atoms within the same hydroxyl group but also hydrogen bonds with hydrogen atoms of adjacent cellulose hydroxyl groups (Yang *et al.* 2020). This facilitates the formation of chemical bonds between fibers, where cellulose acts as an adhesive, aiding in the bonding between intermediates to form cellulose fibers in straw cell walls.

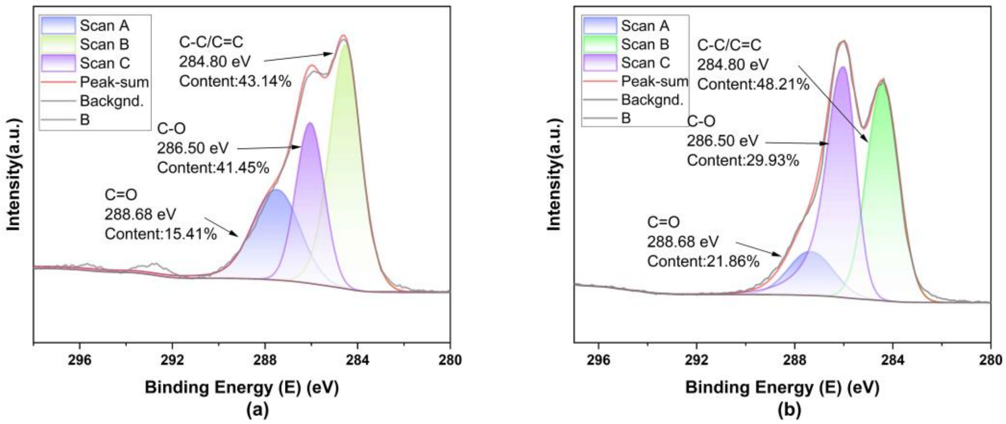

Fig. 9. XPS analysis of rice straw fibers under different pretreatment conditions: (a) XPS analysis of untreated straw fibers; (b) XPS analysis of straw fibers treated with DES

Table 3. Binding Patterns of C1s on the Surface of Wood Fibers

Category	Combination State	Structure	Main Sources	Electron Binding Energy
Type A	C atoms that are only connected to other saturated C or H atoms	$-C^*R_3$	Lignin and certain wood extracts with phenylpropane structural characteristics	285 eV
Type B	C atom connected only to one non carbonyl O atom	$-C^*R_2-O-$	C atoms connected to -OH in cellulose and hemicellulose molecules, and C atoms connected to hydroxyl or ether bonds in lignin	286.5 eV
Type C	C atom connected to one carbonyl O atom or two non carbonyl O atoms	$-C^*R=O$ $-O-C^*R_2-O-$	Acetal structure in hemicellulose molecules and carbonyl groups in lignin	288 eV

CONCLUSIONS

To optimize the process, environmentally friendly formaldehyde-free straw fiber self-bonding technology was employed to produce straw fiberboard. The study investigated the effects of straw fiber moisture content and hot-pressing temperature on board performance.

1. As the moisture content of straw fibers increased, the water resistance and mechanical properties of the boards initially improved and then decreased. Optimal water resistance and mechanical performance were achieved when the moisture content of straw reached 50%. Increasing the hot-pressing temperature also improved both water resistance and mechanical properties. Compared to boards manufactured at 120 °C, those prepared at 180 °C exhibited a bending strength of 13.5 MPa, marking increases of 320% in bending strength, 224% in tensile strength, and 280% in internal bonding strength.
2. The mechanism involves DES-treated straw fibers, where cellulose is exposed with more active hydroxyl groups. DES, composed of choline chloride and oxalic acid, acted as both a hydrogen bond donor and acceptor. The manufacturing process did not include any added adhesive, simplifying production and enhancing efficiency. Eliminating adhesives reduces exposure to harmful chemicals, minimizing associated health and safety risks for both production processes and end users. This approach proves beneficial across production and final application stages.
3. Future work will aim to further investigate the water resistance of the boards by conducting water absorption and thickness swelling tests. These tests will help assess the role of hydrogen bonding in maintaining board integrity under wet conditions. Should the boards demonstrate a significant loss of structural integrity when exposed to water, it will suggest that additional bonding mechanisms, beyond hydrogen bonds, are crucial in enhancing water resistance. This line of research could provide deeper insights into the bonding mechanisms involved in adhesive-free fiberboard production and guide improvements in future formulations.

ACKNOWLEDGMENTS

The author thanks the Key Research and Development Plan Project of Wuhu City (2023yf121) and Educational Commission of Anhui Province of China (2024AH050100).

Author Contributions

Conceptualization, Fangtao Ruan and Chenguang Kan; Methodology, Fangtao Ruan; Validation, Cheng Kang; Formal analysis, Fangtao Ruan; Survey, Hao Wu and Xin Liu; Drafting initial draft, Chenguang Kan; Writing review and editing, Fangtao Ruan and Yi Sun; Supervise Fangtao Ruan; Project Management Yi Sun; Funding to obtain Fangtao Ruan. All authors have read and agreed to the published version of this manuscript.

Conflicts of Interest

The authors declare that there is no conflict of interest. The funders had no role inthe design of the study; the collection, analysis, or interpretation of data; the writing of the manuscript; or the decision to publish the results.

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Article submitted: July 9, 2024; Peer review completed: August 7, 2024; Revised version received and accepted: September 23, 2024; Published: October 15, 2024.
DOI: 10.15376/biores.19.4.9115-9130