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ARTICLE

Evaluation of Strip-Processed Cotton Stalks as a Raw Material for Structural Panels

Aadarsha Lamichhane[1], Arun Kuttoor Vasudevan[1], Ethan Dean[1], Mostafa Mohammadabadi[1,*], Kevin Ragon[1] and Ardeshir Adeli[2]

[1]Department of Sustainable Bioproducts, Mississippi State University, P.O. Box 9820, Starkville, MS 39762, USA
[2]USDA Agricultural Research Service, Research Soil Scientist, Starkville, MS 39762, USA

*Corresponding Author: Mostafa Mohammadabadi. Email: mm5132@msstate.edu

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ABSTRACT: This study explores a novel method for processing cotton stalks—an abundant agricultural byproduct—into long strips that serve as sustainable raw material for engineered bio-based panels. To evaluate the effect of raw material morphology on panel's performance, two types of cotton stalk-based panels were developed: one using long strips, maintaining fiber continuity, and the other using ground particles, representing conventional processing. A wood strand-based panel made from commercial southern yellow pine strands served as the control. All panels were bonded using phenol-formaldehyde resin and hot-pressed to a target thickness of 12.7 mm and density of 640 kg/m^3. Their mechanical and physical properties were evaluated through internal bond, bending, thickness swelling, and water absorption tests. Both cotton stalk-based panels showed improved bonding performance compared to the control. The internal bond of the strip-based panel was nearly four times higher than that of the control, while the particle-based panel exceeded it by a factor of two. The strip-based panel showed approximately 15% lower bending stiffness than the wood strand-based panel, yet it surpassed it in load-carrying capacity by 5%. In contrast, the particleboard showed significantly lower bending performance than the strip-based and control panels, despite particle processing being a more conventional method. Both cotton stalk-based panels exhibited higher water absorption and thickness swelling than the wood strand panel. Overall, cotton stalk-based panels—particularly those using strip processing—show promising mechanical properties, suggesting potential applications in sheathing, furniture, and interior paneling. However, improvements in dimensional stability are needed for broader use.

KEYWORDS: Crop residues; bio-based materials; cotton stalk; experimental testing; bending performance; internal bond; water absorption

1 Introduction

The global population is projected to reach 9.6 billion by 2050, leading to increased food demand and the expansion of agricultural activities worldwide [1]. Agriculture remains the world's largest industry, employing over one billion people and generating more than USD 1.3 trillion in annual economic output [2]. It occupies approximately 38% of the earth's land surface and serves as a vital foundation for both food and fiber production [3]. While the majority of agricultural land is dedicated to growing food crops, a significant portion supports the cultivation of fiber crops, essential to the global textile and manufacturing sectors. Among these, cotton stands out as the most widely grown natural fiber crop, contributing over 80% of natural fiber production by weight [4]. Its distinctive fiber structure makes it highly valuable across industries, including fashion, textiles, and healthcare [5]. Recent estimates suggest that more than 25 million tons of cotton are produced annually worldwide, with India, China, the United States, Pakistan, and Brazil being the leading producers [6,7]. The global cotton market was valued at USD 41.78 billion in 2024 and is anticipated to reach 53.29 billion by 2033 [8]. In the United States alone, cotton is cultivated on over 10 million acres annually, making it one of the nation's most significant agricultural exports [9].

Cotton cultivation generates a significant amount of agricultural residue in the form of stalks after harvesting. With a typical straw-to-fiber ratio of approximately 5:1 [10], an estimated 2–3 t of cotton stalk residue are produced per hectare [11]. A large portion of these stalks is either openly burned in the field to clear land or discarded in landfills. Open burning releases toxic gases—such as carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbons, and fine particulate matter—that harm air quality and public health [12]. Consequently, several countries have implemented bans on open field burning to mitigate these risks [13–15]. Alternative disposal methods, such as burying, also present challenges. The fibrous, lignocellulosic nature of cotton stalks makes them resistant to decomposition, and they are known carriers of agricultural pests like *Pectinophora gossypiella* (pink bollworm), further complicating safe disposal [16]. These environmental, agricultural, and logistical concerns underscore the need for sustainable utilization strategies. One promising solution involves repurposing cotton stalks into long-lived engineered bio-based products. Unlike short-lived uses, such as composting or fuel, where carbon is rapidly released, structural applications like particleboard can retain carbon for extended periods. This contributes to climate change mitigation goals and provides a renewable, underutilized lignocellulosic feedstock for regions with limited forest resources.

Engineered wood-based panels such as particleboard and oriented strand board (OSB) are widely used in construction, furniture, cabinetry, and interior paneling. With the increasing popularity of engineered wood products, recent researchers have adopted innovative strategies to enhance structural performance and promote efficient material utilization. These strategies include densification techniques [17], the development of novel products using corrugated panels [18], and the use of underutilized hardwood species [19]. Concurrently, increasing efforts have focused on converting agricultural residues into value-added products. Researchers have investigated a variety of agro-wastes in the development of particleboards and engineered bio-based products, such as rice straw [20–22], rice husk [23–25], wheat straw [25,26], sugarcane bagasse [27], hemp [28,29], bamboo [30], and grass [31,32]. These alternative materials help reduce reliance on timber while mitigating the environmental impact of residue disposal. Among these options, cotton stalk offers a particularly strong potential for producing sustainable, high-performance panels due to their abundance and woody texture, which provides fibrous structure similar to that of hardwoods [33,34].

Several studies have demonstrated the potential of cotton stalks in particleboard applications. Guler and Ozen reported the viability of particleboards made from debarked cotton stalks as an alternative raw material [33]. Alma et al. fabricated boards using cotton carpels bonded with urea formaldehyde (UF) and melamine urea formaldehyde (MUF) resins, achieving performance comparable to that of general grade particleboards [35]. Kadja et al. used bone resin in cotton stems panels, reporting that the mechanical properties met American National Standards Institute (ANSI) requirements [36]. Other researchers improved board strength by blending cotton stalks with wood fibers at optimal ratios [37]. Nazerian et al. analyzed the effects of press temperature and panel density on boards made from debarked stalks [38]. Further enhancements were achieved by Yasar & İçel through NaOH treatment of cotton particles [39], while Scatolino et al. evaluated hybrid panels combining cotton waste with eucalyptus wood [40]. Nguyen evaluated the effects of particle opening sizes and the amount of cotton boll residue on the mechanical and physical properties of boards fabricated from whole cotton stalks [41].

Unlike particleboard fabrication, Chen et al. [42] developed panels using entire cotton stalks (approximately 450 mm in length) combined with a konjac glucomannan–chitosan adhesive [42]. However, instead of utilizing whole stalks, processing the stalks into thin, elongated strips offers several advantages. First, since panel density is a critical factor influencing the mechanical performance of bio-based products, finer strips enable a more uniform density distribution both along the panel surface and through its thickness compared to thick, unprocessed stalks. Second, thin strips facilitate more effective mechanical interlocking between elements, enhancing stress transfer across the panel and improving load-carrying capacity. Third, the processing procedure splits and opens the stalk, exposing the foamy hurd core—an anatomically weak, highly porous region—to adhesive penetration, thereby improving bonding and contributing to higher internal bond strength. Similar processing concepts have been successfully applied in bamboo and wood scrimber production, where breaking down raw materials into elongated elements has been shown to enhance strength, stiffness, and overall performance [43,44]. The potential benefits of processing cotton stalks into thin, long strips have not been examined.

In this study, a novel strip-processing method was introduced for cotton stalks to produce long, continuous elements aimed at improving stress transfer and maintaining more uniform properties in structural panels. For comparison, particleboards were also fabricated using conventional grinding, which is the most common method for processing cotton stalks. This enabled the evaluation of the effectiveness of this strip-processing method compared to traditional particle processing. In addition, oriented strand board (OSB), a widely used commercial product with a well-established market, was included as a benchmark. Overall, the study aims to develop and evaluate structural panels that can be potentially used in sheathing, furniture, cabinetry, and internal paneling, made from cotton stalks in both strip and particle forms, with performance benchmarks established using a wood strand board as a control.

2 Materials and Methods

2.1 Materials and Sample Preparation

2.1.1 Raw Materials

The cotton stalks harvested from the cotton farm at Mississippi State University, MS, USA, were selected as the primary raw material for this study. The initial processing involved removing cotton bolls and branches from the stalks, as illustrated in Fig. 1. The stalks were cut into small pieces approximately 150 mm in length, similar to commercial wood strands. These pieces were soaked in water for 24 h to soften the fibers and facilitate their processing into strips.

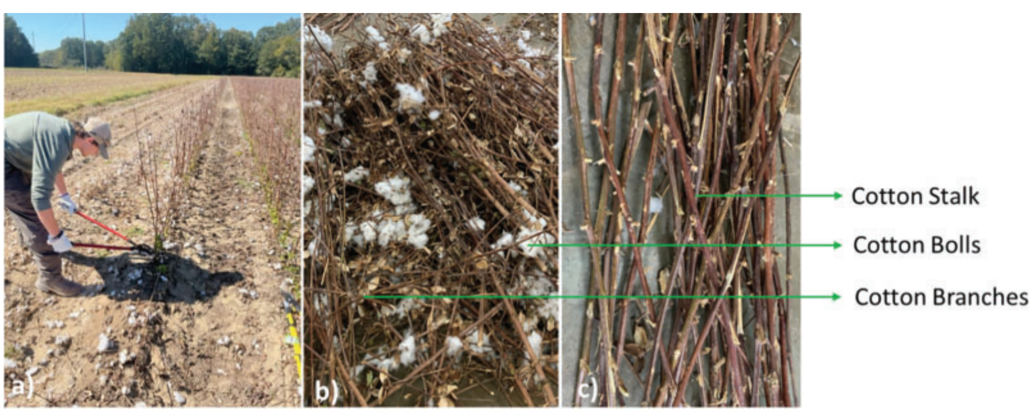

Figure 1: (**a**) Collecting cotton stalks from a farm; (**b**) cotton stalks with bolls and branches; (**c**) stalks after removing bolls and fine branches

After soaking, the bark was manually removed as shown in Fig. 2b. To enhance both the interlocking effect and bonding performance, it is essential to process the cotton stalks into finer pieces, using a method similar to the scrimming process employed for small-diameter logs [44,45] and bamboo [43,46]. Therefore, a manual noodle maker was used to process the softened stalks into strips, as shown in Fig. 2c. This process not only increases the surface area available for resin application, improving bonding performance, but also facilitates more uniform compaction during hot pressing. The use of these strips rather than stalks enables better mat consolidation and a more uniform density distribution. The Fig. 2d shows the long, slender cotton stalk strips produced using the noodle maker, prepared and ready for panel fabrication.

Figure 2: Processing steps: (**a**) wet cotton stalks; (**b**) bark removal; (**c**) converting stalks into strips using a manual noodle maker; (**d**) cotton stalk strips prepared for panel fabrication

For particleboard analogs, cotton stalks were processed using a laboratory-scale hammer mill, as shown in Fig. 3a, to produce fine particles. The final processed particles are shown in Fig. 3b. For comparative analysis, commercial Southern yellow pine strands supplied by West Fraser Company in Guntown, MS, USA, were used to fabricate control panels as shown in Fig. 3c. All bio-based materials, including cotton stalk strips, cotton stalk particles, and wood strands, were oven-dried to a moisture content of 3%–5%.

Figure 3: Preparation of cotton stalk particles for particleboard analogs: (**a**) hammer milling of cotton stalk; (**b**) cotton stalk particles after processing; (**c**) wood strands

2.1.2 Panel Fabrication

Phenol-formaldehyde (PF) resin was used as a binder and was applied at a target resin content of 5% (based on oven-dry weight). The resin was sprayed evenly onto the bio-based materials inside a rotating drum blender to ensure uniform coating. Separate batches were prepared for the three board types: cotton stalk strip board (CSB), cotton stalk particle board (CPB), and wood strand board (WSB), which served as the control. Resin-coated materials were manually formed into mats, known as preform, using a forming box to ensure uniform thickness. Cotton stalk strips and wood strands were manually aligned in parallel orientation using a mechanical orienter. Each mat was hot-pressed at 160°C for 5 min to achieve a target thickness of 12.7 mm and a target density of 640 kg/m^3. After pressing and conditioning, the fabricated panels were trimmed, and test specimens were cut for various evaluations, including internal bond, bending, water absorption, and thickness swelling. The average dimensions of these test specimens are summarized in Table 1.

Table 1: Average dimensions of test specimens, prepared according to ASTM D 1037

Board type	Experimental test	No. of specimens	Average length (mm)	Average width (mm)	Average thickness (mm)	Average weight (gm)	Average density (kg/m^3)
Cotton stalk particle	Bending	8	381.00	76.62	13.31	252.08	648.63
	Internal bond	8	51.27	51.12	13.46	22.68	642.98
	WA and TS	8	152.22	152.37	13.22	192.96	629.22
Average							640.28
Cotton stalk strip	Bending	8	381.40	76.28	13.55	259.40	658.10
	Internal bond	8	51.13	51.20	13.75	22.15	615.37
	WA and TS	8	152.37	152.37	13.30	200.53	649.20
Average							640.89
Wood strand (Control)	Bending	12	381.00	76.96	13.31	264.90	678.65
	Internal bond	12	51.19	51.02	13.05	24.34	714.24
	WA and TS	12	152.90	152.90	13.37	209.80	671.42
Average							688.11

2.2 Experimental Testing

The mechanical and physical properties of the fabricated panels were evaluated through a series of standardized tests following American Society for Testing and Materials (ASTM D1037) [47] to assess their structural viability. To evaluate the feasibility of this process, three key performance parameters were investigated at this phase: internal bond strength, bending performance (modulus of rupture and modulus of elasticity), and dimensional stability through water absorption and thickness swelling. It is important to note that the authors plan to conduct additional tests in future studies, including tensile, compression, hardness, and nail withdrawal tests. Internal bond test measures the tensile strength along the thickness of the panel, indicating the effectiveness of adhesive bonding between biobased fibers. Each specimen was centrally glued to two aluminium blocks and loaded in tension, as shown in Fig. 4a, using a universal testing machine at a loading rate of 1 mm/min until failure. The maximum load was recorded and used to calculate the IB strength using Eq. (1).

$$IB = \frac{P_{max}}{bd} \quad (1)$$

where, P_{max} = Concentrated applied load on the sample.

b, and d = length and width of the sample.

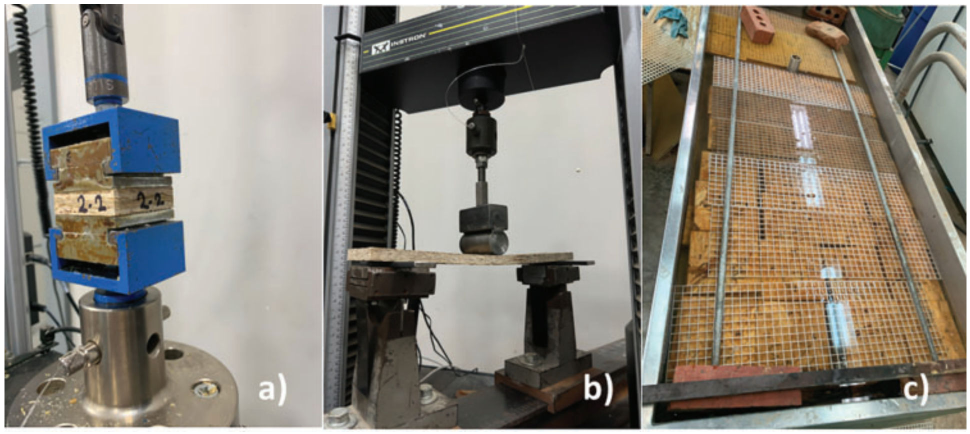

Figure 4: Experimental testing setup: (**a**) internal bond test; (**b**) bending test; (**c**) water absorption and thickness swelling test

Bending performance was evaluated using a three-point bending test, as shown in Fig. 4b. Specimens were simply supported with a clear span of 304.8 mm and loaded at the mid-span using a central point load. The load was applied at a rate of 6 mm/min until failure. The load-deflection behaviour was recorded using a displacement transducer. The slope of the load-deflection curve was used to calculate the bending stiffness using Eq. (2), and the maximum load before failure was used to determine the maximum normal stress, known as the modulus of rupture (MOR), using Eq. (3).

$$EI = \frac{PL^3}{48\Delta} = \frac{mL^3}{48} \quad (2)$$

$$MOR = \frac{3PL}{2bd^2} \quad (3)$$

where, E = Modulus of elasticity

I = Second moment of area (moment of inertia) of the specimen's cross-section

P = Bending load applied at mid-span

Δ = Specimen deflection at mid-span

L = Span length

m = P/Δ is the slope of the load-deflection curve in the elastic region

b = Specimen width

d = Specimen depth.

Water absorption and thickness swelling were measured to evaluate the dimensional stability of the panels. This test followed the 24-h soak procedure outlined in ASTM D1037, as shown in Fig. 4c. Specimens were weighed, and their thickness was measured before being immersed in distilled water at room temperature. After 2 and 24 h, samples were removed, wiped to remove excess water, reweighed, and remeasured. Water absorption was determined as the percentage increase in weight, and thickness swelling as the percentage increase in thickness.

3 Results and Discussions

3.1 Mechanical Property

This section presents experimental results for the mechanical properties, specifically internal bond (IB), bending strength, water absorption, and thickness swelling of three panel types: cotton stalk strip board (CSB), fabricated using cotton stalk strips; cotton stalk particle board (CPB), fabricated from cotton stalk particles; and wood strand board (WSB), fabricated from commercial wood strands. The mechanical performance of each panel type was evaluated to assess the viability of cotton stalk-based panels compared to those made from wood strands. All reported values represent the average across replicate specimens, with standard deviations calculated to capture variability.

Internal bond strength, which represents the tensile strength perpendicular to the panel surface, reflects the effectiveness of bonding between fibers. Fig. 5 presents the IB values for CSB, CPB, and WSB panels. Among the three, CSB panels exhibited the highest IB strength, followed by CPB panels. The WSB panels showed the lowest IB strength among the three, despite all panels being manufactured using the same resin type (phenol-formaldehyde), resin content (5%), and processing conditions. The relatively low performance of WSB panels may be attributed to limitations in the resin curing process within the panel cores. Unlike industrially manufactured oriented strand board (OSB) panels which typically uses polymeric methylene diphenyl diisocyanate (pMDI) in the core due to its lower curing temperature and faster reactivity [48], the control panel in this study was fabricated entirely with phenol-formaldehyde (PF) adhesive to ensure consistent comparison. PF resin requires higher temperatures and longer press times to cure fully [49], which may have led to precuring and incomplete bonding in the panel core. This likely reduced the IB strength of the WSB compared to both the cotton-based panels and standard commercial OSB products. In contrast, both CSB and CPB demonstrated significantly higher IB values than WSB. This enhanced performance may be due to improved compatibility between cotton fibers and PF resin. While further studies are needed, the results suggest that PF may form more effective bonds with cotton-based materials under the same processing conditions.

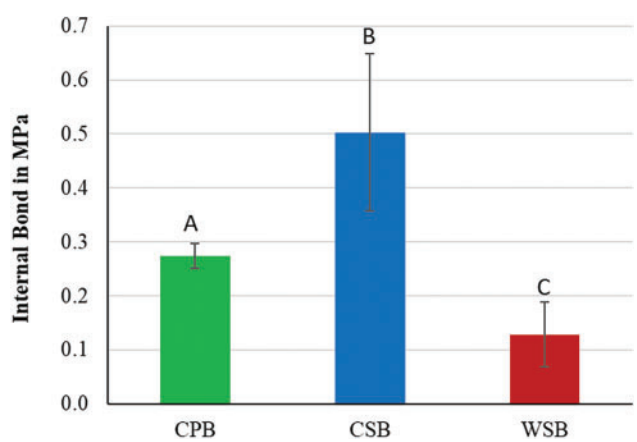

Figure 5: Internal bond strength of different panel types

Between the two cotton stalk-based panels, the CSB panel exhibited the highest IB strength, nearly four times greater than that of WSB and twice that of CPB. This difference is attributed to differences in resin distribution. The CSB panels were composed of thicker, chunkier cotton stalk strips, with a smaller surface area per unit volume. Given the same resin content, this resulted in more adhesive being available per unit surface area, leading to stronger internal bonds. In contrast, the CPB panels consisted of finer particles with a higher surface area, leading to a thinner resin distribution and consequently lower bond strength.

To statistically validate the performance differences, a one-way ANOVA was conducted as shown in Table 2. The results produced a highly significant F-value of 50.91 ($p < 0.0001$), confirming that the mean IB strength values across the three panel types differed significantly at the 95% confidence level. Moreover, the CSB group showed a larger standard deviation than the other two groups, indicating greater variability, most likely due to inconsistencies in the manual processing of cotton stalks into strips. Overall, the findings indicate that cotton stalk fibers, whether in strip or particle form, exhibit better bonding performance with PF resin than wood fibers at the equivalent resin content.

Table 2: ANOVA summary for internal bond for different panel types

Descriptive statistics					
	N analysis	**N missing**	**Mean**	**Standard deviation**	**SE of mean**
CPB	12	0	0.27	0.02	0.01
CSB	12	0	0.50	0.15	0.04
WSB	12	0	0.13	0.06	0.02
Overall ANOVA					
	DF	**Sum of squares**	**Mean square**	**F value**	**Prob > F**
Model	2	0.86	0.43	50.91	<0.0001
Error	33	0.28	0.01		
Total	35	1.13			

Note: Null Hypothesis: The means of all levels are equal. Alternative Hypothesis: The means of one or more levels are different. At the 0.05 level, the population means are significantly different.

Compared to similar studies, the CSB in the present work, manufactured from cotton stalk strips, outperformed the oriented cotton stalk boards, fabricated from whole cotton stalks, reported by Chen et al., who achieved an IB value of only 0.35 MPa at a density of 0.6 g/cm^3 using a konjac glucomannan–chitosan adhesive with 10% resin content and unprocessed whole cotton stalks [42]. This comparison underscores the importance of processing cotton stalks into strips, which substantially enhances bonding performance. Guler and Ozen reported IB values ranging from 0.29 to 0.40 MPa, depending on resin content, for cotton stalk particle boards, which are lower than our CSB results and comparable to those of CPB panels [33].

The results of the three-point bending tests, evaluating bending stiffness and maximum normal stress for the three panel types are presented in Fig. 6. Among them, cotton stalk particle board (CPB) exhibited the lowest bending stiffness, followed by cotton stalk strip board (CSB), while wood strand board (WSB) showed the highest bending stiffness (Fig. 6a). The reduced stiffness of the CPB is primarily due to its short fiber length, which limits effective load transfer under flexural stress. In contrast, CSB panels, fabricated using longer, aligned cotton stalk strips, demonstrated a 3.2-fold improvement in bending stiffness relative to CPB. This highlights the importance of fiber length and alignment in enhancing flexural rigidity. Although the cotton stalk strips were comparable in length to the wood strands, CSB still exhibited about 15% lower bending stiffness than WSB. Since the moment of inertia (I) was constant across all panel types owing to their identical dimensions, this difference can be attributed primarily to the modulus of elasticity (E) of the constituent materials. This indicates that cotton stalk strips likely possess a lower modulus of elasticity compared to wood strands, thereby reducing the overall stiffness of CSB panels. To verify this hypothesis, future work should include direct testing of individual elements, such as cotton stalk strips and wood strands, to better quantify their intrinsic elastic properties and clarify their contributions to panel performance. Additionally, a one-way ANOVA analysis of bending stiffness (Table 3), produced a highly significant F-value of 240.16 ($p < 0.0001$), confirming that the mean bending stiffness values among the three panel types differ statistically at the 95% confidence level.

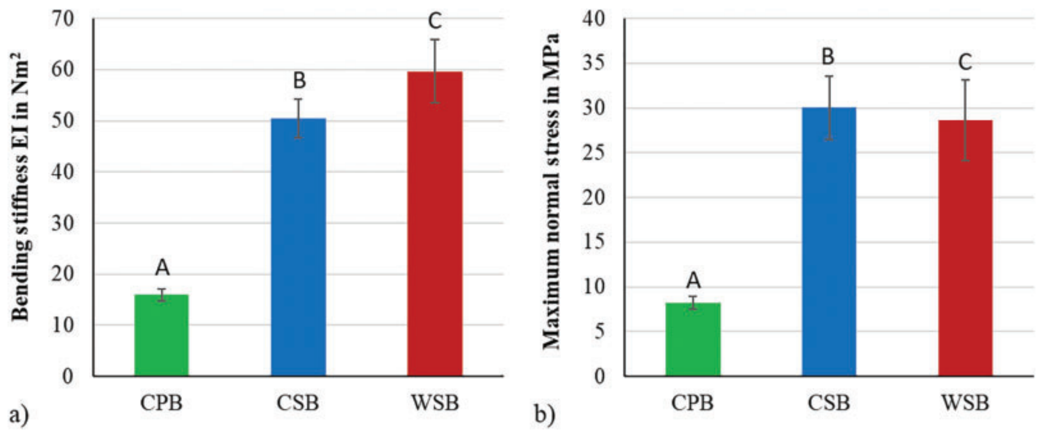

Figure 6: Bending results of different panel types: (**a**) bending stiffness (EI); (**b**) maximum normal stress

Table 3: ANOVA summary for bending stiffness of different panel types

Descriptive statistics					
	N analysis	**N missing**	**Mean**	**Standard deviation**	**SE of mean**
CPB	8	0	15.91	1.21	0.43
CSB	8	0	50.49	3.72	1.32
WSB	8	0	59.66	6.15	2.18
Overall ANOVA					
	DF	**Sum of squares**	**Mean square**	**F value**	**Prob > F**
Model	2	8518.34	4259.17	240.16	<0.0001
Error	21	372.43	17.73		
Total	23	8890.78			

Note: Null Hypothesis: The means of all levels are equal. Alternative Hypothesis: The means of one or more levels are different. At the 0.05 level, the population means are significantly different.

In terms of failure mode, both CPB and CSB panels exhibited typical bending failure, marked by tension-induced rupture at the outer fiber. In contrast, the WSB panel failed in shear (Fig. 7), indicating weak bonding in the core region, consistent with its lower internal bond (IB) strength. Unlike commercial OSB panels that often incorporate pMDI in the inner layers to improve curing and bond quality, the uniform use of PF resin in this study likely led to incomplete curing in the core. Because CPB and CSB experienced bending-type failure, the maximum normal stress at the outermost fiber can be considered as their Modulus of Rupture (MOR). In contrast, for WSB, shear failure means that the measured maximum normal stress does not reflect its true MOR; the actual value is expected to be higher.

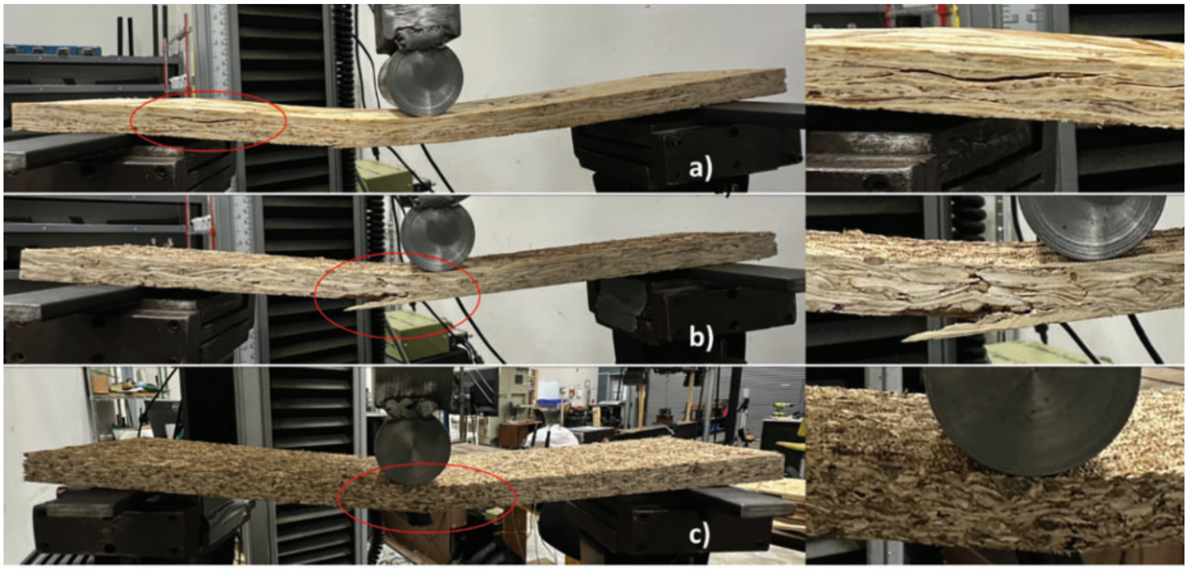

Figure 7: Failure mode of three different panels: (**a**) wood strand board (WSB); (**b**) cotton stalk strip board (CSB); (**c**) cotton stalk particle board (CPB)

As shown in Fig. 6b, CSB panels achieved the highest MOR, outperforming WSB by approximately 5%. This enhanced performance is likely due to stronger bonding between the PF resin and cotton stalk strips, particularly within the core, resulting in more effective stress transfer under flexural loading. In comparison, WSB's weaker core bonding limited its load-carrying capacity. CPB panels made with short cotton fibers, demonstrated the lowest MOR, nearly 3.6 times lower than that of CSB, underscoring the significance of fiber length and continuity in resisting flexural stresses. Given their limited bending capacity, CPB panels are better suited for non-load-bearing applications such as insulation boards, sound-absorbing panels, cabinetry, furniture, or as core materials in sandwich panels for interior building use. As shown in Table 4, the one-way ANOVA performed on maximum normal stress revealed a statistically significant F-value of 106.10, confirming that the mean values among the three panel types differ significantly at the 95% confidence level.

Table 4: ANOVA summary for maximum normal stress of different panel types

Descriptive statistics					
	N analysis	**N missing**	**Mean**	**Standard deviation**	**SE of mean**
CPB	8	0	8.19	0.73	0.26
CSB	8	0	30.03	3.56	1.26
WSB	8	0	28.61	4.54	1.60
Overall ANOVA					
	DF	**Sum of squares**	**Mean square**	**F value**	**Prob > F**
Model	2	2388.97	1194.48	106.10	<0.0001
Error	21	236.42	11.26		
Total	23	2625.38			

Note: Null Hypothesis: The means of all levels are equal. Alternative Hypothesis: The means of one or more levels are different. At the 0.05 level, the population means are significantly different.

When comparing the bending results with the literature, the results obtained for CPB were found to be slightly lower. Guler and Ozen reported that the maximum normal stress for a particleboard made with cotton stalks and a density of 0.6 g/cm^3 ranged from 10 to 12 MPa, depending on the different resin ratios [33]. Similarly, Kadja et al. reported 11 MPa for the same, which were pressed for 25 min [36].

3.2 Dimensional Stability

Dimensional stability of these bio-based panels was evaluated by immersing them in water and measuring the water absorption (WA) and thickness swelling (TS). These properties indicate the panel's resistance to moisture-induced deformation, which is essential for durability in practical applications. WA and TS results for all three panel types after 2 and 24 h of water immersion are presented in Fig. 8. The WSB panels exhibited the lowest water absorption at both intervals, followed by CSB and then CPB (Fig. 8a). The higher water absorption observed in the cotton-based panels is attributable to the anatomical structure of the cotton stalk. As shown in Fig. 9, the hurd, characterized by its foamy and porous texture, is particularly susceptible to moisture uptake, resulting in elevated overall water absorption in both CSB and CPB panels compared to the wood strands used in WSB. Between the two-cotton stalk-based panels, CPB showed 25% and 11% higher water absorption than CSB after 2 and 24 h, respectively. This difference is primarily attributed to the finer particle size and greater surface area of CPB, which facilitate greater moisture intake. Additionally, the lower internal bond strength of CPB compared to CSB may have contributed to weaker adhesive bonding, thereby further enhancing its susceptibility to moisture penetration. For particleboards made with cotton stalk bonded with bone adhesive at comparable density and resin content, Kadja et al. reported even higher WA values of approximately 155% (2 h) and 211% (24 h), indicating that the present CSB and CPB panels performed moderately better [36].

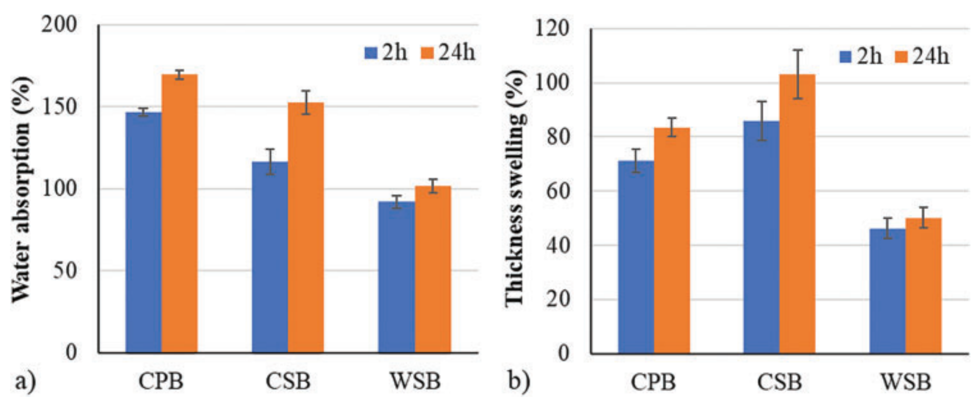

Figure 8: Dimensional stability test on three different panels: (**a**) water absorption; (**b**) thickness swelling

Consistent with the water absorption trends, wood strand board (WSB), fabricated with wood strands exhibited the lowest TS values, reflecting superior dimensional stability as shown in Fig. 8b. However, despite having lower water absorption than the cotton stalk particle board (CPB), the cotton stalk strip board (CSB) displayed the highest TS, 20% and 23% greater than CPB after 2 and 24 h of immersion, respectively. While a parallel relationship between water absorption and thickness swelling was expected, this unexpected divergence suggests that additional mechanisms may be involved. The CSB was manufactured using thicker elements (cotton stalk strips) compared to the particles used in CPB, resulting in a higher degree of compression during hot pressing. Specifically, the preform thickness for CSB was approximately 165 mm, nearly double that of CPB at 89 mm, while the WSB preform was about 120 mm. This likely created greater compaction ratio, which were released as "spring-back" upon water immersion. This finding underscores the importance of optimizing strip geometry, such as producing thinner strips, to help mitigate swelling. Fig. 10 provides a visual comparison of panel samples made from these natural fibers, highlighting the variation in thickness swelling after the water absorption test. The thickness swelling for layered cotton particleboard with Ureal Formaldehyde resin studied by Guler and Ozen was lower reporting 26% for 2 h and 35% for 24 h than those recorded for CPB in the present study [33].

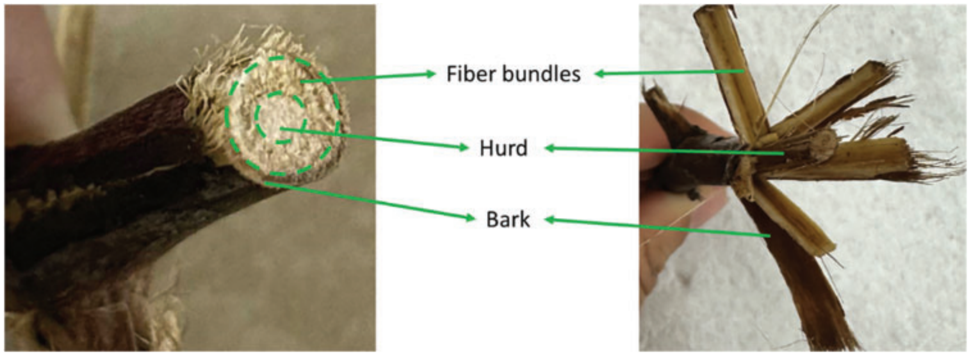

Figure 9: Anatomical structure of cotton stalk showing hurd (center), fiber bundles (middle), and bark (outer layer)

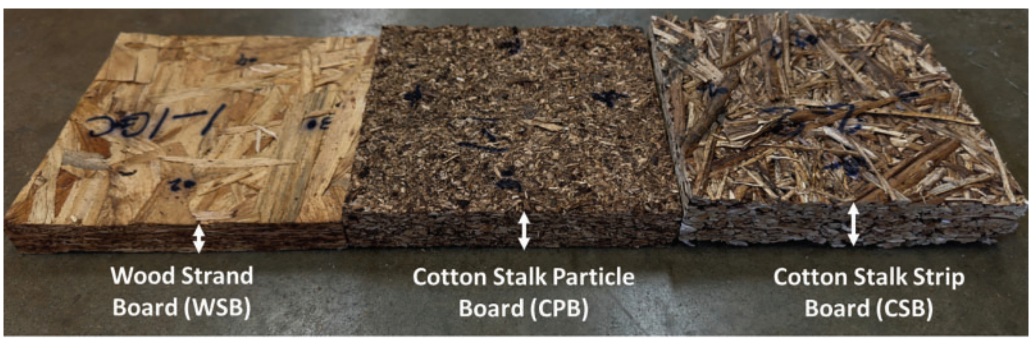

Figure 10: Visual representation of thickness swelling comparison for three different panels after water absorption test. The panels, from left to right, are: (1) wood strand board (WSB), (2) cotton stalk particle board (CPB), and (3) cotton stalk strip board (CSB)

These results suggest that both CSB and CPB panels are more suitable for applications in dry or controlled-moisture environments, as they exhibit increased susceptibility to moisture-induced dimensional changes. To enhance the moisture resistance of cotton-based panels, future research could explore surface treatments or additives such as paraffin or wax. Previous studies have shown that wax significantly reduced 24-h water absorption and thickness swelling in hydrophobic cotton-based panels compared to untreated controls, offering a promising approach for improving dimensional stability [50]. Additionally, exploring the use of alternative adhesives such as polymeric methylene diphenyl diisocyanate (pMDI) may further reduce water absorption and thickness swelling, presenting another viable strategy for enhancing performance in humid conditions.

4 Conclusions

This study evaluated the structural performance and dimensional stability of panels fabricated from cotton stalk strips, processed using a manual noodle maker. For comparison, panels were also made from cotton stalk particles, representing the most common processing method and wood strand-based panels.

The results highlighted that panels fabricated with cotton stalk strips demonstrated structural performance comparable to wood strand-based panels and significantly superior to a cotton stalk particle board. The following key points were identified:

1. Both cotton stalk-based panels exhibited greater internal bond (IB) strength than wood strand board (WSB). The cotton stalk strip board (CSB) achieved the highest IB value, nearly four times that of WSB, primarily due to enhance interaction between PF adhesive and the cotton stalk strips. CPB also outperformed WSB, showing approximately double the IB strength.
2. The maximum normal stress of CSB exceeded that of WSB by 5%. CSB also exhibited bending stiffness comparable to WSB, with only a 15% reduction, highlighting strong potential for cotton stalk strips in flexural applications.
3. Both CSB and CPB absorbed more water than WSB, mainly due to the cotton stalk's porous, pith-like interior. CPB showed the highest water absorption, while CSB had the greatest thickness swelling, suggesting different responses to moisture between the two cotton-based panels.
4. The parallel alignment of long cotton stalk strips significantly enhanced mechanical performance compared to particle-based panels, highlighting the importance of the processing method.

Our findings demonstrate not only the manufacturing feasibility of cotton stalk strip panels but also their high structural performance. Since their production involves both scrimber and hot-pressing techniques, the product has strong potential for scale-up. Hot-pressing is a well-established method for producing a variety of wood-based products, including medium-density fiberboard (MDF), OSB, and plywood. The scrimber technique, on the other hand, is widely applied in the manufacture of high-strength wood and bamboo scrimber products. However, given that cotton stalk seis a seasonal agricultural residue, comprehensive techno-economic assessments are required to evaluate production costs, raw material availability, supply chain logistics, and market competitiveness.

Overall, these findings support the potential use of waste cotton stalks, especially in strip form, as a sustainable raw material for structural biobased panels. While the mechanical properties of CSB panels are promising, further improvements in dimensional stability are needed. Future research should focus on enhancing dimensional stability by using hydrophobic additives, such as wax or paraffin, and alternative adhesives, like polymeric methylene diphenyl diisocyanate (pMDI). Additional studies are also required to assess toughness, impact resistance, and long-term durability under service conditions, including creep resistance, fatigue behavior, and cyclic exposure to moisture and temperature, to ensure reliable performance in structural applications.

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