MECHANICAL AND PHYSICAL PROPERTIES OF BIOCOMPOSITES FOR FURNITURE AND THERMAL INSULATION

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The objective of this work was to evaluate the performance of three natural fibers, namely, bagasse, kenaf bast fibers and cotton stalk, to produce particleboard suitable for application in green furniture and thermal insulation, using tannins and casein as natural matrices at the concentration of 15%. The particleboards were tested according to the relevant European standards to determine their mechanical properties, physical properties and thermal conductivity. The results showed that particleboards made from bagasse fibers and cotton stalks with casein adhesives exhibited higher mechanical performance and complied with European standards for board used for furniture and interior fitments. The particleboards prepared using tannins failed to satisfy the EN standards. All particleboards met the thermal conductivity requirements of the European standards.

Keywords: sugarcane bagasse, kenaf bast fibers, cotton stalks, casein, tannins

INTRODUCTION

Biomass residues from agricultural waste have gained considerable attention as a valuable resource for producing composite materials. These residues, which include crop and wood wastes, straw, bagasse, and other agricultural by-products, offer several advantages in terms of cost efficiency, environmental sustainability, and renewability.[1] Research is being conducted by the scientific community to address environmental and economic concerns by using more renewable resources to produce wood-based materials. On the other hand, in addition to their exceptional performance, particleboards have gained popularity as a widely utilized substitute for solid wood or plywood primarily due to their cost-effectiveness.[2,3] The production of particleboard in 2020 was estimated at 96.01 million m^3 worldwide. The largest producer of particleboard is Asia, while Europe is second, followed by the Americas, Africa, and finally Oceania. The highest reported volume comes from China, with a volume of 29.43 million m^3, representing 30.65% of the global production volume. Germany, Poland, Italy, Austria, and France are the most prominent European producers of particleboard.[4] Appropriate technologies for producing particleboard make it possible to use a wide range of forestry and agricultural products as raw materials.[5]

During hot pressing, adhesives are usually added to glue the fibers together to form a composite material.[6] Urea-formaldehyde (UF) resin is one of the leading adhesives in the manufacture of particleboards. It is widely used in the furniture industry due to its versatile properties.[7] The renewed interest in particleboard manufacturing in the context of green chemistry is leading to low or free formaldehyde emissions.[8–10] Using bio-based adhesives to bond particleboard, instead of synthetic adhesives, is an attractive alternative.[11] Tannin is a highly water-soluble substance[12] and a complex mixture of organic compounds characterized by their phenolic structure.[13] Casein is the protein contained in milk, which can be extracted from skimmed milk by a separation process. Milk is acidified to a pH of 4.5, so that casein can be separated and then used as an adhesive.[14,15] Most casein-based adhesives are used as a powder, while water is added at the time of use.[16]

De Almeida *et al.*[17] mention that materials' physical and mechanical properties are fundamental in determining their applications and uses. Mechanical properties include the response of a material to loading, including elastic and plastic deformation, and can be quantified by determining the maximum fracture rate. The flexural strength of materials, including particleboard, is influenced by several factors, one of them being the adhesive type used and the tensile/compressive strength of the face sheets and the shear strength of the core zone.[18,19] The water absorption of composites is influenced by many factors, such as the type of fibers and matrix, the environmental conditions (temperature and humidity), the water distribution in the composite and the reaction between water and matrix, the porosity, and the volume fraction of the fibers.[20] The attractiveness of particleboard for residential construction, furniture manufacturing, and interior design (wall and ceiling cladding) has continued to increase.[21] However, furniture production has a huge global carbon footprint. Each piece of furniture generates an average of 47 kg of carbon dioxide equivalents. This is the same amount of greenhouse gases caused by burning 20 L of petrol. Every year, 10 million tons of furniture are either incinerated or dumped in a landfill, in EU countries alone. It is important to think about how the carbon footprint could be reduced.[22] Several articles have been published on the utilization of bagasse, cotton stalks and kenaf to produce particleboard for furniture applications with interesting results.[23-25] However, challenges for their utilization to produce 100% green composites with natural matrices for furniture applications have not been adequately studied and covered.

The principal objective of this work is to investigate the possibility of producing 100% green particleboards for furniture and interior fitments, such as thermal insulation materials, in the construction industry. It also aimed to evaluate and compare the properties of particleboards made from three different types of fibers: bagasse, cotton stalk, and kenaf bast fibers, using two different natural matrices, namely tannins and casein. The mechanical, physical and thermal insulation properties of produced panels were studied and evaluated.

EXPERIMENTAL

Materials

Sugarcane bagasse was provided by the Al-Gunied Sugar Factory, which is located in Gezira State, central part of Sudan. Kenaf grew on the demonstration farm of the University of Gezira in Gezira State, South of Khartoum. Kenaf bast fibers were obtained after peeling the outer part of the kenaf fresh stalks and immersed in the water for one week, then washed thoroughly with water and dried at room temperature. Cotton stalks were collected from the Gezira project, Gezira State, Sudan. The fibers were used without any further treatments.

Mimosa condensed tannin (*Acacia*) was supplied by GREEN'ING Company. Acros Organics Company provided the casein adhesive. Hexamethylenetetramine (99%) and sodium bicarbonate were obtained from Fisher Scientific (France). All products were used as received.

Methods

Preparation of fibers

Sugarcane bagasse was used as such, no further processing was done, the size of particles was 10 to 20 mm. Cotton stalks and kenaf bast fibers were manually reduced to the same particle size as the bagasse. They were then placed in the oven at 105 °C for 24 hours to reduce the moisture content to 3%.

Preparation of bio-based adhesives

An aqueous solution with a concentration of 35% was prepared from the spray-dried powder of commercial mimosa tannins. The initial pH was raised to 9. To the tannin solids extract, 6.5% hexamethylenetetramine (hexamine) was added as a hardener.

An aqueous solution of 30% casein was used, sodium bicarbonate (25% w\w of casein) was added as a hardener. 15% of each adhesive (on the oven dry weight of the fibers) was used.

Preparation and testing of particleboards

The particleboards were produced in the laboratory of the Department of Materials Science and Engineering (SGM), at the University of Pau, the Adour Region, UPPA.

Single-layer laboratory particleboards (dimensions: 340×340×20 mm^3) bonded with the tannin, and casein adhesives at loading level of 15% of each of the two adhesives were produced. In the pressing cycle, the maximum pressure of 2.5 MPa, different pressing time durations of 480 s, 240 s, 120 s and 60 s, and pressing temperature of 180 °C were used.

The density profiles of the panels were measured on a GreCon DAX 5000 device (Fagus-GreCon Greten GmbH & Co. KG, Alfeld/Hannover, Germany), with direct scanning X-ray densitometry across the panel thickness, with an incremental step of 0.02 mm. The average of the readings was calculated for each type of panels made.

The panels were preconditioned at 20 °C and 65% humidity for three days in order to homogenize their moisture content prior testing.

Mechanical properties, *i.e.* internal bond (IB), modulus of elasticity (MOE) and modulus of rupture (MOR), were determined in accordance with the relevant European standards (EN 319 and EN 310).[26,27] Physical properties, such as thickness swelling (TS) and water absorption (WA), were tested according to appropriate EN standards (EN 317).[28] The thermal conductivity of the panels was determined according to EN 12664.[29]

RESULTS AND DISCUSSION

Casein-based particleboards

Mechanical properties

Table 1 illustrates the results of the modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond (IB), as well as the densities for the particleboards made from the three fibers and casein adhesive. Among the three fibers tested, the bagasse and cotton stalks particleboards had the highest MOR and MOE values, which exceeded the minimum requirements of EN standards for particleboard use for furniture and interior fitments under dry conditions, respectively, EN 312-2 (1996); EN 312-3 (1996). These values were slightly lower than those of other panels made from treated fibers and bio-sourced adhesives.[29-31] They are also comparable with those reported for panels made from treated bagasse and commercial UF and emulsifiable polymeric isocyanate PMD adhesives, but higher than the values achieved by panels made from soybean.[29-31] However, it is essential to note that the casein adhesive offers advantages, such as environmental friendliness and cost-effectiveness, over the synthetic adhesives mentioned above.

The internal bond strength of the bagasse and cotton stalks panels also satisfied EN 312-2 and EN 312-3 requirements for furniture application. The result indicates that the particleboards with bagasse and cotton stalks showed satisfactory performance in terms of its mechanical strength. It is worth noting that their densities were also comparable. Unexpectedly, the panels made from kenaf bast fibers and casein exhibited low mechanical performance. Their MOR, MOE and IB values did not meet the EN standard. This could be attributed to the small percentage of the resin used, in comparison with the large volume of kenaf fibers, which have low density, and as a result the fibers and the resin had less intimate contact and loosely bonded.

Nevertheless, the board density was slightly higher than the densities of the board prepared from the other two fibers. It could also be because of the low initial pressure used (2.5 MPa), as it was found to be a significant factor affecting the mechanical properties of the board.[32,33] It is interesting to note that this value was still higher than some values reported in the literature.[34] It is also in line with the value achieved by Escobar,[35] who indicated that voids per unit area in kenaf bast fiber particleboards could lead to failure under load, resulting in lower strength properties. It is worth noting that kenaf particleboard has been made from 100% kenaf bast fibers. Therefore, it could be suggested that it is better to use the whole kenaf stem, without separating the fibers, which could result in panels with improved strength properties.[36] This approach eliminates the need for costly manual separation, followed by water retting. Although more information is needed on the use of casein adhesive in particleboard production, the results of this study showed that it has a promising performance. In particular, using casein adhesive with bagasse and cotton stalks produced particleboards with favorable properties suitable for various applications, such as furniture, interior fitting, and insulation.

Thickness swelling and water absorption

Table 2 shows the results of thickness swelling (TS) and water absorption (WA) for the panels made from casein adhesive and the three fibers, after water immersion for 24 hours. The TS values obtained by the bagasse and cotton stalks were 14.4 and 19.3%, respectively. These values were slightly higher than the value recommended by EN 312:3 (14%) for non-load boards for use in humid conditions. The kenaf bast fiber particleboards had significantly higher TS, recording a value of 70.9%. However, these values were expected, as no wax or any hydrophobic materials were added during the preparation of panels, as is the case in industrial production. Furthermore, the bagasse and cotton stalks were used without depithing or any further processing in order to reduce the cost of manufacturing. These values were lower than the one achieved by other fibers bonded with UF adhesives.[29] The high TS values suggest that the casein particleboards had a higher tendency to swell and absorb moisture, and thus they can be recommended for interior applications.

The WA values for bagasse, cotton stalks and kenaf bast fibers particleboards were 75, 96.3 and 192%, respectively. In previous research work, it has been observed that the type of fiber, the adhesive matrix, the panel's density and the manufacturing process can significantly influence the water absorption properties of particleboard.[37,38] It has been observed that kenaf particleboards had the biggest density among the fibers studied. The differences between the three fibers towards water absorption and swelling could be related to this fact.

Table 1
Mechanical properties of panels made from the three fibers and casein adhesives

Fibers	MOR (N/mm²)*	MOE (N/mm²)*	IB (N/mm²)*	Density (kg/m³)*
Bagasse	15.6 ± 0.67	2316 ± 130	0.39 ± 0.03	613.75 ± 11.90
Cotton stalks	14.4 ± 1.16	2230 ± 106	0.36 ± 0.04	606.25 ± 17.64
Kenaf bast fibers	2.8 ± 0.55	433 ± 55	0.07 ± 0.01	627.1 ± 24.21
Standard value	EN 310: 11 N/mm²	EN 310: 1600 N/mm²	EN 319: 0.35 N/mm²	

*Values are means ± SD

Table 2
Thickness swelling and water absorption for casein adhesive particleboards

Casein adhesive particleboards	WA (%)* 24 h	TS (%)* 2 h	TS (%)* 24 h	Density* (kg/m³)
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 fibers	214 ± 19.38	50.6 ± 3.66	70.9 ± 7.3	627.1 ± 24.21

*Values are means ± SD

Table 3
Thermal conductivity for panels made from the three fibers and casein adhesive

Fibers	Thermal conductivity (W/m.K) *
Bagasse	0.082 ± 0.002
Cotton stalks	0.056 ± 0.01
Kenaf bast fibers	0.089 ± 0.007
EN 12664	0.12

*Values are means ± SD

Thermal conductivity

Table 3 presents the results of the thermal conductivity for the particleboards made of bagasse, kenaf bast fibers, and cotton stalks with casein. The results revealed good thermal conductivity, below the EN standard value (0.12 W/m.K). The thermal conductivity of the bagasse particleboard exhibited a value of 0.082 W/m.K. The cotton stalk particleboard had a value of 0.056 W/m.K, while kenaf bast fibers recorded a value of 0.089 W/m.K. The three fibers exhibited lower values than what was reported in the literature for fenugreek and hemp fibers.[39,40] The lower values of thermal conductivity indicate that such particleboards can effectively limit heat transfer and, therefore, are suitable for improving thermal insulation in various applications. The use of natural fibers in the manufacture of infrastructure materials offers several advantages. Firstly, it helps to minimize the carbon footprint associated with the manufacturing process, as these fibers are obtained from renewable sources. In addition, these natural fibers offer excellent mechanical properties that make them a suitable alternative to conventional materials.

Thermal conductivity is a crucial parameter in assessing the suitability of a material for thermal insulation applications in the construction industry, specifically, as wall panels, ceiling, doors, roof.[41] Moreover, using natural fibers is often cost-effective, which contributes to the affordability of these materials.[42,43] It is worth noting that the thermal conductivities of particleboards can be further optimized by considering factors, such as density, cell structure, and thickness during the manufacturing process. This optimization can lead to the development of particleboards with even better thermal insulation properties, offering improved energy efficiency and comfort in buildings and other related industries.

Tannin-based particleboards

Mechanical properties

Table 4 shows the MOR, MOE and IB values for the tannin-based particleboards made from the three fibers. It was found that the MOR and MOE values obtained were lower than those of casein-based ones, and they did not meet the minimum requirement values stated in EN 312-2 (1996) and EN 312-3 (1996). This could be attributed to the fact that the acidic pH (pH 5) of the fibers may lower the pH of glued particles, affecting the tannins curing, which usually hardened at an alkaline pH, and resulted in boards with poorer mechanical properties. This phenomenon was previously reported by Osman *et al.*[44] Although the pH of the tannin adhesives was raised to 9, this caused the tannins to autocondense at room temperature[45] and become a thick solution that was difficult to be evenly sprayed on the fibers. Furthermore, the percentage of resin used was small in comparison with the large volume of kenaf fibers.

In contrast, the isoelectric pH of the casein makes it more soluble at alkaline pH, as it can be sprayed evenly on the fibers to achieve complete coverage and good mechanical properties. Furthermore, the addition of sodium bicarbonate, as a hardener, balanced the acidic pH of the fibers. It was also observed that casein, which, unlike tannins, is a heterogeneous polymer, can rapidly crosslink into a strong network thanks to the heat treatment provided by the hot press.[46] Among the three fibers studied, the bagasse and cotton stalks particleboards had the highest MOR and MOE values, while kenaf bast fibers showed the lowest value. This could also be related to a number of factors, one of these is the relatively large fiber particle size used in this study (10 to 20 mm). It had been observed that the use of smaller particle sizes – of 3 and 4 mm – could produce better mechanical properties. It has been observed that the bagasse and cotton stalks performed well with both adhesives and produced better mechanical properties. This may be due to the fact that both bagasse and cotton stalks fibers were used without further screening to eliminate the fine particles (dust), which resulted in compacted panels, which facilitated the heat transfer evenly throughout the boards and contributed to the adhesives curing and the superior mechanical performance.[47]

Table 4
Mechanical properties for panels made from the three fibers and tannins

Fibers	MOR (N/mm²)*	MOE (N/mm²)*	IB (N/mm²)*	Density (kg/m³)*
Bagasse	8.8 ± 0.45	1263 ± 95	0.22 ± 0.07	633.75 ± 15.70
Cotton stalks	8.4 ± 0.77	1401 ± 117	0.21 ± 0.04	616.25 ± 19.31
Kenaf bast	1.6 ± 0.29	577 ± 102	0.04 ± 0.35	657.10 ± 31.46
Standard value	EN 312:2: 11 N/mm²	EN 312:2: 1600 N/mm²	EN 312:2: 0.35 N/mm²	

*Values are means ± SD

Table 5
Water absorption and thickness swelling for tannin-based particleboards

Tannin-based particleboards	WA (%)* 24h	TS (%)* 24h	Density* (kg/m³)
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

*Values are means ± SD; Standard EN 312:3: TS = 14%

Thickness swelling and water absorption

Table 5 shows the results of TS and WA for the tannin particleboards. The TS values achieved for cotton stalks and bagasse were in agreement with EN 312:3. As expected, kenaf bast fibers recorded the highest value, however, it is lower than the one achieved when used with the casein adhesive. All panels showed a high rate of water absorption. This could be understood in the context of the polar and hydrophilic nature of cellulosic fibers that lower the moisture resistance.[48] Furthermore, the physical properties of particleboard can be influenced by the internal bond strength of the boards (IB). The strong bond strength between particles can lead to an improvement of specific physical properties, as it lowered the panels' porosity. This relationship is also highlighted in the study of Paridah *et al.*[49]

The tannin-based particleboards showed good physical properties, compared to the casein-based ones. This difference can be attributed to casein's relatively lower water resistance than that of tannin, and the differences in the densities of the boards. However, the water resistance of casein adhesive can be improved by increasing the proportion of hardeners in the range of 15 to 25% and smaller amount of wax.[15,50] According to Ochi,[51] heat treatment scenarios can improve dimensional stability, as evidenced by reduced water absorption and thickness swelling. It is important to note that, while these treatments can improve specific properties, they can also affect the mechanical properties of the particleboard as a whole and increase the cost of manufacturing. Therefore, the current study focused on producing biocomposites without any costly pretreatment of the fibers in order to assess their performance with the adhesives.

Thermal conductivity

The results obtained for the thermal conductivity of the tannin particleboards made from bagasse, kenaf bast fibers, and cotton stalks showed values below the standard value of EN (0.12 W/m.K), which is desirable for insulation applications. Among the three fibers, the highest thermal conductivity was achieved by kenaf bast fiber (0.083 W/m.K), while the lowest (0.05 W/m.K) was recorded by cotton stalks. The bagasse particleboards recorded a thermal conductivity value of 0.057 W/m.K (Table 6). These results indicate that the panels can serve as a viable and healthier alternative to the insulation materials currently in use.[52] Insulation materials with lower thermal conductivity values can contribute to energy efficiency by reducing heat loss or gain through building structures. They can help maintain stable indoor temperatures, reduce the need for excessive heating or cooling, and ultimately lead to energy savings.

Table 6
Thermal conductivity for panel made of the three fibers and the tannins adhesive

Fibers	Thermal conductivity (W/m.K)*
Bagasse	0.057 ± 0.009
Cotton stalks	0.050 ± 0.012
Kenaf bast fibers	0.083 ± 0.005
EN 12664	0.12

*Values are means ± SD

CONCLUSION

The study provided insights into the mechanical, physical, and thermal properties of particleboards made from bagasse, cotton stalks, and kenaf bast fibers, with casein and tannin adhesives, comparing the performance of the three fibers and the adhesives used. It highlights the importance of fiber type and adhesive selection in achieving the desired properties. Based on the results of the study, the following conclusions can be drawn:

- The study succeeded in producing 100% green panels that met the European standard for panels suitable for furniture usage, thermal insulation and interior applications, from the bagasse and cotton stalks, without any pretreatment of the fibers;
- The light weight of kenaf bast fibers compensated by a larger fiber volume leads to panels with poor mechanical properties;
- Casein adhesive performed better compared to the tannins, with regard to the mechanical properties;
- Casein-based particleboards generally had higher values for modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB), compared to tannin-based particleboards. As deduced from previous research work by some of the authors of the current study, tannin adhesives work better in alkaline media, and it is

recommended to alter the acidic pH of the fibers in order to avoid tannins autocondensation;

- Kenaf fibers could be used as whole stalks, without costly retting, and may yield better mechanical properties – this direction will be investigated in future research;
- Both casein and tannin particleboards met the standard requirements (EN 12664) for thermal conductivity, indicating their suitability for the production of the bio-insulation materials.

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