

Orthogonal Optimisation and Interfacial Enhancement of Alkali and Silane Modified Wheat Straw/PLA Composites

Yuqing Wang

wangyuqing@student.usm.my

Universiti Sains Malaysia

Fangmin Yuan

Universiti Sains Malaysia

Zhonghua Yang

Hebei University of Science and Technology

Shilong Zheng

Hebei University of Science and Technology

Huasheng Lai

Fujian Agriculture and Forestry University

Kangjie Sun

Hebei University of Science and Technology

Siti Suhaily Surip

Universiti Sains Malaysia

Article

Keywords: wheat straw/PLA composites, orthogonal hot-pressing optimisation, silane coupling agent, alkali treatment, interfacial adhesion

Posted Date: September 11th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10799022/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Orthogonal Optimisation and Interfacial Enhancement of Alkali and Silane Modified Wheat Straw/PLA Composites

YuqingWang^{a,*} FangminYuan^a ZhonghuaYang^b ShilongZheng^b Huasheng Lai^c
Kangjie Sun^{b,*} Siti Suhaily Surip^{a,*}

^a School of the Arts, Universiti Sains Malaysia (USM), 11800 Penang, Malaysia

^b School of Civil Engineering, Hebei University of Science and Technology, Shijiazhuang, Hebei 050018, China

^c College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, Fuzhou 350000, China

Correspondence Author:

Siti Suhaily Surip, Email: suhaily@usm.my

Kangjie Sun, Email: sunkangjie0606@sina.com

Abstract

To promote the value-added utilisation of agricultural residues and reduce dependence on petroleum-based materials, wheat straw/poly(lactic acid) biocomposites were prepared, and the hot-pressing parameters were optimized while the effects of alkali and silane surface treatments were comparatively evaluated. An $L_9(3^3)$ orthogonal design was employed to investigate the effects of temperature, pressure, and holding time on the tensile, flexural, and impact strengths of WS/PLA composites containing 40 wt% wheat straw and 60 wt% PLA. Range analysis and ANOVA showed that pressure had the greatest influence on tensile and flexural strength, whereas temperature was the dominant factor affecting impact strength. The optimal hot-pressing conditions were determined to be 180 °C, 14 MPa, and 20 min. Under these conditions, wheat straw was treated with 2 wt% NaOH or KH560. Both treatments improved the mechanical properties of the composites, with KH560 treatment producing the greatest enhancement. The tensile, flexural, and impact strengths of the KH560-treated composites reached 19.81 MPa, 29.25 MPa, and 18.84 kJ m⁻², respectively, corresponding to increases of 14.9%, 16.96%, and 21.09% compared with the untreated composites. FTIR and SEM analyses indicated that alkali treatment removed surface impurities and increased fibre roughness, whereas KH560 treatment altered the surface chemical environment and produced a denser fibre-matrix interface. These results demonstrate that combining optimized hot-pressing conditions with KH560 surface modification effectively improves the interfacial adhesion and mechanical performance of WS/PLA composites, providing a feasible route for the value-added utilization of agricultural residues.

Keywords

wheat straw/PLA composites; orthogonal hot-pressing optimisation; silane coupling agent; alkali treatment; interfacial adhesion.

1. Introduction

Conventional petroleum-based polymers are generally resistant to microbial degradation and may persist in the environment for prolonged periods, resulting in increasing concerns regarding plastic accumulation and associated ecological impacts. Consequently, the development of biodegradable and bio-based alternatives has become an important research direction in materials science [1,2]. Poly(lactic acid) (PLA) is a biodegradable aliphatic polyester derived from lactic acid and has attracted considerable attention because of its good mechanical properties, biocompatibility, and processability [3,4]. Nevertheless, its relatively low toughness, limited heat resistance, and comparatively high production cost restrict its broader application [4-6]. Incorporating natural plant fibres into PLA is considered an effective strategy for reducing material costs and improving the stiffness and sustainability of PLA-based composites. Natural fibres offer several advantages, including renewability, low density, low cost, biodegradability, and high specific mechanical properties [7-9].

Wheat straw is an abundant agricultural residue, but a considerable proportion remains underutilized or is disposed of through open burning, which causes resource loss and contributes to pollutant and greenhouse-gas emissions [10-12]. Converting wheat straw into reinforcement for biodegradable PLA composites therefore provides a potential route for its value-added utilization [13]. Wheat straw is mainly composed of cellulose, hemicellulose, and lignin [14]. However, its heterogeneous surface chemistry, including hydroxyl-rich polysaccharides, waxes, extractives, lignin, and inorganic silica, may result in poor wetting and weak interfacial adhesion with the PLA matrix [14,15]. These interfacial limitations can lead to fibre agglomeration, void formation, and inefficient stress transfer, thereby restricting the mechanical performance of wheat straw/PLA composites. Various surface modification strategies have been developed to improve the compatibility between lignocellulosic fibres and PLA. Alkali treatment can partially remove waxes, lignin, hemicellulose, and other non-cellulosic components while increasing fibre-surface roughness and mechanical interlocking with the polymer matrix [16,17]. Silane coupling agents can modify the chemical environment of the fibre surface and promote stronger interactions between lignocellulosic fillers and PLA [18-20]. Recent studies have further demonstrated that KH560 and related silane agents can improve fibre dispersion, interfacial adhesion, and the mechanical performance of natural-fibre/PLA composites [21-24]. In addition to surface treatment, hot-pressing parameters such as temperature, pressure, and holding time strongly influence PLA melting, fibre wetting, void elimination, composite consolidation, and possible thermal degradation [25,26].

Although both processing optimization and fibre surface modification have been widely investigated, their combined effects on wheat straw/PLA composites under a unified experimental framework remain insufficiently clarified. Therefore, this study employed an $L_9(3^3)$ orthogonal design to evaluate and optimize the effects of hot-pressing temperature, pressure, and holding time on the tensile, flexural, and impact properties of WS/PLA composites. Under the optimized processing conditions, untreated, 2 wt% NaOH-treated, and KH560-treated wheat straw fibres were

comparatively investigated. Mechanical testing, FTIR spectroscopy, and SEM characterization were subsequently conducted to clarify the effects of the two modification methods on fibre-surface chemistry, interfacial morphology, and composite performance.

2. Materials and methods

2.1. Materials and Equipment

Wheat straw (WS), with the wheat ears removed, was collected from Shijiazhuang, Hebei Province, China. Poly(lactic acid) (PLA, grade 4032D) was supplied by NatureWorks LLC, USA. The silane coupling agent γ -glycidoxypolytrimethoxysilane (KH560), anhydrous ethanol (analytical grade, $\geq 99.5\%$), and hydrochloric acid (analytical grade, 37 wt%) were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China).

The main instruments used in this study included a forced-air drying oven (DHG-9140A, Shanghai Yiheng Scientific Instrument Co., Ltd., Shanghai, China), a constant-temperature magnetic stirrer (DF-101S, Shanghai Lichenbang Scientific Instrument Co., Ltd., Shanghai, China), a benchtop pH meter (PHS-3C, Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China), an ultrasonic disperser (Dingtai Instrument Technology Co., Ltd., China), a circulating-water vacuum pump (SHZ-D(III), Gongyi Yuhua Instrument Co., Ltd., Gongyi, China), an analytical balance (ME204E, Mettler Toledo, Switzerland), a hot press (PCH-600H, Changsha Miqi Instrument Equipment Co., Ltd., Changsha, China), an electronic universal testing machine (CMT-6104, MTS Systems (China) Co., Ltd., Shenzhen, China), a pendulum impact tester (JZ-JZL-15D, Shenzhen Jinzhun Instrument Equipment Co., Ltd., Shenzhen, China), a Fourier-transform infrared spectrometer (Nicolet iS5, Thermo Fisher Scientific, USA), and a scanning electron microscope (JSM-IT300, JEOL Ltd., Japan).

2.2. Pretreatment of raw materials

The wheat straw was thoroughly rinsed with deionized water to remove surface impurities, dried, and crushed for 10 min. It was then further dried in an electric oven at 80 °C for 6 h and stored in sealed bags until use. PLA (4032D) was dried in a constant-temperature oven at 40 °C for 8 h and subsequently stored in sealed bags [27].

2.3. Experimental Methods

Fig.1 summarizes the overall experimental workflow of this study. First, an $L_9(3^3)$ orthogonal design was employed to investigate the effects of hot-pressing temperature, pressure, and holding time on the tensile, flexural, and impact strengths of WS/PLA composites. Range analysis was used to evaluate the relative influence of each processing parameter, while analysis of variance (ANOVA) was performed to determine the statistical significance of the investigated factors and identify the optimal hot-pressing conditions. Subsequently, wheat straw was treated with either 2 wt% NaOH or the silane coupling agent KH560, and the resulting modified fibres were used to prepare WS/PLA composites under the optimized conditions. Finally, the mechanical properties of the composites were evaluated by tensile, flexural, and impact tests, while FTIR and SEM analyses were conducted

to characterize changes in the chemical structure, surface morphology, and fibre-matrix interfacial interactions induced by the different surface treatments [20].

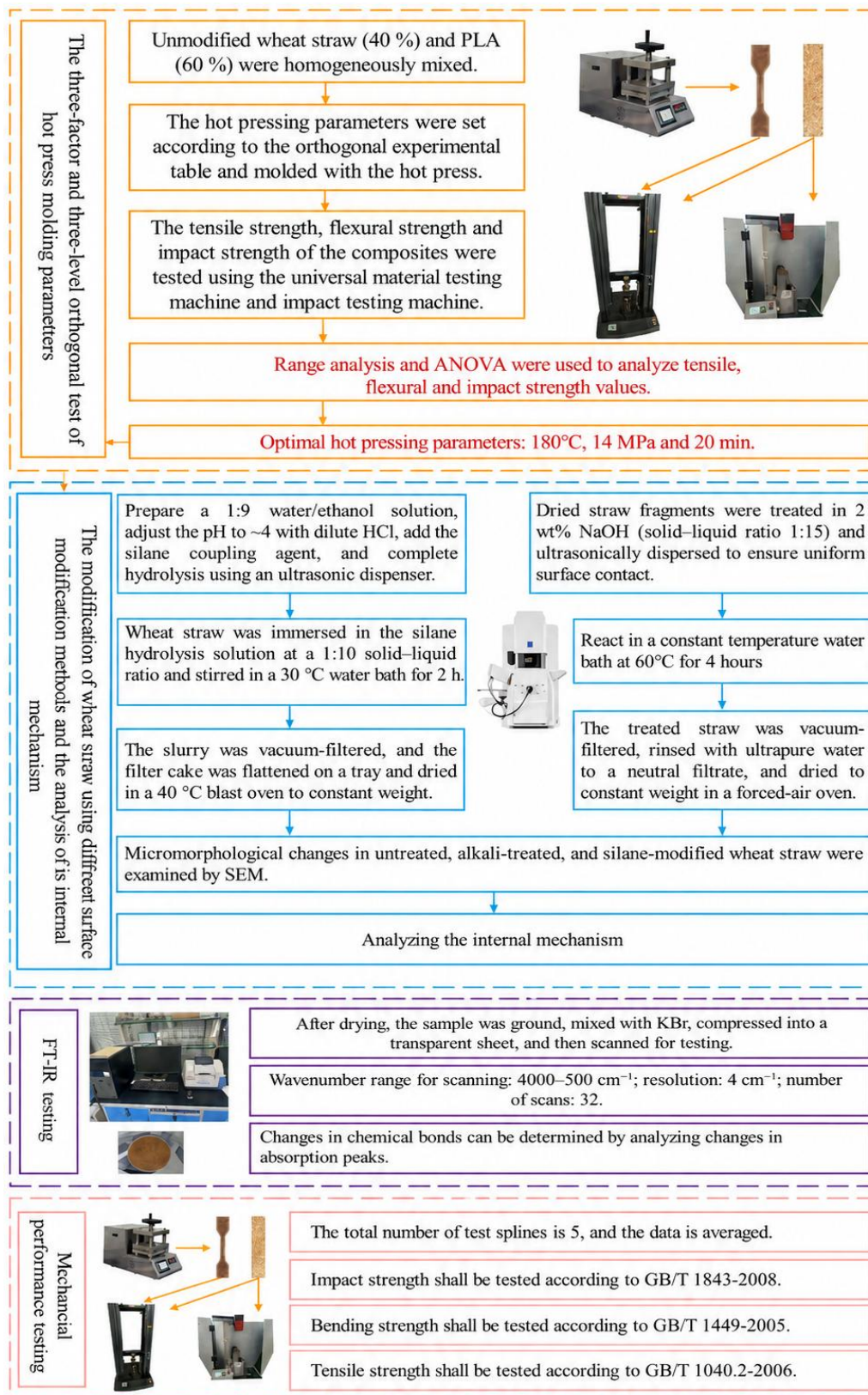


Fig. 1. The Flowchart of the Experiment.

2.3.1 Hot compression moulding method

Unmodified wheat straw and wheat straw modified with silane coupling agent were mixed evenly with PLA, put into two different moulds of 2mm thick, and pressed under control to get the required shapes. Fig. 2 shows the hot press machine, the moulds, and the materials used to mould the product. it gives an illustration of the hot press, the mould, and the moulded samples.

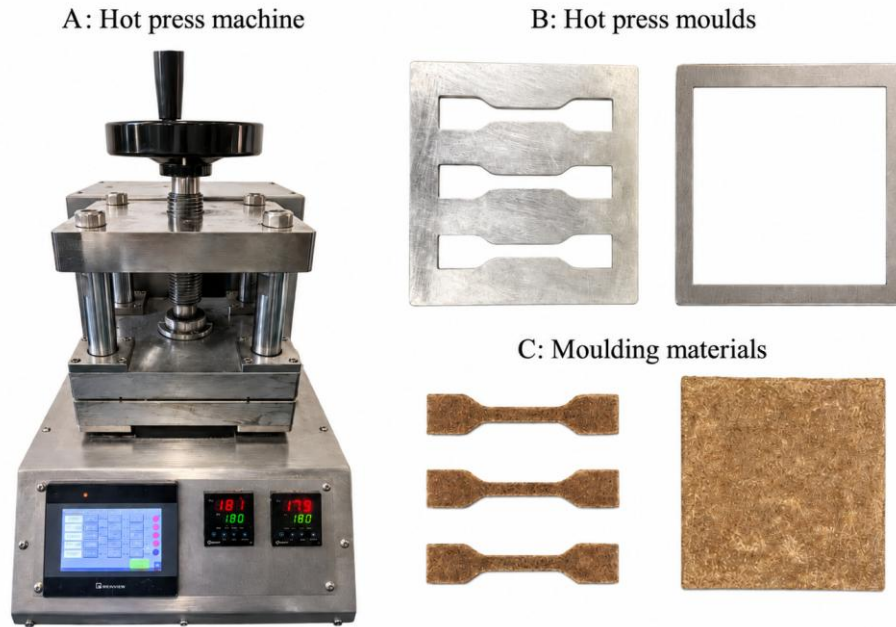


Fig.2. Hot press machine, moulds and moulding materials

2.3.2 Hot compression moulding parameter orthogonal experiment

The base formula used is 40% unmodified wheat straw and 60% PLA. A three-factor, three-level orthogonal experimental design (Table 1) is employed to investigate the effect of various hot press moulding parameters on the tensile, bending, and impact strength of the composites. To fully assess the effects of these factors, range analysis and ANOVA were used to determine the optimal hot press moulding conditions that enhance the overall performance of the composites [26].

Table1

Factors and levels used in the $L_9(3^3)$ orthogonal design.

Level	A: Temperature (°C)	B: Pressure (MPa)	C: Holding time (min)
1	170	10	15
2	180	12	20
3	190	14	25

2.4 Surface modification of wheat straw

The processing conditions for the silane coupling treatment and alkali treatment were independently selected according to their different modification mechanisms. Silane treatment mainly involves the hydrolysis of KH560 and its subsequent interaction with hydroxyl groups on the wheat straw surface, whereas alkali treatment removes waxes, lignin, hemicellulose, and other

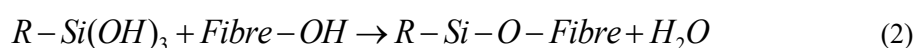
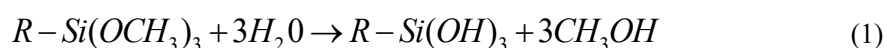
non-cellulosic components through dissolution and swelling. Therefore, the two treatments require different solid-to-liquid ratios, temperatures, and treatment times, and identical processing conditions would not be appropriate for both methods.

2.4.1 Silane coupling treatment

KH560 was selected as the silane coupling agent because its hydrolysable alkoxy groups can form silanol groups and subsequently interact with the hydroxyl-rich surface of wheat straw, while its epoxy functional group can enhance the interfacial compatibility between wheat straw and the PLA matrix [21-23]. Therefore, KH560 was used as a representative silane coupling agent in this study rather than being selected through a comparative screening of different silanes. Anhydrous ethanol and deionized water were mixed at a volume ratio of 9:1 to prepare the hydrolysis medium. KH560 was then added at a dosage of 4 wt% relative to the dry mass of wheat straw. The ethanol-rich medium improved the dispersion of KH560 and the wetting of the wheat straw surface, whereas the water fraction provided the necessary conditions for hydrolysis of the alkoxy groups [28,29]. A 0.03 mol L⁻¹ HCl solution was added dropwise under continuous pH monitoring until the solution reached pH 4. The amount of HCl added was determined by the target pH rather than by a fixed volume. The solution was subsequently ultrasonicated for 1 h to promote the hydrolysis of KH560.

The crushed wheat straw was then added to the hydrolysed solution at a solid-to-liquid ratio of 1:6 (g mL⁻¹). The mixture was continuously stirred in a water bath at 30 °C for 1 h to ensure sufficient impregnation and uniform contact between the hydrolysed silane and the fibre surface. The relatively mild treatment temperature was selected to promote controlled surface adsorption while limiting premature self-condensation of silanol groups [28,29]. Finally, the mixture was vacuum-filtered, and the collected solid residue was dried at 40 ± 1 °C to a constant mass in an electric drying oven. The detailed treatment procedure is illustrated in Fig. S1 of the Supporting Information.

Silane coupling modification proceeds through three main stages. First, during the hydrolysis stage, the methoxy groups of KH560 react with water under acidic conditions to form silanol groups, as described by Eq. (1) [28]. Subsequently, the hydrolysed silanol groups interact with the hydroxyl groups on the wheat straw surface through hydrogen bonding and condensation reactions. As shown in Eq. (2), dehydration between the silanol groups and fibre hydroxyl groups can form Si-O-C linkages, thereby grafting KH560 onto the fibre surface [28].



During the subsequent drying and hot-pressing processes, the remaining silanol groups may further undergo self-condensation to form Si-O-Si structures, while additional Si-O-C bonds can develop at the fibre surface [29]. These reactions establish a silane-derived interfacial layer that reduces the surface polarity of wheat straw and improves its compatibility and interfacial adhesion with the PLA matrix. Consequently, the modified fibres exhibit enhanced interfacial bonding and

improved mechanical performance of the resulting composites.

2.4.2 Alkali treatment

The pre-dried wheat straw fragments were immersed in a 2 wt% NaOH solution [16,17] at a solid-to-liquid ratio of 1:15. This relatively mild alkali concentration can effectively remove surface waxes, lignin, hemicellulose, and other non-cellulosic components while minimizing excessive degradation of the cellulose structure. The suspension was stirred and ultrasonically dispersed to ensure uniform contact between the fibres and the alkali solution, and was then maintained in a water bath at 60 °C for 4 h. The higher temperature of 60 °C was employed to enhance the penetration of the NaOH solution into the fibre structure and promote fibre swelling and the removal of waxes, lignin, hemicellulose, and other non-cellulosic components [17]. After treatment, the wheat straw fibres were separated by vacuum filtration and repeatedly rinsed with ultrapure water until the filtrate became neutral. Finally, the treated fibres were dried to a constant mass in a forced-air oven for subsequent use. The detailed alkali-treatment procedure is illustrated in Fig. S2 of the Supporting Information.

The main chemical effect of alkali treatment can be represented schematically by Eq. (3). As indicated in Eq. (3), NaOH interacts with hydroxyl-containing components on the wheat straw surface and facilitates the removal of waxes, lignin, hemicellulose, ash, and other surface impurities. This treatment exposes a cleaner cellulose-rich surface, increases fibre roughness, and promotes mechanical interlocking and interfacial adhesion with the PLA matrix [17,30]. The visual differences among the unmodified, alkali-treated, and silane-modified wheat straw samples are shown in Fig. 3.

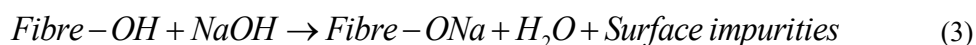


Fig.3. Appearance of wheat straw subjected to different surface treatments: (A) unmodified wheat straw, (B) alkali-treated wheat straw, and (C) silane-modified wheat straw.

2.5 Microstructural and chemical characterization

2.5.1 Fourier transform infrared spectroscopy (FTIR)

Fourier-transform infrared spectroscopy was performed using a Thermo Scientific Nicolet iS5 FTIR spectrometer. The samples were dried, finely ground, mixed with KBr, and compressed into transparent pellets. The spectra were recorded over the wavenumber range of 4000-500 cm^{-1} at a resolution of 4 cm^{-1} , with 32 scans collected for each sample. The resulting spectra were used to

compare changes in the characteristic functional groups of the untreated and modified samples and to evaluate their interfacial chemical interactions [31,32].

2.5.2 Scanning Electron Microscopy (SEM)

The surface morphology of wheat straw and the fracture morphology of the WS/PLA composites were examined using a JSM-IT300 scanning electron microscope. The composite specimens were cryogenically fractured in liquid nitrogen to preserve the fracture surfaces. Before observation, the samples were coated with an approximately 10 nm thick gold layer to improve electrical conductivity. SEM observations were conducted at an accelerating voltage of 10 kV and magnifications ranging from $\times 200$ to $\times 5000$.

2.6 Mechanical properties

The mechanical properties of the WS/PLA composites were evaluated through tensile, flexural, and impact tests. All specimens had a thickness of 2 mm, and their dimensions and geometries are shown in Fig. 4. Tensile and flexural tests were conducted using a universal material testing machine, whereas impact tests were performed using a pendulum impact tester. The corresponding testing instruments and experimental setups are provided in Fig. S3 of the Supporting Information. Five specimens were tested for each condition, and the results reported in Tables 4-8 represent the mean values.

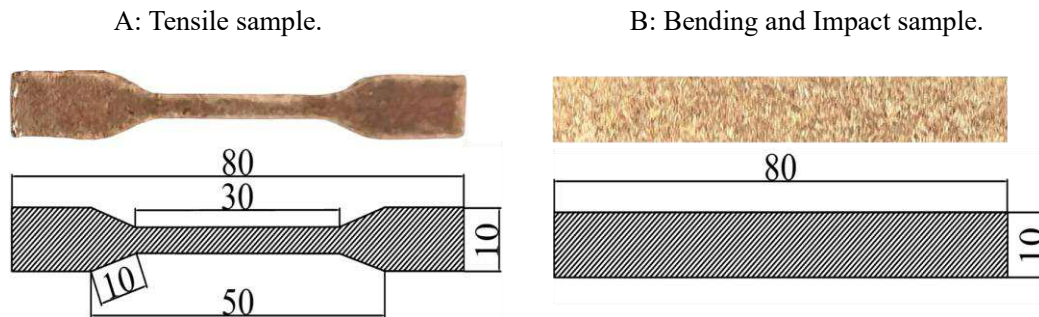


Fig.4. Tensile spline, bending and impact sample.

2.6.1. Tensile strength

Tensile properties were measured according to GB/T 1040.2-2006 at a crosshead speed of 5 mm min⁻¹. The specimen was mounted in the grips of the universal testing machine and loaded until failure. The maximum tensile load was recorded, and the tensile strength was calculated using Eq. (4):

$$\alpha_t = \frac{P}{bd} \quad (4)$$

where α_t is the tensile strength (MPa), P is the maximum tensile load (N), b is the specimen width (mm), and d is the specimen thickness (mm).

2.6.2. Bending strength

Flexural properties were determined according to GB/T 1449-2005 using a three-point bending configuration. The support span was 60 mm, and the crosshead speed was 2 mm min⁻¹. The

maximum load at failure was recorded, and the flexural strength was calculated using Eq. (5):

$$\sigma_f = \frac{3PL}{2bh^2} \quad (5)$$

where σ_f is the flexural strength (MPa), P is the maximum load (N), L is the support span (mm), b is the specimen width (mm), and h is the specimen thickness (mm).

2.6.3. Impact strength

Impact properties were measured according to GB/T 1843-2008 using a pendulum impact tester. The absorbed impact energy was recorded, and the impact strength was calculated using Eq. (6):

$$\alpha_3 = \frac{E}{bd} \times 10^3 \quad (6)$$

where α_i is the impact strength ($\text{kJ} \cdot \text{m}^{-2}$), E is the absorbed impact energy (J), b is the specimen width (mm), and d is the specimen thickness (mm).

3. Results and discussion

3.1. Analysis of orthogonal test results

This section uses the orthogonal experiment design method to determine the optimum hot-pressing parameters of wheat straw/polylactic acid WS/PLA composites, which can reach a whole system with the best mechanical performance. From the description of the preparation process, three process variables, A, B, and C, are heating temperature, pressurization pressure, and pressurization time. Factor each with 3 levels is adopted and $L_9(3^3)$ orthogonal array is used to produce experimental matrix. To limit the number of experiments, we search for the effect of all factors involved and their interaction, while taking the material as a whole. Factors & Levels are listed in table 3.

3.1.1. Extreme variance analysis of orthogonal tests

Table 2 presents the $L_9(3^3)$ orthogonal experimental design and the corresponding tensile, flexural, and impact strengths of the WS/PLA composites. The main effects of hot-pressing temperature, pressure, and holding time on the three mechanical properties are illustrated in Fig. 5. Range analysis was further performed using the mean response at each factor level, and the resulting K_1 , K_2 , K_3 , and R values are summarized in Table 3. A larger R value indicates a greater influence of the corresponding processing factor on the evaluated property.

For tensile strength, the R values of factors A, B, and C were 0.98, 0.55, and 0.22, respectively, indicating that their influence followed the order $A > B > C$. As shown in Fig. 5, the mean tensile strength increased markedly when the hot-pressing temperature increased from 170 to 180 °C, but decreased slightly at 190 °C. At 180 °C, the PLA matrix likely achieved sufficient melting and flowability to wet the wheat straw surface and promote effective stress transfer. A further increase to 190 °C did not provide an additional benefit and may have increased the risk of excessive thermal exposure of the PLA matrix and wheat straw. Increasing the pressure from 10 to 14 MPa continuously improved the tensile strength, which can be attributed to enhanced material

consolidation, reduced internal voids, and improved fibre–matrix contact. Holding time had the smallest effect, with the highest mean tensile strength obtained at 20 min. The range-analysis-predicted optimal combination for tensile strength was therefore A₂B₃C₂, corresponding to 180 °C, 14 MPa, and 20 min.

Table 2

L₉(3³) orthogonal experimental design and mechanical properties of WS/PLA composites.

No.	A / °C	B / MPa	C / min	Tensile Strength(MPa)	Bending Strength (MPa)	Impact Strength(kJ·m ⁻²)
1	170	10	15	9.10±0.21	14.20±0.31	6.35±0.16
2	170	12	20	9.75±0.24	15.10±0.36	6.90±0.18
3	170	14	25	9.45±0.20	15.50±0.34	7.05±0.17
4	180	10	20	10.10±0.27	15.00±0.39	7.65±0.22
5	180	12	25	10.45±0.23	15.75±0.42	7.80±0.20
6	180	14	15	10.70±0.26	16.30±0.45	8.05±0.24
7	190	10	25	9.85±0.22	14.80±0.33	6.80±0.19
8	190	12	15	10.20±0.25	15.90±0.41	7.40±0.21
9	190	14	20	10.55±0.24	16.10±0.43	7.55±0.15

For flexural strength, pressure exhibited the greatest effect, with the R values following the order B > A > C. The mean flexural strength increased from 14.67 MPa at 10 MPa to 15.97 MPa at 14 MPa, demonstrating that greater pressure improved the compactness of the composite and strengthened the mechanical interlocking and load transfer between wheat straw and PLA. The flexural strength also increased substantially as the temperature increased from 170 to 180 °C, followed by only a slight decrease at 190 °C. In contrast, increasing the holding time from 15 to 25 min resulted in only a small reduction in the mean flexural strength, confirming that holding time was the least influential factor. Accordingly, the predicted optimal combination for flexural strength was A₂B₃C₁, corresponding to 180 °C, 14 MPa, and 15 min.

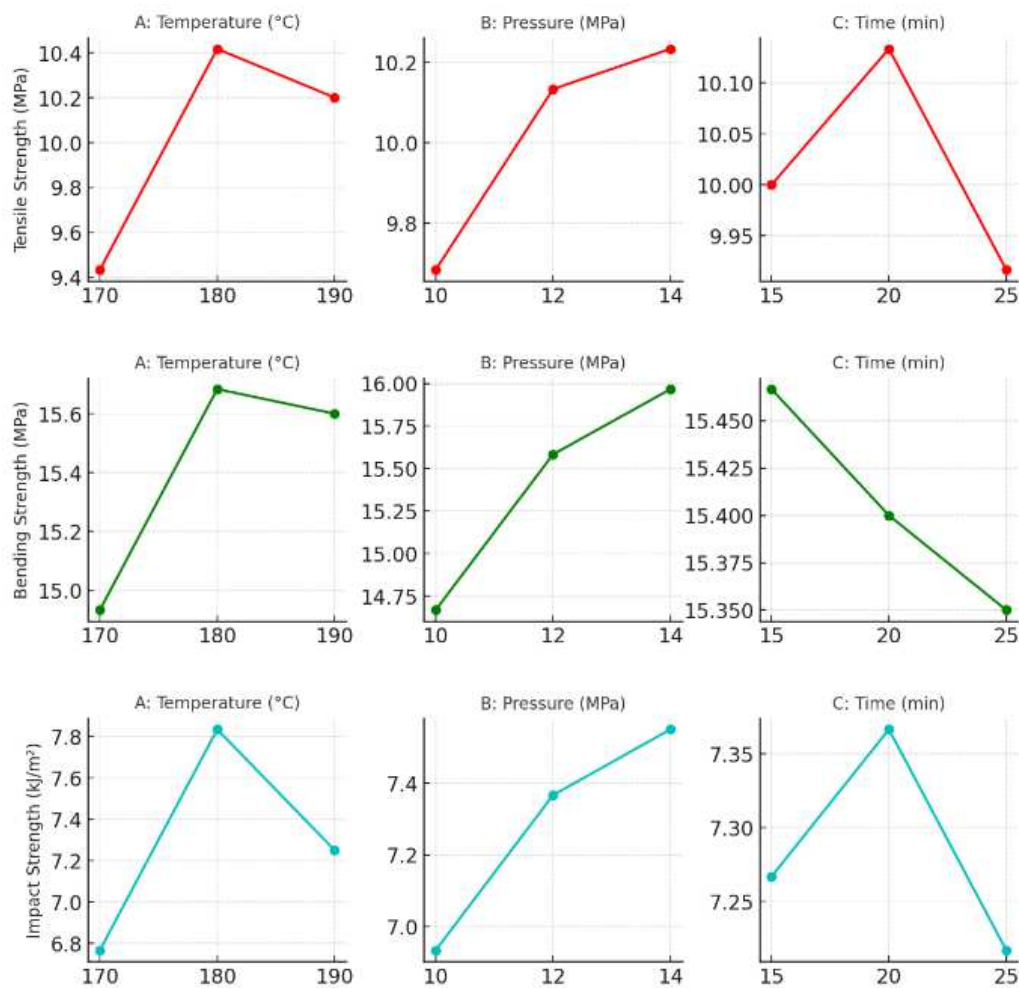
For impact strength, the R values of factors A, B, and C were 1.07, 0.62, and 0.15, respectively, giving an influence order of A > B > C. The impact strength reached its maximum mean value at 180 °C. An appropriate hot-pressing temperature facilitates PLA melting and fibre wetting, resulting in a more uniform interface capable of transferring and dissipating impact energy. However, the reduction observed at 190 °C suggests that excessive thermal exposure may weaken the energy-absorption capability of the composite. The impact strength increased progressively with pressure, indicating that improved consolidation and reduced porosity were beneficial to impact resistance. Holding time again showed only a limited influence, although 20 min produced the highest mean value. The predicted optimal factor combination for impact strength was therefore A₂B₃C₂.

Table 3

Range analysis results and optimal factor combinations for the mechanical properties of WS/PLA composites.

Property	K ₁	K ₂	K ₃	R	Factor Priority	Optimal Level Combination
Tensile Strength	9.43	10.42	10.20	0.99	B > A > C	B ₃ A ₂ C ₂
Bending Strength	14.93	15.68	15.60	0.75	B > A > C	B ₃ A ₂ C ₁
Impact Strength	6.77	7.83	7.25	1.06	A > B > C	A ₂ B ₃ C ₂

Overall, hot-pressing temperature was the dominant factor affecting tensile and impact strengths, whereas pressure exerted the greatest influence on flexural strength. Holding time had the smallest effect on all three properties. Considering the three mechanical responses together, A₂B₃C₂, corresponding to a hot-pressing temperature of 180 °C, a pressure of 14 MPa, and a holding time of 20 min, was selected as the overall optimal processing combination. Because this exact combination was not included among the original nine orthogonal runs, its performance should be verified through a confirmation experiment

**Fig.5.** Effect Curves of Orthogonal Test for WS/PLA Composites

3.1.2 Analysis of Variance for Orthogonal Experiments

Statistically verify the significance of factor effects using ANOVA to address problems with range analysis. Conduct ANOVA tests on the impact of heating temperature A, pressurization pressure B, and pressurization time C. Results are shown in Table 4. Analysis of variance is used to determine if there are differences among multiple average values; it allows qualitative judgments about the importance of each factor influencing material properties by comparing the ratio of the mean square (MS) of each factor to the MS of the error term (F-value).

Table 4

Orthogonal experimental variance analysis of WS/PLA composite materials

Index	Factor	Sum Of Square	DF	Mean Square (MS)	F Ratio	Fcritical value ($\alpha=0.05,2,6$)
Tensile Strength (MPa)	A(Temperature)	0.276	2	0.138	4.90	5.14
	B(Pressure)	2.268	2	1.134	40.19	5.14
	C(Time)	0.016	2	0.008	0.28	5.14
	Deviation	0.169	6	0.028	—	—
	Total	2.729	12	—	—	—
Bending Strength (MPa)	A(Temperature)	0.312	2	0.156	3.38	5.14
	B(Pressure)	1.445	2	0.723	15.70	5.14
	C(Time)	0.140	2	0.070	1.52	5.14
	Deviation	0.276	6	0.046	—	—
	Total	2.173	12	—	—	—
Impact Strength (KJ/m ²)	A(Temperature)	0.972	2	0.486	9.72	5.14
	B(Pressure)	0.342	2	0.171	3.42	5.14
	C(Time)	0.062	2	0.031	0.62	5.14
	Deviation	0.300	6	0.050	—	—
	Total	1.676	12	—	—	—

The results show that B, which is the applied pressure, has the greatest impact on the tensile and bending strength of the composite material. The corresponding F values are 40.19 and 15.70, respectively, both above the critical value $F_{0.05}(2,6)=5.14$. This indicates that, at a 95% confidence level, the applied pressure has a significant effect on the interfacial bonding and mechanical properties of the composite. It aligns with our previous highest R number from the range analysis, which suggests that pressure is important for increasing both the density and structure of our composite. On the other hand, heating temperature (A) has little effect on these properties. Although not at a very high level, it can still influence the melt flowability of PLA and improve fiber wettability. As for the pressing time (C), it has the least impact on the properties mentioned above.

Impact strength, A, is the most influential element. The F value is 9.72, which exceeds 5.14, indicating it has a significant impact. In other words, temperature indeed significantly affects a material's toughness and its ability to absorb energy. The pressure was B, showing the second largest

effect, while the duration of pressure was C, with only a slight effect. Generally, the order of influence of the three factors on different properties was as follows: tensile and bending strength: $B > A > C$; impact strength: $A > B > C$. The analysis of variance results align with the range analysis conclusion, confirming that the experiment data are reliable and the data trend is stable. The above also demonstrates the scientific validity and statistical significance of the chosen orthogonal design scheme.

3.1.3 Determination of Moulding Process for WS-PLA Composite Material

This study thoroughly compared and optimized the three main process parameters: heating temperature, pressurization pressure, and pressurization time, based on the range and variance analysis results of the referenced orthogonal experiments. From the experimental data, it is evident that pressurization pressure has the greatest effect on the moulding outcome, followed by heating temperature, with pressurization time having the least impact. Pressure influences material density and the quality of interfacial bonding, while temperature mainly affects the melt flowability of PLA and the uniformity of coating on wheat straw particles.

Combining considerations of experimental operability and energy consumption, we identified the optimal process parameters as a heating temperature of 180°C, a pressurization pressure of 14 MPa, and a pressurization time of 20 minutes (Experiment Number $A_2B_3C_2$). This setup ensures that the PLA matrix melts and mixes thoroughly while preventing excessive degradation of the polylactic acid due to heat and avoiding the burning (carbonization) of wheat straw fibers. Applying the correct pressurization duration helps control heat conduction and gas release inside, reducing the risk of bubbles and delamination in the final product.

The final process parameters were chosen based on the compatibility with the experimental equipment, the stability of material processing, and the practicality of shaping furniture parts afterward. This process plan will serve as a standard for producing composite material sheets in future research, making them a dependable source of raw materials. This approach will support consistent studies on the material's physical, thermal, and mechanical properties. Fig. 6 illustrates the optimized process flow for moulding WS/PLA composite material, clearly depicting the logical sequence of the experimental design and data analysis.

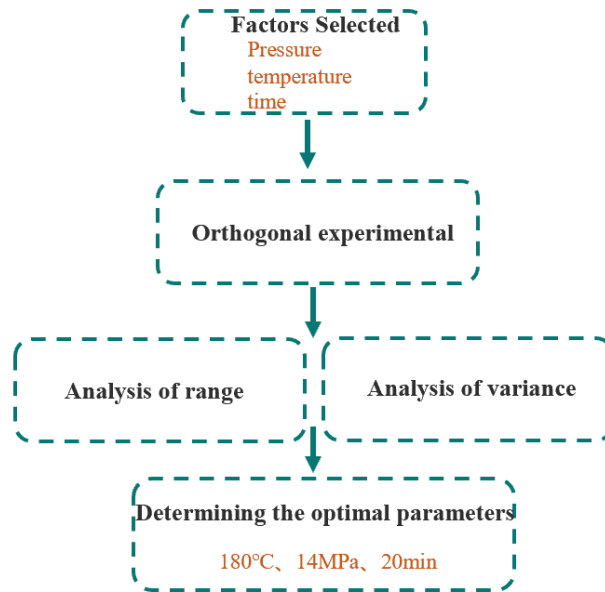


Fig.6. Optimisation process flow for moulding parameters of WS/PLA composite materials

3.2 Effects of different surface modification methods on the properties of WS/PLA composite materials

Under the optimised hot-pressing conditions, both NaOH and KH560 treatments improved the mechanical properties of the WS/PLA composites. However, KH560 treatment produced greater improvements than alkali treatment. The differences in mechanical performance were further interpreted using the FTIR and SEM results. It should be emphasised that the percentage increases reported in this section are relative to the untreated WS/PLA composite rather than neat PLA.

3.2.1 Analysis of Mechanical Performance Test Results

As shown in Fig. 7, the untreated WS/PLA composite exhibited tensile, flexural, and impact strengths of 17.24 MPa, 25.01 MPa, and 15.56 kJ m⁻², respectively. After NaOH treatment, these values increased to 18.52 MPa, 27.53 MPa, and 16.87 kJ m⁻², corresponding to improvements of 7.42%, 10.08%, and 8.42%.

The improvement after alkali treatment was mainly attributed to the partial removal of waxes, lignin, hemicellulose, and other surface components. This treatment produced a cleaner and rougher fibre surface, increased the contact area with PLA, and improved mechanical interlocking. Similar improvements after mild alkali treatment have been reported in natural-fibre/PLA composites [16,17]. KH560 treatment resulted in tensile, flexural, and impact strengths of 19.81 MPa, 29.25 MPa, and 18.84 kJ m⁻², representing increases of 14.90%, 16.96%, and 21.09%, respectively. The greater improvement indicates that KH560 produced a more compatible fibre-matrix interface. In particular, the larger increase in impact strength suggests that the modified interface delayed fibre-matrix debonding and crack propagation, allowing more impact energy to be absorbed before failure.

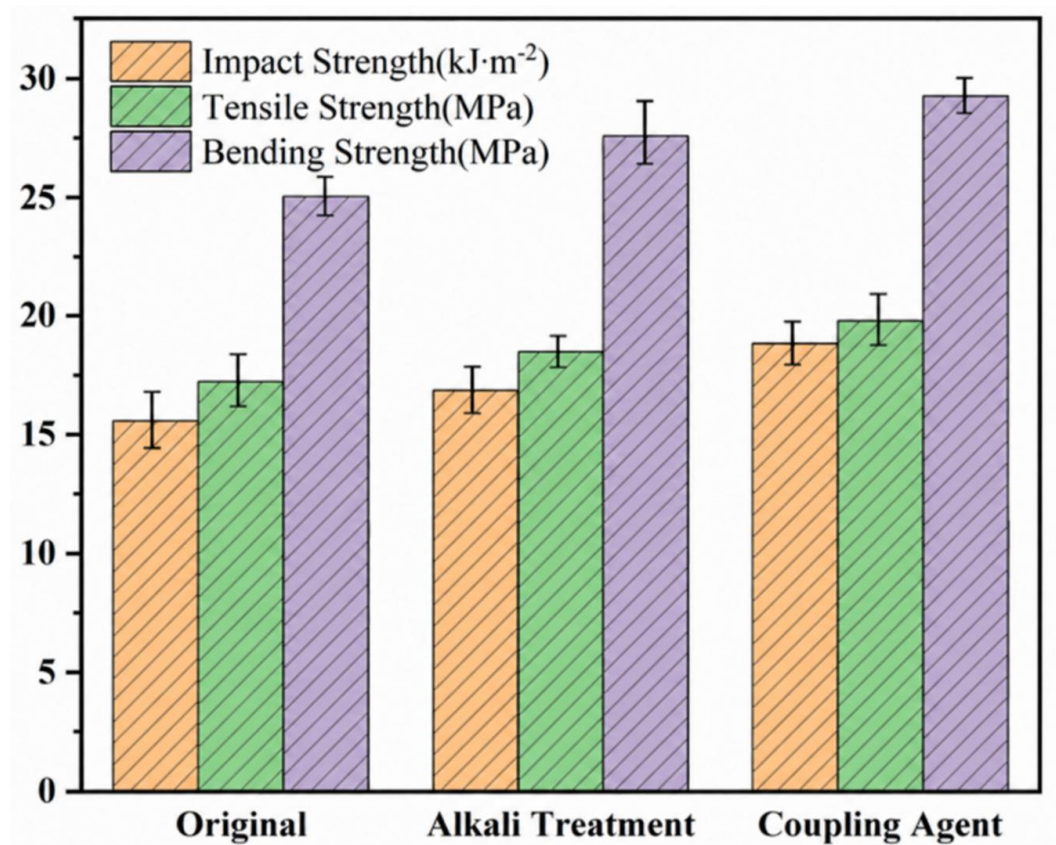


Fig.7. Effect of Different Surface Modification on the Properties of WS/PLA Composites

The mechanical results were consistent with the FTIR and SEM observations. Changes in the hydroxyl and silicon-containing FTIR regions suggested the deposition and condensation of hydrolysed KH560 on the wheat-straw surface. Meanwhile, the KH560-treated composite showed fewer interfacial gaps and fibre pull-out cavities than the untreated composite. Previous studies have similarly reported that silane treatment improves fibre dispersion, interfacial adhesion, and mechanical performance in wheat-straw/PLA and other lignocellulosic-fibre/PLA composites [18,19,21-23].

Overall, NaOH treatment mainly improved mechanical interlocking through surface cleaning and roughening, whereas KH560 treatment produced a stronger improvement in interfacial compatibility. Therefore, KH560 was more effective in enhancing the overall mechanical performance of the WS/PLA composites.

3.2.2 Analysis of Characterization Performance Test Results

3.2.2.1 Analysis of FTIR Test Results

Fig. 8 compares the FTIR spectra of untreated, NaOH-treated, and KH560-treated wheat straw. All samples showed a broad O-H stretching band at 3050-3700 cm⁻¹, a C-H stretching band near 2895 cm⁻¹, carbonyl-related absorption around 1740 cm⁻¹, and strong C-O/C-O-C vibrations near 1080 cm⁻¹. These bands are characteristic of cellulose, hemicellulose, and lignin in wheat straw [14,33].

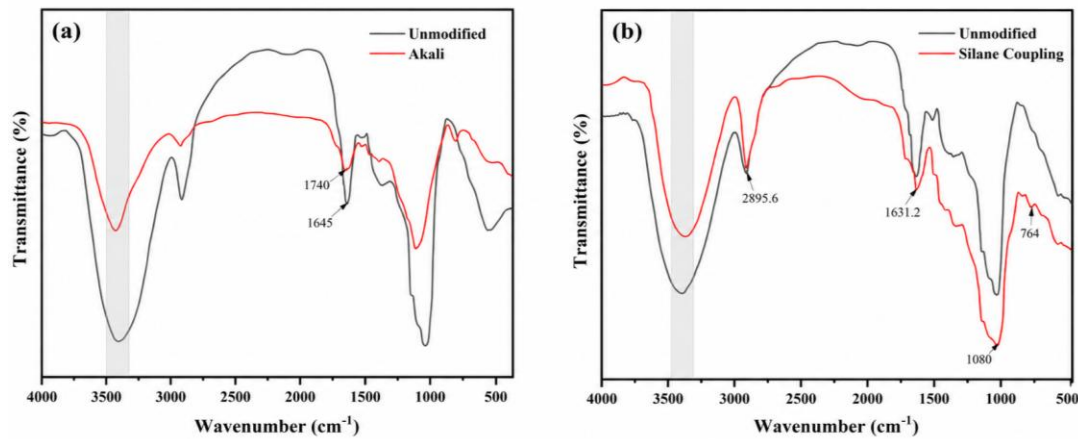


Fig.8. FTIR spectra of wheat straw before and after surface treatment: (a) untreated and NaOH-treated samples; (b) untreated and KH560-treated samples.

After NaOH treatment, the band near 1740 cm⁻¹ was markedly reduced, indicating the partial removal of hemicellulose, lignin, waxes, and other ester-containing surface components. The change in the broad O-H band reflects modification of the hydrogen-bonding environment and possible exposure of cellulose hydroxyl groups rather than the simple removal of hydroxyl groups. The persistence of the band near 1080 cm⁻¹ shows that the cellulose-rich structure remained after the mild alkali treatment [17,33].

Following KH560 treatment, the O-H band decreased and changed in shape, suggesting interaction between hydrolysed silanol groups and hydroxyl groups on the wheat-straw surface. The increased intensity and broadening near 1080 cm⁻¹, together with the more distinct band near 764 cm⁻¹, are consistent with additional Si-O-Si and silane-derived structures formed through hydrolysis and condensation [28,29]. However, the 1080 cm⁻¹ region also contains C-O/C-O-C vibrations from polysaccharides, and the band near 764 cm⁻¹ may partly originate from the intrinsic silica in wheat straw. Therefore, these peaks support KH560 deposition and condensation but do not independently prove the formation of specific Si-O-C covalent bonds [29,33].

Overall, the FTIR results indicate that NaOH treatment mainly altered the non-cellulosic surface components, whereas KH560 treatment changed the hydroxyl environment and introduced additional silicon-containing structures. When considered together with the mechanical and SEM results, these spectral changes support improved fibre-matrix interfacial adhesion after surface treatment [18,21,24].

3.2.2.2 Analysis of SEM Test Results

Fig. 10 compares the fracture-surface morphologies of the untreated, NaOH-treated, and KH560-treated WS/PLA composites. The images were examined mainly in terms of interfacial gaps, fibre pull-out, matrix residue, and void distribution. As shown in Fig. 10(A), the untreated composite exhibited visible gaps around the wheat-straw fibres, several pull-out cavities, and limited PLA residue on the exposed fibre surfaces. These features indicate that interfacial debonding and fibre

pull-out contributed to the fracture process, resulting in inefficient stress transfer between the wheat straw and PLA matrix. After NaOH treatment, fewer open gaps and pull-out cavities were observed, while the fracture surface became more compact, as shown in Fig. 10(B). The reduction in interfacial gaps after NaOH treatment was consistent with the expected surface cleaning and roughening effects of alkali treatment reported in previous studies. This morphological change was consistent with the moderate increases in tensile, flexural, and impact strengths after alkali treatment. The KH560-treated composite exhibited closer fibre-matrix contact, fewer visible voids, and more PLA residue attached to the fibre surfaces, as shown in Fig. 10(C). These observations suggest that fibre pull-out and interfacial separation were reduced. The more continuous interface was consistent with the greater improvements in mechanical properties, particularly the 21.09% increase in impact strength, because stronger interfacial adhesion can delay debonding and crack propagation under impact loading.

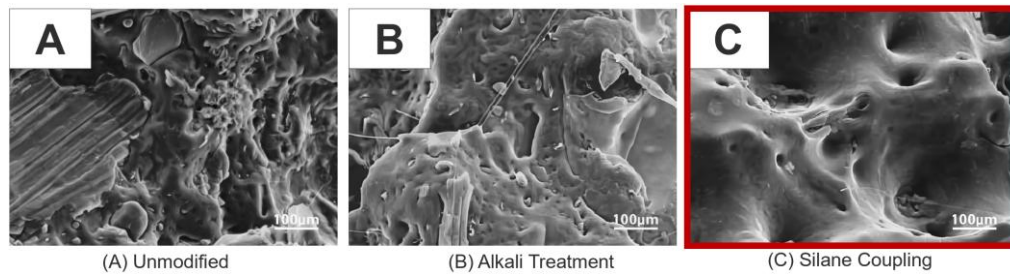


Fig.10. SEM images of different surface modifications

Overall, the SEM observations indicate that NaOH treatment mainly improved mechanical interlocking, whereas KH560 treatment produced a more compact and continuous fibre-matrix interface. However, SEM provides morphological evidence only and cannot directly confirm the formation of specific Si-O-C or other covalent bonds. The interfacial mechanism should therefore be interpreted together with the FTIR and mechanical results.

3.3 Proposed interfacial modification mechanism of silane-treated WS

A water-ethanol mixture with a mass ratio of 1:9 was first prepared as the hydrolysis medium. Ethanol improved the dispersion of KH560 and the wettability of the wheat straw surface, whereas water provided the reactant required for hydrolysis of the methoxy groups. The pH of the solution was adjusted to approximately 4 by the dropwise addition of dilute hydrochloric acid. Under these weakly acidic conditions, the hydrolysis of KH560 was promoted while excessive premature condensation of the resulting silanol groups was limited. KH560 and water were brought into sufficient contact during ultrasonic treatment. As shown in Eq. (7), the methoxy groups of KH560 underwent acid-catalysed hydrolysis to form silanol groups, while methanol was produced as a by-product.



In the reaction described by Eq. (7), protonation of the methoxy groups increases the

susceptibility of the silicon centre to nucleophilic attack by water. Consequently, the $-\text{OCH}_3$ groups are progressively replaced by $-\text{OH}$ groups, producing hydrolysed silanol species. Here, R represents the organofunctional glycidoxypyrpyl group of KH560. The corresponding molecular reaction process is illustrated by the ball-and-stick model in Fig. 11.

In general, the silane coupling process between KH560 and wheat straw fibre can be divided into three stages [28,29].

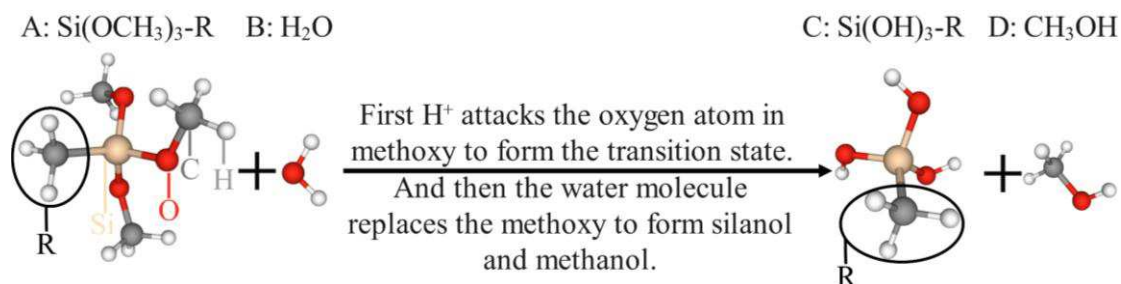
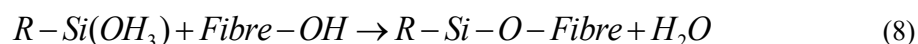


Fig.11. Hydrolysis of silane coupling agent.

Hydrolysis stage. Under weakly acidic conditions, the methoxy groups, $-\text{Si}(\text{OCH}_3)_3$, of KH560 react with water to form silanol groups, as described by Eq. (7).

(ii) Condensation and surface-grafting stage. The newly formed silanol groups can undergo self-condensation to form low-molecular-weight siloxane oligomers containing Si-O-Si structures. These silanol species can also adsorb onto the wheat straw surface through hydrogen bonding with the hydroxyl groups of the lignocellulosic components. During the subsequent drying and hot-pressing processes, condensation between the silanol groups and fibre hydroxyl groups may occur, forming Si-O-C linkages and releasing water. This surface-grafting reaction is schematically expressed by Eq. (8) and illustrated in Fig. 12.



In Eq. (8), Fibre-OH represents the hydroxyl groups present mainly in cellulose, hemicellulose, and lignin. The resulting silane-derived interfacial layer can reduce the surface polarity of wheat straw and strengthen its interfacial interaction with the PLA matrix.

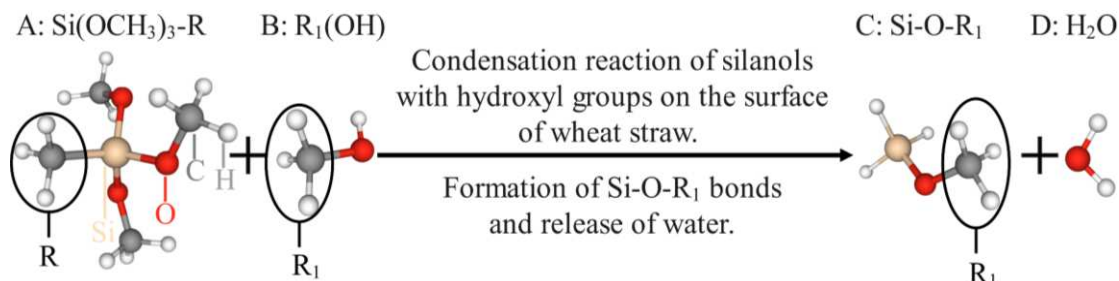


Fig.12. Silanols undergo condensation reactions with hydroxyl groups on the surface of wheat straw.

(iii) Covalent bonding stage: During the subsequent hot pressing process, some hydrogen-bonded interfaces undergo further dehydration, resulting in the formation of stable covalent Si-O-C

(R-Si-O-Fibre) and Si-O-Si bonds in the interfacial region. This chemical coupling mechanism enhances the interfacial adhesion between the silane-modified wheat straw fibres and the PLA matrix.

Through this modification mechanism, the polarity and chemical activity of the wheat straw fibre surface are significantly increased, the surface roughness is improved, and the interfacial bonding with the matrix is strengthened, thereby providing a solid foundation for enhancing the mechanical properties and water resistance of the resulting composite material [29].

Although the mechanical, FTIR, and SEM results consistently indicate improved interfacial compatibility after KH560 treatment, direct verification of the proposed chemical interactions would require additional surface-sensitive techniques, such as XPS. Therefore, the proposed mechanism should be regarded as an interpretation supported by the combined experimental results rather than direct confirmation of specific covalent bonds.

4. Conclusions

This study optimized the hot-pressing parameters of wheat straw/poly(lactic acid) (WS/PLA) composites and comparatively evaluated the effects of alkali and KH560 treatments on their mechanical and interfacial properties. The $L_9(3^3)$ orthogonal analysis showed that hot-pressing temperature exerted the greatest influence on tensile and impact strengths, whereas pressure was the dominant factor affecting flexural strength. Holding time had the least effect on all three properties. Considering the overall mechanical performance, the optimal processing conditions were determined to be 180 °C, 14 MPa, and 20 min. Both surface treatments improved the performance of the WS/PLA composites. Alkali treatment partially removed waxes and other non-cellulosic components, increased fibre-surface roughness, and enhanced mechanical interlocking with the PLA matrix. KH560 treatment produced the most pronounced improvement, yielding tensile, flexural, and impact strengths of 19.81 MPa, 29.25 MPa, and 18.84 kJ·m⁻², respectively. These values represented increases of 14.9%, 16.96%, and 21.09% compared with the untreated composites. FTIR and SEM analyses further indicated that alkali treatment generated a cleaner and rougher fibre surface, whereas KH560 treatment altered the hydroxyl environment and produced spectral changes near 1080 and 764 cm⁻¹, consistent with silane adsorption and condensation. Consequently, KH560 modification promoted a denser fibre–matrix interface and more effective stress transfer. The conclusions of this study are limited to WS/PLA composites containing 40 wt% wheat straw because a neat PLA control was not included. In addition, direct surface-chemical, thermal, moisture-resistance, and biodegradation characterizations were not performed. Future work should therefore incorporate XPS, DSC, TGA, water-absorption, ageing, and standardized biodegradation tests to further clarify the interfacial reactions, thermal stability, durability, and end-of-life behaviour of the composites.

5. Supporting Information

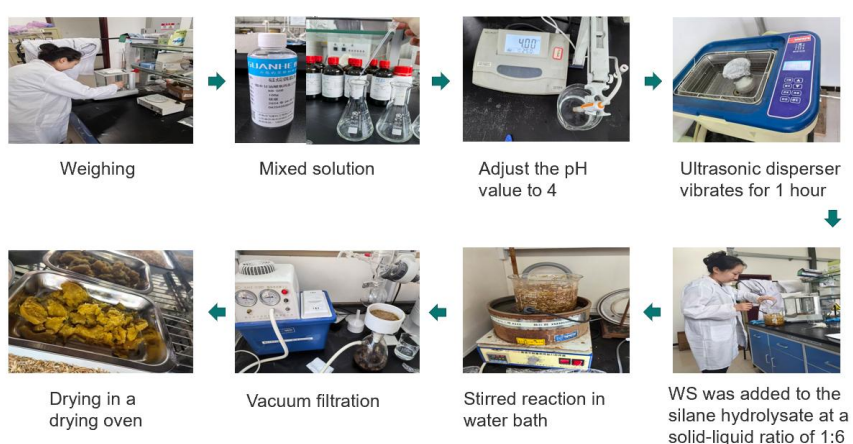


Fig. S1. Fig. S1. Photographic procedure for the KH560 silane treatment of wheat straw. The individual shown in Fig. S1 is the first author, Yuqing Wang, who has provided consent for publication of these images.

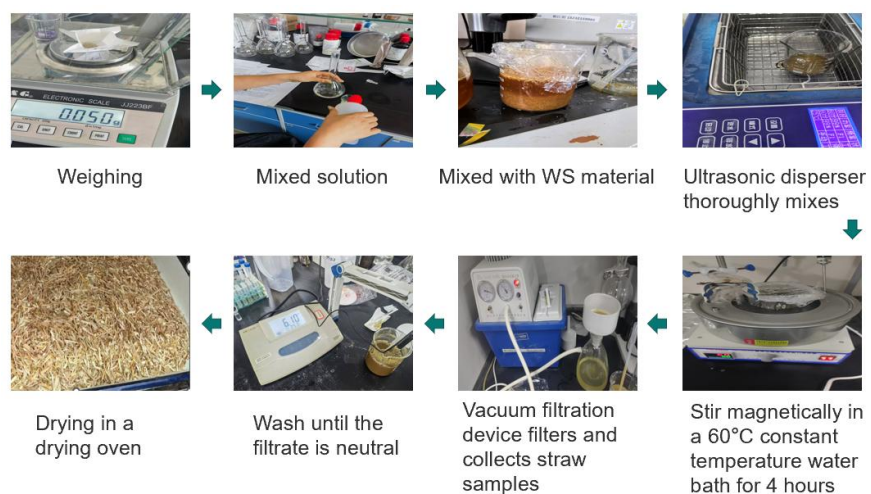


Fig. S2. Photographic procedure for the alkali treatment of wheat straw.

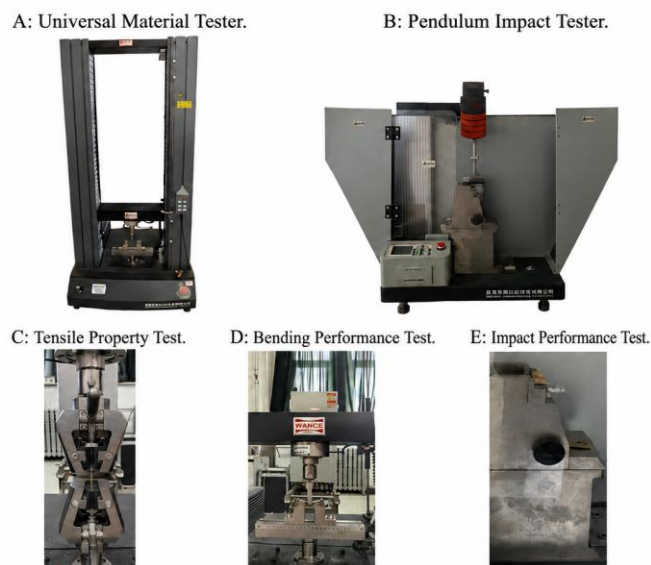


Fig. S3. Tensile, bending, and impact testing instruments and experimental setups.

Funding: No Funding

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

ACKNOWLEDGEMENT: The author would like to express sincere appreciation to Universiti Sains Malaysia (USM) and Nusantara Institute of Creative Arts (INSAN), UiTM. The author values the institute's commitment to fostering artistic innovation and interdisciplinary engagement under 600-RMC/MOHE HICOE INSAN (002/2025-2).

6. References

- [1] E. Fiandra, L. Shaw, M. Starck, C. McGurk, C. Mahon, Designing biodegradable alternatives to commodity polymers, *Chemical Society Reviews* (2023). <https://doi.org/10.1039/d3cs00556a>.
- [2] C. Maraveas, Production of sustainable and biodegradable polymers from agricultural waste, *Polymers* 12 (2020). <https://doi.org/10.3390/polym12051127>.
- [3] T. Swetha, V. Ananthi, A. Bora, N. Sengottuvelan, K. Ponnuchamy, G. Muthusamy, A. Arun, A review on biodegradable polylactic acid (PLA) production from fermentative food waste - its applications and degradation, *International Journal of Biological Macromolecules* (2023) 123703. <https://doi.org/10.1016/j.ijbiomac.2023.123703>.
- [4] E. Balla, V. Daniilidis, G. Karlioti, T. Kalamas, M. Stefanidou, N. Bikiaris, A. Vlachopoulos, I. Koumentakou, D. Bikiaris, Poly(lactic acid): A versatile biobased polymer for the future with multifunctional properties—from monomer synthesis, polymerization techniques and molecular weight increase to PLA applications, *Polymers* 13 (2021). <https://doi.org/10.3390/polym13111822>.
- [5] Y. Cho, J. Kim, J. Shin, S. Park, H. Kim, I. Choi, High-performance biodegradable poly(lactic acid) composites with xylan and lignin copolymer, *International Journal of Biological*

cal Macromolecules (2025) 145985. <https://doi.org/10.1016/j.ijbiomac.2025.145985>.

[6] W. Tissanan, P. Phinyocheep, T. Amornsakchai, Sustainable materials with improved biodegradability and toughness from blends of poly(lactic acid), pineapple stem starch and modified natural rubber, *Polymers* 16 (2024). <https://doi.org/10.3390/polym16020232>.

[7] S. Ismail, E. Akpan, H. Dhakal, Review on natural plant fibres and their hybrid composites for structural applications: Recent trends and future perspectives, *Composites Part C: Open Access* (2022). <https://doi.org/10.1016/j.jcomc.2022.100322>.

[8] M. Balasubramanian, R. Saravanan, S. T., Exploring natural plant fibre choices and treatment methods for contemporary composites: A comprehensive review, *Results in Engineering* (2024) 103270. <https://doi.org/10.1016/j.rineng.2024.103270>.

[9] S. Mahmud, K. Hasan, M. Jahid, K. Mohiuddin, R. Zhang, J. Zhu, Comprehensive review on plant fibre-reinforced polymeric biocomposites, *Journal of Materials Science* 56 (2021) 7231-7264. <https://doi.org/10.1007/s10853-021-05774-9>.

[10] M. Sun, X. Xu, C. Wang, Y. Bai, C. Fu, L. Zhang, R. Fu, Y. Wang, Environmental burdens of the comprehensive utilization of straw: Wheat straw utilization from a life-cycle perspective, *Journal of Cleaner Production* 259 (2020) 120702. <https://doi.org/10.1016/j.jclepro.2020.120702>.

[11] X. Xu, Y. Ye, J. Li, Z. Xu, M. Sun, C. Li, L. Zhang, Y. Xue, GHG emissions of straw treatments in rural China and scenario simulation based on life cycle perspective, *Journal of Cleaner Production* (2022). <https://doi.org/10.1016/j.jclepro.2022.134377>.

[12] T. Huang, S. Wen, M. Zhang, Y. Pan, X. Chen, X. Pu, M. Zhang, P. Dang, M. Meng, W. Wang, X. Qin, K. Siddique, Effect on greenhouse gas emissions (CH₄ and N₂O) of straw mulching or its incorporation in farmland ecosystems in China, *Sustainable Production and Consumption* (2024). <https://doi.org/10.1016/j.spc.2024.02.024>.

[13] B. Cui, J. Ding, H. Xie, T. Ji, C. Yang, Y. Cui, X. Shu, W. Dai, W. Wang, S. Li, Processing wheat straw into strong and flexible cellulose fibre bundle: Waste-to-wealth strategy, *International Journal of Biological Macromolecules* (2025) 144382. <https://doi.org/10.1016/j.ijbiomac.2025.144382>.

[14] L. Zhang, A. Larsson, A. Moldin, U. Edlund, Comparison of lignin distribution, structure, and morphology in wheat straw and wood, *Industrial Crops and Products* (2022). <https://doi.org/10.1016/j.indcrop.2022.115432>.

[15] W. Li, L. Zheng, D. Teng, D. Ge, F. Farha, F. Xu, Interfacial modified unidirectional wheat straw/poly(lactic acid) composites, *Journal of Industrial Textiles* 51 (2020) 272S-284 S. <https://doi.org/10.1177/1528083720918172>.

- [16] H. Abdallah, B. Abu-Jdayil, M. Iqbal, The effect of alkaline treatment on poly(lactic acid)/date palm wood green composites for thermal insulation, *Polymers* 14 (2022). <https://doi.org/10.3390/polym14061143>.
- [17] R. Thandavamoorthy, Y. Devarajan, S. Thanappan, Analysis of the characterization of NaOH-treated natural cellulose fibre extracted from banyan aerial roots, *Scientific Reports* 13 (2023) 12579. <https://doi.org/10.1038/s41598-023-39229-9>.
- [18] K. Chen, C. Liao, P. Li, X. Li, X. Li, Y. Zuo, A compatible interface of wheat straw/poly(lactic acid) composites collaboratively constructed using KH570-nano TiO₂, *Journal of Polymers and the Environment* 30 (2022) 2209-2221. <https://doi.org/10.1007/s10924-021-02359-0>.
- [19] K. Chen, P. Li, X. Li, C. Liao, X. Li, Y. Zuo, Effect of silane coupling agent on compatibility interface and properties of wheat straw/poly(lactic acid) composites, *International Journal of Biological Macromolecules* (2021). <https://doi.org/10.1016/j.ijbiomac.2021.05.207>.
- [20] Z. Dinç, S. Eren, Y. Öz, H. Eren, Influence of surface modifications on interfacial and mechanical properties in fibre-reinforced composites, *Journal of Reinforced Plastics and Composites* (2024). <https://doi.org/10.1177/07316844241259870>.
- [21] M. Yang, J. Su, Y. Zheng, C. Fang, W. Lei, L. Li, Effect of different silane coupling agents on properties of waste corrugated paper fiber/poly(lactic acid) composites, *Polymers* 15 (2023) 3525. <https://doi.org/10.3390/polym15173525>.
- [22] K. Zhang, Z. Chen, M. Boukhir, W. Song, S. Zhang, Bioinspired polydopamine deposition and silane grafting modification of bamboo fiber for improved interface compatibility of poly(lactic acid) composites, *International Journal of Biological Macromolecules* 201 (2022) 121-132. <https://doi.org/10.1016/j.ijbiomac.2021.12.119>.
- [23] G. Herbst, R.J. Aguado, Q. Tarrés, M.L. Corazza, L.P. Ramos, P. Mutjé, M. Delgado-Aguilar, Silane-modified high-yield lignocellulosic fibers as reinforcement of poly(lactic acid): Enhancement of interfacial adhesion for high-performance biocomposites, *Industrial Crops and Products* 218 (2024) 119027. <https://doi.org/10.1016/j.indcrop.2024.119027>.
- [24] F. Mulana, M. Aulia, S. Aprilia, Coconut fibre and fly ash polymer hybrid composite treated with silane coupling agent: Study on morphology, physical, mechanical, and thermal properties, *South African Journal of Chemical Engineering* (2024). <https://doi.org/10.1016/j.sajce.2024.07.008>.
- [25] F. Ji, Optimisation of wood-plastic composites by response surface method, *BioResources* 19 (2024) 5949-5960. <https://doi.org/10.15376/biores.19.3.5949-5960>.
- [26] Q. Wang, D. Jia, X. Pei, X. Wu, F. Xu, Z. Ye, H. Wang, Mechanical performance o

f graphenex/poly(ether ketone ketone) composite sheets by hot pressing, *Scientific Reports* 12 (2022). <https://doi.org/10.1038/s41598-022-08221-0>.

[27] R. Hamid, S. Husni, T. Ito, S. Maidin, M. Maharof, Effect of filament pre-drying on the microstructure and porosity of 3D printed PLA, *Journal of Advanced Research in Micro and Nano Engineering* (2024). <https://doi.org/10.37934/armne.24.1.8594>.

[28] M.C. Salon, M. Abdelmouleh, S. Boufi, M.N. Belgacem, A. Gandini, Silane adsorption onto cellulose fibres: Hydrolysis and condensation reactions, *Journal of Colloid and Interface Science* 289 (1) (2005) 249-261. <https://doi.org/10.1016/j.jcis.2005.03.070>.

[29] Y. Xie, C.A.S. Hill, Z. Xiao, H. Militz, C. Mai, Silane coupling agents used for natural fibre/polymer composites: A review, *Composites Part A: Applied Science and Manufacturing* 41 (7) (2010) 806-819.

[30] C. Liao, Y. Xiao, K. Chen, P. Li, Y. Wu, X. Li, Y. Zuo, Synergistic modification of polylactic acid by oxidized straw fibres and degradable elastomers: A green composite with good strength and toughness, *International Journal of Biological Macromolecules* (2022). <https://doi.org/10.1016/j.ijbiomac.2022.09.023>.

[31] X. Chen, Z. Zeng, Y. Ju, M. Zhou, H. Bai, Q. Fu, Design of biodegradable PLA/PBAT blends with balanced toughness and strength via interfacial compatibilization and dynamic vulcanization, *Polymer* (2022). <https://doi.org/10.1016/j.polymer.2022.125620>.

[32] W. Liu, Y. Wang, S. Xiang, H. Liu, Unveiling the effect of enhanced interfacial compatibility on the mechanical properties of PLA/PBAT blends, *Polymer* (2024). <https://doi.org/10.1016/j.polymer.2024.126815>.

[33] J. Yao, X.W. Xu, Y.Y. Feng, FTIR studies on the chemical composition of wheat straw in different layers, *Spectroscopy and Spectral Analysis* 23 (1) (2003) 58-60. <https://pubmed.ncbi.nlm.nih.gov/12939968/>.