Eco-friendly biocomposites: green chemistry approaches for sustainable furniture and thermal insulation

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Context and objectives

Biomass residues from agricultural waste, such as crop and wood wastes, straw, and bagasse, have garnered significant attention as a sustainable resource for producing composite materials. These materials offer advantages in cost efficiency, environmental sustainability, and renewability (Saeed et al 2017). Particleboards, commonly used as alternatives to solid wood or plywood, are popular due to their cost-effectiveness and widespread availability (Gumowska el al 2021, Holt et al 2014). In 2020, global particleboard production reached 96.01 million m^3, and 102 million m^3 in 2023, with China being the largest producer, followed by Germany, Poland, and other European nations (Hua et al 2022). Global market world in 2023 is 24,2 billion USD and expanding at an annual growth of 3.9% during 2024–2032. The market growth is attributed to the high demand for cost-effective and eco-friendly furniture across the globe.

The production process typically involves adhesives like urea-formaldehyde (UF) resin, widely used for its versatile properties in the furniture industry (Baharoğlu et al 2012). However, bio-based adhesives, such as tannin and casein, are gaining attention as eco-friendly alternatives due to their low or zero formaldehyde emissions (Ndiwe et al 2019).

Mechanical and physical properties, such as flexural strength, water absorption, and tensile strength, are crucial for determining composite material applications (Kowaluk, et al 2017). These factors are influenced by the type of adhesive, fibres, and environmental conditions (Chiang et al 2014). Despite the growing demand for particleboards in furniture and construction (Nourbakhsh et al 2010), the carbon footprint of furniture production remains significant, with 47 kg of CO_2 equivalents generated per piece of furniture (Forrest et al 2017). This highlights the need for more sustainable solutions. While bagasse, cotton stalks, and kenaf have shown potential for producing particleboards, challenges remain in developing 100% green composites using natural matrices (Shahril et al 2020).

This study aims to explore the production of fully green particleboards for furniture and thermal insulation in the construction industry, comparing the properties of particleboards made from bagasse, cotton stalk, and kenaf fibres with natural adhesives like tannin and casein.

Material and methods

Materials

Sugarcane bagasse was sourced from Al-Gunied Sugar Factory in Gezira State, Sudan. Kenaf was grown on the University of Gezira's demonstration farm. Kenaf bast fibres were extracted by peeling the stalks, soaking them in water for one week, then washing and drying them at room temperature. Cotton stalks were collected from the Gezira project. These fibres were used without additional treatments. Mimosa condensed tannin (Acacia) was provided by GREEN'ING Company.

Casein adhesive was sourced from Acros Organics. Hexamethylenetetramine (99%) and sodium bicarbonate were obtained from Fisher Scientific. All products were used as received.

Methods

Preparation of Fibres

Sugarcane bagasse was used without further processing, with particle sizes ranging from 10 to 20 mm. Cotton stalks and kenaf bast fibres were manually reduced to match this size and then dried in an oven at 105 °C for 24 hours to achieve a moisture content of 3%.

Preparation of Bio-Based Adhesives

A 35% aqueous solution of spray-dried commercial mimosa tannins was prepared, with the pH raised to 9. To this, 6.5% hexamethylenetetramine was added as a hardener. Additionally, a 30% casein solution was mixed with 25% sodium bicarbonate (w/w of casein) as a hardener, using 15% of each adhesive based on the oven-dry weight of the fibres.

Preparation and Testing of Particleboards

Particleboards were produced in the laboratory of the Department of Materials Science at the Technical University Institute of the University of Pau, the Adour Region (UPPA). Single-layer particleboards (dimensions: 340×340×20 mm^3) were created using 15% tannin and casein adhesives. The pressing cycle involved a maximum pressure of 2.5 MPa, with varying pressing times of 60, 120, 240, and 480 seconds, at a temperature of 180 °C. Density profiles were measured using a GreCon DAX 5000 device. The panels were preconditioned at 20 °C and 65% humidity for three days to ensure uniform moisture content before testing. Mechanical properties, including internal bond (IB), modulus of elasticity (MOE), and modulus of rupture (MOR), were assessed following European standards (EN 319 and EN 310). Physical properties such as thickness swelling (TS) and water absorption (WA) were tested according to EN 317, and thermal conductivity was determined following EN 12664.

Results and discussions

Mechanical properties

Tab. 1 presents the results for modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB), and densities of particleboards made from bagasse, cotton stalks, and kenaf bast fibers, using casein adhesive. Particleboards from bagasse and cotton stalks achieved the highest MOR and MOE values, surpassing EN 312-2 (1996) and EN 312-3 (1996) standards for furniture and interior fitments in dry conditions. These values, though slightly lower than those using treated fibers and synthetic adhesives, are comparable to panels made from bagasse with UF and PMDI adhesives. Casein adhesive offers environmental and cost benefits over synthetic alternatives.

The internal bond strength of bagasse and cotton stalks also met EN standards, demonstrating good mechanical performance at similar densities. However, the kenaf fiber boards showed poor mechanical properties, failing to meet EN standards. This was likely due to the lower resin-to-fiber ratio and the low initial pressure applied during pressing. To improve kenaf board strength, using the whole kenaf stem instead of just bast fibers is suggested. Overall, casein adhesive shows promise, particularly with bagasse and cotton stalks, for applications like furniture, interior fitting, and insulation.

As shown in Tab. 1, all panels had good thermal conductivity(λ) , below the EN standard of 0.12 W/m.K. Bagasse showed a conductivity of 0.082 W/m. K, cotton stalks 0.056 W/m.K and kenaf 0.089 W/m.K. These values are lower than those reported for fenugreek and hemp fibers (Pujari et al 2017), indicating effective heat insulation properties

Tab. 1: Mechanical properties for the panels made from the three fibers and Casein adhesives

Fibres	MOR (N/mm²)[a]	MOE (N/mm²)[a]	IB (N/mm²)[a]	λ (W/m. k)[a]
Bagasse	15.6 ± 0.67	2316 ± 130	0.39 ± 0.03	0.082 ± 0.002
Cotton stalks	14.4 ± 1.16	2230 ± 106	0.36 ± 0.04	0.056 ± 0.01
Kenaf bast fibers	2.8 ± 0.55	433 ± 55	0.07 ± 0.01	0.089 ± 0.007
Standard value	EN 310: 11 N/mm²	EN 310: 1600 N/mm²	EN 319: 0.35 N/mm²	EN 12664: 0.12 W/m.k

[a] Values are means ± SD.

Physical properties

Tab. 2 shows the thickness swelling (TS) and water absorption (WA) results for particleboards made from bagasse, cotton stalks, and kenaf bast fibres using casein adhesive after 24 hours of water immersion. The TS values for bagasse (14.4%) and cotton stalks (19.3%) slightly higher that the EN 312-3 (14%) value recommended for non-load-bearing boards in humid conditions. Kenaf fibre boards showed a significantly higher TS at 70.9%, which was expected due to the poor quality of adhesion between the fibres. WA values for bagasse, cotton stalks, and kenaf boards were 75%, 96.3%, and 192%, respectively. Differences in water absorption among the fibres can be attributed to variations in fibre type, adhesive, panel density, and manufacturing process. Overall, casein-based particleboards are more suitable for interior applications due to their tendency to swell and absorb moisture.

Tannin-based particleboards

Mechanical properties

Tab. 3 presents the MOR, MOE, and IB values for tannin-based particleboards made from three fibers. The MOR and MOE values were lower than those of casein-based boards and did not meet the EN 312-2 (1996) and EN 312-3 (1996) standards. This may be due to the acidic pH (pH 5) of the fibers, which affected the curing of tannins, typically cured at alkaline pH, leading to weaker mechanical properties. Osman et al (2009) previously reported this issue. Although the tannin adhesive pH was raised to 9, it auto condensed at room temperature, complicating application.

Tab. 2: Thickness swelling and water absorption for casein adhesive particleboards.

Fibres	WA (%) 24ha	TS (%) 2ha	TS (%) 24ha	Density (kg/m3) a
Bagasse	118 ± 14	8.9 ± 2.5	14.4 ± 4.36	613.75 ± 11.90
Cotton stalks	137 ± 13.5	9.3 ± 2.7	19.3 ± 3.92	606.25 ± 17.64
Kenaf bast fiber	214 ± 19.38	50.6 ± 3.66	70.9 ± 7.3	627.1 ± 24.21

Values are means ± SD.

The thermal conductivity results (Tab. 3) for tannin-based particleboards made from bagasse, kenaf bast fibers, and cotton stalks were all below the EN standard of 0.12 W/m.K, making them suitable for insulation applications. These values suggest that the panels are a viable, healthier alternative to conventional insulation materials (Liu et al 2012).

Tab. 3: Mechanical properties for the panel are made from the three fibers and the tannins.

Fibres	MOR (N/mm²)	MOE (N/mm²)	IB (N/mm²)	λ (W/m. k)[a]
Bagasse	8.8 ± 0.45	1263 ± 95	0.22 ± 0.07	0.057 ± 0.009
Cotton stalks	8.4 ± 0.77	1401 ± 117	0.21 ± 0.04	0.050 ± 0.012
Kenaf bast fibre	1.6 ± 0.29	577 ± 102	0.04 ± 0.35	0.083 ± 0.005
Standard value	EN 312:2: 11 N/mm²	EN 312:2: 1600 N/mm²	EN 312:2: 0.35 N/mm²	EN 12664: 0.12 W/m. k

a Values are means ± SD.

Physical properties

Tab. 4 shows the TS and WA results for tannin-based particleboards. The TS values for cotton stalk and bagasse met EN 312:3 standards, while kenaf bast fibers recorded the highest value, though lower than when used with casein adhesive. All panels exhibited high water absorption due to the hydrophilic nature of cellulosic fibers, which reduces moisture resistance (Sahu et al 2022). The internal bond strength (IB) also influences physical properties, as stronger bonds reduce panel porosity, improving water resistance, as noted by Paridah et al 2014. Tannin-based boards demonstrated better physical properties compared to casein-based ones, likely due to tannin's higher water resistance and differences in board density.

Tab. 4: Water absorption and thickness swelling for tannin particleboards.

Fibres	WA (%) 24ha	TS (%) 24ha	Density (kg/m3) a
Bagasse	110.3 ± 13	7.4 ± 3.5	633.75 ± 15.70
Cotton stalks	115.3 ± 14.5	10.3 ± 3.3	616.25 ± 19.31
Kenaf bast fibers	193.1 ± 17	48.6 ± 5.9	657.10 ± 31.46
Standard	EN 312:3 =14%		

Values are means ± SD.

Conclusion and perspectives.

The study examined the mechanical, physical, and thermal properties of particleboards made from bagasse, cotton stalks, and kenaf bast fibers using casein and tannin adhesives. Key findings include:

- The production of 100% green and sustainable panels from bagasse and cotton stalks met European standards for furniture, thermal insulation, and interior applications, without fiber pretreatment.
- Kenaf bast fibers' light weight and larger volume resulted in panels with inferior mechanical properties.
- Casein adhesive outperformed tannins in mechanical properties, with higher modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) values. Tannin adhesives are more effective in alkaline conditions, suggesting a need to adjust the fiber's acidic pH to prevent auto-condensation.
- Whole stalks of kenaf may improve mechanical properties and will be explored in future research.

- Both casein and tannin particleboards satisfied EN 12664 thermal conductivity standards, confirming their potential for bio-insulation materials.

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