

Development and Characterization of Formaldehyde-free Particleboards using Detarium senegalense seed powder as an environmentally friendly Bio-binder.

Abubakar Sadiq Imam

Sharda University

Kamesh Bodduru

boddurukamesh@sharda.ac.in

Sharda University

Kennedy Sarangapani

Sharda University

L.A.M Kolo

University of Maiduguri

Research Article

Keywords: Detarium senegalense, Bio-binder, Particleboard, Sawdust, FTIR, and SEM

Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11032653/v1>

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

[Read Full License](#)

Additional Declarations: No competing interests reported.

Development and Characterization of Formaldehyde-free Particleboards using *Detarium senegalense* seed powder as an environmentally friendly Bio-binder.

Abstract

This study evaluates the potential of *Detarium senegalense* seed powder as an all-natural binder for the processing of particleboard without the use of formaldehyde. The aim of the study was to investigate the feasibility of using *Detarium senegalense* seed powder as a natural binder for the production of particleboard with sawdust as a reinforcing material without formaldehyde. Particleboards were produced using a low-energy cold pressing technology with a binder content of 10, 20, and 30 wt% and then characterized for their chemical, physical, mechanical, and morphological properties. FTIR spectroscopy analysis revealed the presence of hydroxyl, amide, carbonyl, and glycoside functional groups in the bio-binder, which are observed as polysaccharides and proteins, indicating the presence of adhesive properties in the bio-binder. Adding a higher binder content resulted in an increase in density from $576.67 \pm 35.12 \text{ kg/m}^3$ to $872.78 \pm 80.70 \text{ kg/m}^3$. The formulation with 10% binder content had low water resistance and disintegrated in water, while the formulation with 30% content had the lowest water absorption ($59.43 \pm 5.90\%$). Scanning electron microscopy also revealed an increase in matrix continuity, an increase in interfacial adhesion, and a decrease in void content with an increase in binder content. The results showed that *Detarium senegalense* seed powder can be used as an alternative renewable bio-binder for particleboard production, and that the formulation with 30% seed powder content is the most promising. This study demonstrates the potential of underutilized tropical bio-resources as a basis for sustainable wood composites and green building materials.

Keywords: *Detarium senegalense*, Bio-binder, Particleboard, Sawdust, FTIR, and SEM.

1. Introduction

Most conventional particleboards are manufactured using synthetic resin-based adhesives, particularly urea-formaldehyde adhesives, which are well known for their high bond strength but have serious environmental and health drawbacks due to formaldehyde emissions, poor biodegradability, dimensional instability in wet weather, and difficulties in end-of-life

disposal [1], [2], [3]. In the future, with the increasing demand for wood composites and the depletion of forest resources, the need for sustainable raw materials and alternative production methods is increasing, making an abundant and renewable by-product of the wood processing industry, namely sawdust, a valuable raw material for particleboards and other value-added products [3], [4]. In this context, research has turned to the use of biodegradable binders from renewable biomass and attempted to replace petroleum-based resins, but there is insufficient information on the long-term performance and durability [5]. Biodegradable particleboards also comply with the principles of circular bio-economy, as they can be used as green building materials that are environmentally friendly, provide thermal and sound insulation, reduce waste and improve resource efficiency [5], [6].

Formaldehyde-based synthetic adhesives, such as urea-formaldehyde, phenol-formaldehyde, melamine-urea-formaldehyde, and polyurethane resins, are used in manufacturing and applications and pose significant environmental and health concerns, particularly due to formaldehyde emissions throughout the product's life cycle; formaldehyde is classified as a carcinogen by the International Agency for Research on Cancer (IARC) and the Environmental Protection Agency (EPA) [7], [8]. Furthermore, the use of most synthetic adhesives is associated with environmental pollution, greenhouse gas emissions, and sustainability issues related to fossil fuel depletion and market price fluctuations [4], [9]. The use of synthetic resins as a binder in particleboard makes them partially non-biodegradable and difficult to manage at end-of-life, contributing to their environmental impacts [10]. These concerns have led to increased research activity focused on biodegradable binders that are renewable, biosafe and environmentally friendly for wood composite products [4].

Adhesives based on natural polymers, known as bio-bonds, have gained popularity as an environmentally friendly alternative to synthetic adhesives in wood composites. Gums derived from plants (mucilaginous gums, seed gums, and exudate gums) are found in various parts of plants and possess good water-binding and gelling properties, making them potential candidates for bio-adhesives [11]. Several studies have also shown that suitable particleboard can be produced from various agricultural wastes that are recyclable and readily available locally, but water resistance and mechanical properties remain problematic [2]. Although lignin is used in particleboard production as a formaldehyde-based binder, such methods still contain petroleum-based components, are expensive, prone to formaldehyde emissions, and have limited recyclability, further highlighting the need for fully bio-based, environmentally friendly binders for particleboard production [12].

Detarium senegalense is a tropical leguminous tree whose seeds contain natural gums, polysaccharides, and proteins with water-binding and gelling properties [13], [14], [15]. Although *Detarium senegalense* is readily available and biochemically suitable, it has been little used in wood composite research, and only a few studies have been conducted to explore the potential of using wood as a biobased binder. Therefore, the use of *Detarium senegalense* as an exclusive adhesive offers opportunities to valorize the underutilized biomass resource and facilitate the development of sustainable, formaldehyde-free particleboards.

The novelty of this study lies in the first systematic investigation using *Detarium senegalense* seed powder as the only fully biodegradable binder for the production of formaldehyde-free particleboard using a low-energy hydraulic cold pressing method. Unlike conventional petroleum- or formaldehyde-based synthetic resins used in particleboard systems, this study utilizes an underutilized tropical seed resource, rich in polysaccharides and proteins, as a natural adhesive for wood sawdust-based composites. The study also establishes the relationship between the bio-binder content of *Detarium senegalense* and the resulting chemical, physical, mechanical, and morphological properties of particleboard. Specifically, IR spectroscopy and SEM were used to systematically evaluate the effect of binder concentration (10–30 wt%) on density, water absorption, flexural strength, tensile strength, and interfacial morphology. The results provide new experimental evidence that this underutilized tropical bio-resource is a formaldehyde-free, renewable alternative to synthetic binders in particleboard production. Thus, this study contributes to the development of sustainable lignocellulose composites and promotes biomass utilization and the development of a circular bio-economy.

2. Materials and Methods

To test the feasibility of using *Detarium senegalense* seed powder as a natural binder for the production of formaldehyde-free particleboards, an experimental study was conducted. Wood sawdust was used as the lignocellulosic material, and *Detarium senegalense* seed powder was used as the bio-binder. The following subsections describe the materials, preparation procedures, particleboard production, curing conditions, and characterization methods.

2.1. Materials

Wood sawdust obtained from a local sawmill was used as the lignocellulosic raw material for the production of particleboard. *Detarium senegalense* seed powder remaining

after the oil extraction process [16] was used as a bio-binder. All binder preparation and formulation processes were carried out using distilled water. A universal testing machine (UTM) at the School of Engineering and Science, Sharda, was used for the mechanical characterization of the manufactured particleboards. A steel mold measuring 140 x 140 x 10 mm was fabricated in the mechanical engineering workshop and used for the production of the boards.

2.2. Preparation of sawdust

Sawdust was collected and pre-cleaned manually to remove visible impurities and foreign materials such as wood chips, bark, and other unwanted substances. The sawdust was then dried in an oven at 105°C for 24 hours to produce a drier, more dehydrated material for use. The sawdust was dried, then cooled and sieved to obtain particles with a nominal size of 400 µm. The sieved sawdust was collected and stored in dry conditions. The prepared sawdust was immediately used for preparation and mixing in the production of particleboard to reduce moisture absorption from the environment.

2.3. Preparation of *Detarium senegalense* bio-binder

Detarium senegalense seed powder was first oven-dried at 60°C for 24 hours and then ground using a laboratory mill to obtain a fine powder. The ground powder was sieved to a nominal particle size of 250 µm to produce a uniform powder for the bio-binder. The bio-binder was prepared by mixing the sieved seed powder with preheated distilled water at 80°C at a powder-to-water ratio of 1:1.5 (w/v) under continuous stirring by manual wetting to ensure uniform dispersion of the powder. This mixture was then held at 80°C for 10 minutes to activate the binder components and produce a thick paste. The bio-binder was then activated and cooled before mixing with sawdust to produce particleboard.

2.4. Mix formulation

The particleboard formulation was developed using a desired board density of 700 kg/m³. The required dry mass of each board was calculated based on the target density and mold internal volume using Equation 1, as in previous studies [7], [9]. Three different sawdust to *Detarium senegalense* seed bio-binder ratios were selected: 90:10, 80:20, and 70:30 (%) (w/w) of sawdust to bio-binder to study the effect of increasing the bio-binder amount on the physical, mechanical, and morphological properties of the produced particleboards. The

sawdust to bio-binder ratios were adjusted so that the total dry mass of the boards remained the same, approximately 137 g per board, for each formulation, but the bio-binder amount varied from 10 to 30 wt%. The amounts of sawdust and *Detarium senegalense* seed powder required for specific formulations are shown Table 1.

$$Density (\rho) = \frac{Mass (kg)}{Volume (m^3)} \quad (1)$$

Table 1: Material quantities per board sample

Material	Sample A		Sample B		Sample C	
	%	Mass (g)	%	Mass (g)	%	Mass (g)
Sawdust	90	123	80	110	70	96
<i>Detarium senegalense</i> seed powder	10	14	20	27	30	41
Total dry solids	100	137	100	137	100	137

2.5. Mold design and board formation

A steel mold with internal dimensions of $140 \times 140 \times 10$ mm was used to produce particleboard. A very thin, uniform layer of release oil was applied to the inner surfaces of the mold to ensure easy removal of the compacted board from the mold after pressing. The mold was then securely put together. A fixed amount of *Detarium senegalense* bio-binding paste was slowly added to a measured amount of sawdust in a bowl and mixed thoroughly to evenly distribute the binder and ensure good coverage of the sawdust. The mixture was then placed in a mold, spread evenly, and compacted manually to remove entrapped air and prevent the formation of internal voids [9]. The filled mold was then ready for hydraulic cold pressing, as shown in Figure 1(a).

2.6. Cold pressing using a hydraulic press and curing

Uniformity of the different particleboard types was ensured by using identical cold pressing conditions. The filled mold was compressed under a constant pressure of 10 MPa for 30 minutes in a hydraulic press. The pressure was then slowly released after pressing to prevent cracking or damage to the newly formed board. The mold was then removed from the molding press and carefully opened, after which the newly formed (green) board was carefully removed to avoid deformation due to the board's low initial strength. These boards were laid on a non-

absorbent film surface and allowed to air-cure at room temperature for 24 hours to allow moisture to be gradually and uniformly removed from the boards with minimal warping. This was followed by oven curing for 8 hours at 80°C. The boards were then cured and conditioned for an additional 7 days at 25°C and 65% relative humidity (RH) under standard conditions before being subjected to physical and mechanical testing [17]. The overall pressing and curing process is shown in Figure 1(b).

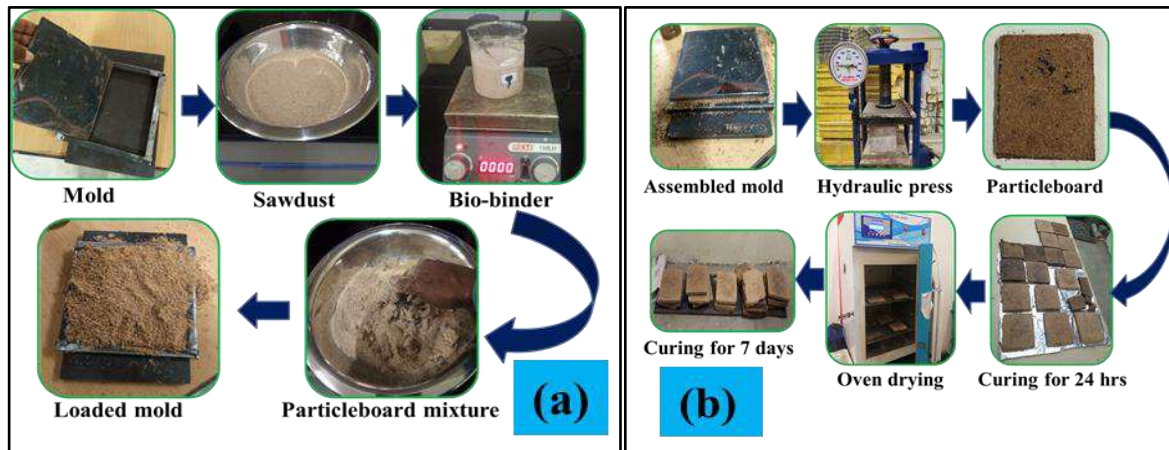


Figure 1: (a) Mold design and board formation, (b) Cold hydraulic press and curing

3. Chemical composition of *Detarium Senegalense* seed powder determination

Using Fourier transform infrared spectroscopy (FTIR), the chemical composition of *Detarium senegalense* seed powder was analyzed to identify the main functional groups present in the seed powder. The analysis was conducted to identify chemical components that may contribute to the potential adhesive properties of the seed powder and to determine the suitability of the seed powder as a natural bio-binder for particleboard production. The identified absorption bands were used to characterize functional groups primarily associated with polysaccharides and proteins, such as hydroxyl, amide, carbonyl, and glycosidic groups. These functional groups indicate chemical components that may facilitate the interaction and bonding between the biobinder and sawdust particles. Figure 4 shows the FTIR spectrum of *Detarium senegalense* seed powder.

4. Property testing

The physical and mechanical properties of the manufactured particleboards were tested according to ASTM D1037. After curing and conditioning, each board was carefully cut with a fine-tooth saw into specimens of the appropriate dimensions for the respective tests. Specimens for bending and tensile testing were cut to dimensions of 150 × 20 × 6 mm, and for

water absorption testing, they were cut to dimensions of $50 \times 20 \times 6$ mm. For each property, three specimens were prepared for each bio-binder formulation (10, 20, and 30 wt%), and the results are presented as mean values with standard deviations.

4.1. Physical property testing

The physical properties of the resulting particleboards were studied to determine water absorption and density at different levels of the *Detarium senegalense* bio-binder content.

4.1.1. Density determination

The mass and size of each prepared board were used to calculate the density of the resulting particleboards. All boards were weighed using a digital scale, and their length, width, and thickness were measured at appropriate points using calipers. The dimensions of each board in the experiment were measured, the volume was calculated from these dimensions, and the density was determined as the ratio of the board mass to the corresponding volume according to Equation 1.

4.1.2. Water Absorption (WA)

Water absorption (WA) was measured to assess the water resistance of the resulting particleboards. Each prepared sample was weighed using a digital scale before immersion. The initial mass (M_0) of each prepared sample was determined using a digital scale before immersion. The samples were then completely immersed in water at room temperature for 24 hours. The specimens were then removed from the water, the surface water was carefully removed with an absorbent cloth, and the final mass (M_1) was measured, as shown in Figure 2 [1]. Water absorption was determined and expressed as a percentage of the original specimen mass according to the following Equation 2 [9], [18].

$$WA (\%) = \frac{M_1 - M_0}{M_0} \times 100 \quad (2)$$

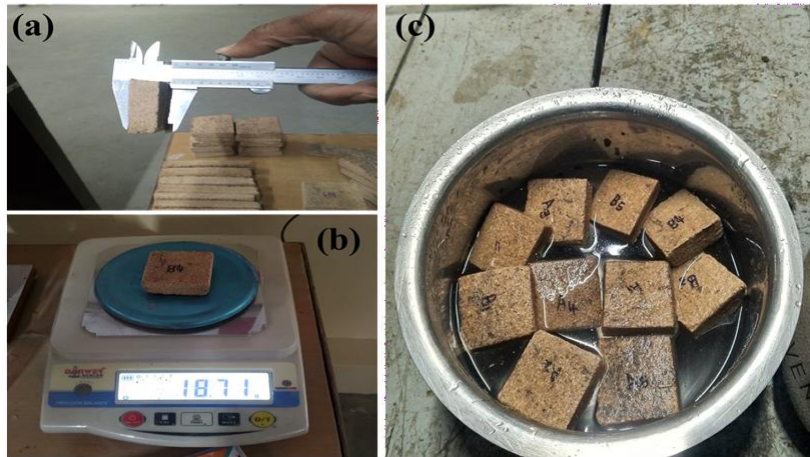


Figure 2: (a) Dimensions taking (b) Weight measurement (c) Samples immersed in water

4.2. Mechanical property testing

The mechanical properties of the resulting particleboards were tested using a universal testing machine (UTM) with a 5 kN load cell. The test was conducted at a constant crosshead speed of 5 mm/min, and the load was gradually increased until failure. Mechanical characterization was performed to evaluate the structural performance and potential suitability of the particleboards for practical applications. For each bio-binder formulation, three specimens were tested separately under three test conditions (three-point bending and tensile strength) to improve the reproducibility and reliability of the test results [1], [8]. Mechanical properties, such as flexural and tensile characteristics, were obtained from the load-strain curves of the respective specimens in accordance with ASTM D1037 [1], [9].

4.2.1. Flexural Properties

The mechanical properties of the prepared particleboards were tested using a universal testing machine (UTM) to determine their flexural and tensile load-bearing capacity. The prepared specimen was then firmly inserted between the upper and lower clamps of the UTM, and a tensile force was gradually applied until failure, as shown in Figure 3(a). The specimen was tested for flexural properties, with the load applied at the midpoint of the specimen in a three-point bending configuration with a 150 mm span between two supports, as shown in Figure 3(b). The tests were conducted at a constant crosshead speed of 5 mm/min, and the load and strain were continuously recorded until failure. The measured parameters were used to compare the load-bearing capacity and flexural properties of particleboards with different *Detarium senegalense* bio-binder contents [1], [9].

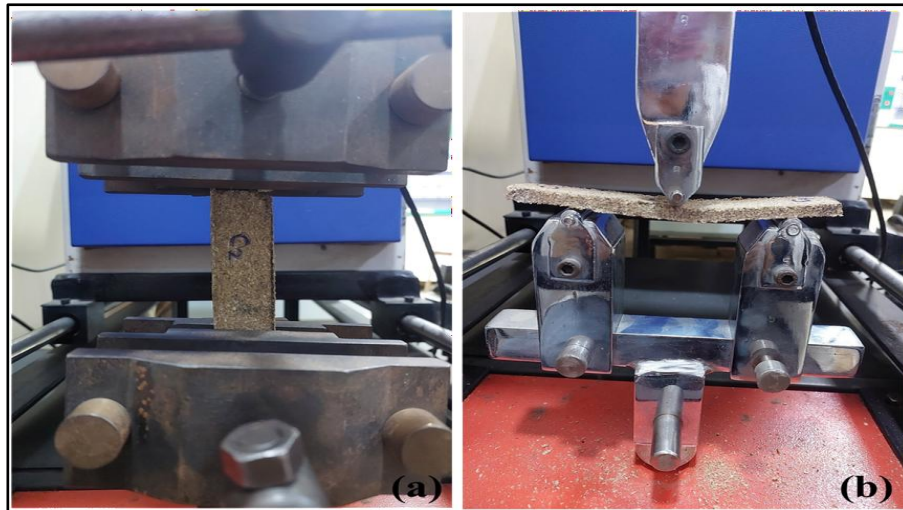


Figure 3: Flexural Properties, (a) 3-point bending test and (b) Tensile strength test

4.2.2. Scanning Electron Microscopy (SEM) Analysis

The surface morphology and fracture properties of the resulting particleboards were analyzed using scanning electron microscopy (SEM) at different levels of the *Detarium senegalense* bio-binder. SEM analysis was used to evaluate the interfacial adhesion between wood sawdust particles and the bio-binder matrix, as well as the distribution and continuity of the bio-binder within the board structure. The fracture surfaces of the samples with each mixing ratio were examined to identify differences in bio-binder binding, void formation, surface morphology, and matrix continuity at different bio-binder contents. The resulting micrographs were used as a qualitative criterion for the effect of *Detarium senegalense* bio-binder concentration on the internal structure and adhesion properties of the particleboards.

4.3. Experimental design and statistical analysis

Each experiment was repeated three times for each particleboard formulation to ensure reproducibility. Experimental results are presented as mean $\pm$ standard deviation (SD). Mean values were used as an indicator of the central tendency of the measured properties, and standard deviation as an indicator of sample variability. The data were organized and processed in Microsoft Excel, and statistical analysis of the experimental results was performed.

5. Results and Discussion

This section presents and discusses the chemical, physical, mechanical, and morphological properties of particleboards produced using *Detarium senegalense* seed powder as a bio-binder. The results are analyzed to examine the effect of bio-binder content on the overall

performance of the produced boards. The results of IR spectroscopy, water absorption, mechanical testing, and SEM characterization are discussed in terms of adhesion behavior, structural integrity, moisture resistance, and the suitability of the particleboards for potential applications.

5.2. Chemical composition of *Detarium Senegalense* seed powder

The FTIR spectrum of *Detarium senegalense* seed powder exhibits absorption bands, as shown in Figure 4, which are characteristic of polysaccharides and proteins, suggesting that it has potential as a natural bio-binder [19]. The broad bands at 3742 and 3283 cm^{-1} correspond to O–H and N–H stretching vibrations, respectively, and are thought to be due to hydroxyl and amide groups, which can form hydrogen bonds and promote adhesion to sawdust particles. The peak at 2903 cm^{-1} corresponds to aliphatic C–H stretching vibrations, and the weak band at 2340 cm^{-1} is due to atmospheric CO_2 . The amide I band at 1647 cm^{-1} indicates protein components capable of participating in the formation of cohesive bonds, while the amide II band at 1546 cm^{-1} indicates amide II. The bands at 1345, 1215, and 1025 cm^{-1} are associated with the C–N, C–O, and C–O–C vibrational frequencies, respectively, while the strong band at 1025 cm^{-1} suggests a significant contribution from the polysaccharide component. Overall, all identified functional groups underlie the adhesive activity of *Detarium senegalense* seed powder during cold pressing. At the same time, a high content of hydroxyl groups may also lead to higher water absorption in the resulting particleboards.

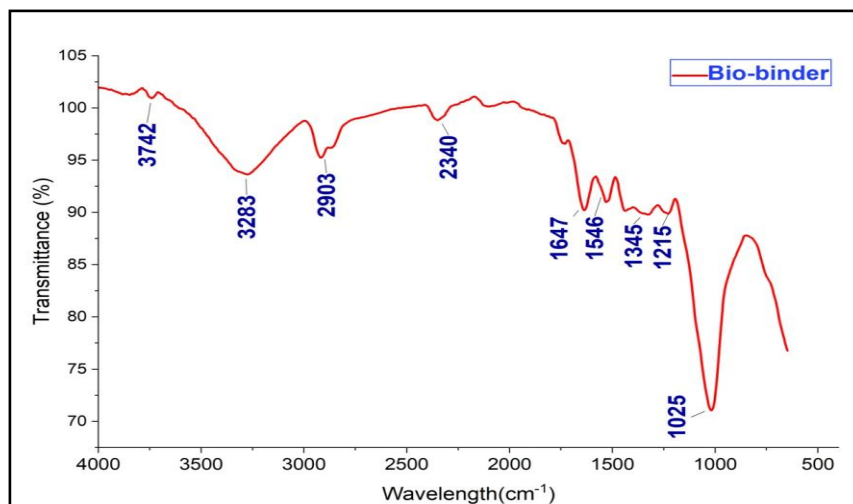


Figure 4: FTIR spectrum of *Detarium senegalense* seed powder

5.3. Physical properties

It was observed that the bio-binder content clearly influenced the physical properties of the particleboards as shown in Table 2. The density of *Detarium senegalense* boards improved

with an increase in binder content from 10% to 30%, ranging from $576.67 \pm 35.12 \text{ kg/m}^3$ to $872.78 \pm 80.70 \text{ kg/m}^3$, respectively, indicating improved particle compaction. However, water resistance was inversely proportional to the binder content. The board with a 10% binder content disintegrated when immersed in water after 24 hours, indicating that the amount of binder used was insufficient to maintain the integrity of the board in a wet state. The highest water absorption was obtained with a composition with a 20% binder content – $75.49 \pm 2.28\%$, which may be due to the hydrophilic properties of the bio-binder (rich in polysaccharides/proteins). Interestingly, the binder content had a minimum water absorption value of $59.43 \pm 5.90\%$ when using 30 wt% binder, which was the lowest water absorption value among the tested formulations. This decrease, despite the higher board density, could be due to better coating and encapsulation of wood sawdust particles and less interpore connectivity, which impedes water penetration into the board. Similar trends have been noted in previous studies [2]. Overall, the results showed that using higher levels of *Detarium senegalense* bio-binder provided higher board density, better water resistance, and the highest level of physical performance at 30 wt%. At 10 wt%, the level of *Detarium senegalense* bio-binder was too low to maintain board integrity when immersed in water.

Table 2. Physical properties of *Detarium senegalense*–bonded particleboards

Binder content (%)	Density (kg/m ³)	Water absorption in 24 h (%)
10	576.667 ± 35.12	Dissolved
20	776.111 ± 67.29	75.493 ± 2.28
30	872.778 ± 80.70	59.426 ± 5.9

5.4. Mechanical properties

The manufactured particleboards were subjected to mechanical properties assessment to determine the effect of the *Detarium senegalense* bio-binder on load-bearing capacity, flexural strength, flexural stiffness, and tensile behavior. The results of the flexural and tensile tests are presented and analyzed in the following subsections.

5.4.1. Flexural strength

The three-point flexural test of particleboard showed a significant effect of the *Detarium senegalense* bio-binder content as shown in Figure 5(a). However, at 10 wt% bio-binder, flexural strength was relatively low, due to poor matrix formation and weak adhesion between sawdust particles. The higher the bio-binder content, the higher the load-bearing

capacity and the better the deformation behavior of the boards, indicating increased stress transfer and improved matrix continuity. The composition with 30 wt% bio-binder demonstrated the highest flexural capacity and the highest flexural strain before failure, indicating better flexural strength and energy absorption under flexural loading. This behavior may be due to better particle encapsulation, improved interparticle adhesion, and improved crack bridging, which may delay catastrophic failure under flexural loading.

5.4.2. Tensile strength

The tensile load-deflection properties shown in Figure 5(b) indicate that the tensile properties of the particleboards were significantly altered by the *Detarium senegalense* bio-binder content. The 20 wt% formulation had the highest load-bearing capacity, while the deformation after reaching the peak load was the lowest, indicating the best stress transfer and relatively good continuity of the binder matrix in the board structure. The 10 wt% formulation showed a relatively sharp failure soon after reaching the maximum load, which may be explained by the lack of binder coating or insufficient interparticle bonding. The 30 wt% formulation showed a lower peak load, but the deformation after reaching the peak load was higher compared to the 20 wt% board, indicating a greater degree of deformation resistance. This behavior may be due to localized binder accumulation and greater structural heterogeneity at a higher binder content. Overall, the results showed that the material containing 20 wt% bio-binder exhibited the best tensile load-bearing properties, while the material containing 30 wt% bio-binder exhibited higher deformability after reaching the peak load.

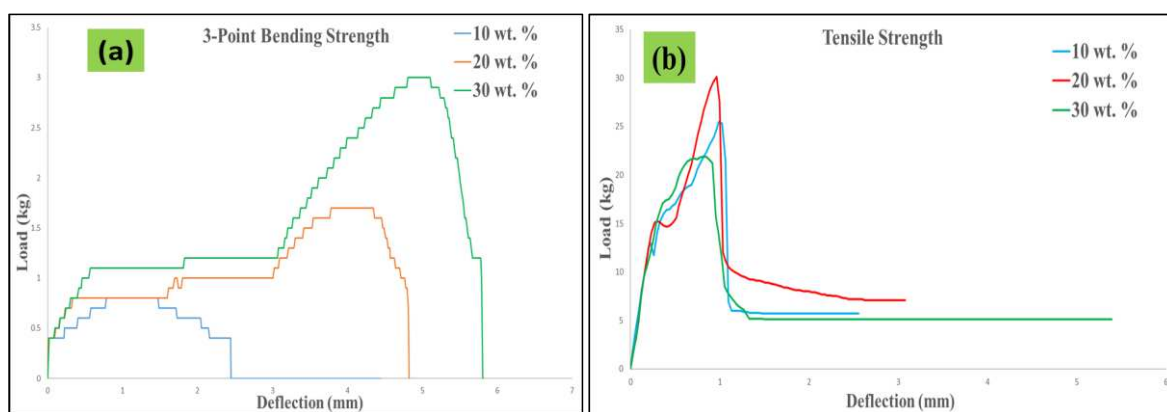


Figure 5: Load–deflection curves (a) 3-point bending strength and (b) Tensile testing

5.5. Summary of the properties

The physical and mechanical properties of the particleboards were significantly affected by the *Detarium senegalense* bio-binder content, as shown in Table 3. The results showed that with an increase in the binder content from 10 wt% to 30 wt%, the board density increased from $576.67 \pm 35.12 \text{ kg/m}^3$ to $872.78 \pm 80.70 \text{ kg/m}^3$, respectively, due to increased particle consolidation and a decrease in internal voids. The water resistance of the 10 wt% formulation was low, as it completely degraded after 24 hours in water, indicating that the amount of binder was insufficient to maintain the integrity of the board when exposed to water. The 20 wt% formulation had higher water absorption ($75.50 \pm 2.28\%$) and moderate flexural strength (MOR) of $4.17 \pm 0.03 \text{ MPa}$ and modulus of elasticity (MOE) of $839.89 \pm 0.04 \text{ MPa}$, which demonstrated better structural performance than the 10 wt% formulation. The water absorption decreased to $59.43 \pm 5.90\%$ when the binder content was 30%, while the MOR and MOE increased significantly to $7.36 \pm 0.01 \text{ MPa}$ and $2189.73 \pm 0.04 \text{ MPa}$, respectively, which was consistent with the results of previous studies [2], [10]. This performance improvement is likely due to better particle encapsulation, stronger interparticle bonding, and lower pore connectivity, which is a result of the increased amount of binder used. Overall, the formulation with a 30 wt.% bio-binder content proved to be the best of the studied formulations, as it offers the best combination of density, water resistance, flexural strength, and stiffness.

Table 3: Summary of physical and mechanical properties

Binder content (%)	Density (kg/m^3)	WA (%)	MOR (MPa)	MOE (MPa)
10	576.67 ± 35.12	Dissolved	1.96 ± 0.03	762.59 ± 0.02
20	776.11 ± 67.29	75.50 ± 2.28	4.17 ± 0.03	839.89 ± 0.04
30	872.78 ± 80.70	59.43 ± 5.9	7.36 ± 0.01	2189.73 ± 0.04

5.6. Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscope (SEM) micrographs, shown in Figure 6, show that the morphology and interfacial adhesion of the particleboards change significantly with increasing *Detarium senegalense* bio-binder content. For the sample with a 10 wt.% bio-binder content in Figure 6 (a), the microstructure reveals insufficient binder distribution, interfacial gaps, and relatively large gaps between lignocellulosic particles, indicating inadequate binder distribution and weak adhesion between the particles/lignocellulose and the binder. The microstructure at 20 wt% in Figure 6 (b) appears more compact and continuous, with improved adhesion between the sawdust particles and the bio-binder, and a decrease in the amount of

voids in the microstructure. This indicates that at this intermediate binder content, greater particle consolidation and better matrix continuity are observed. The structure at 30 wt% in Figure 6 (c) is relatively well consolidated, but with areas of binder agglomeration and microcracks. This may be due to the higher amount of bio-binder and localized shrinkage during drying and curing. Overall, the SEM observations are consistent with the physical and mechanical results, indicating that higher bio-binder content generally results in more uniform particle-binder interactions and a lower in-situ void volume, but may cause localized heterogeneity when too much binder is used.

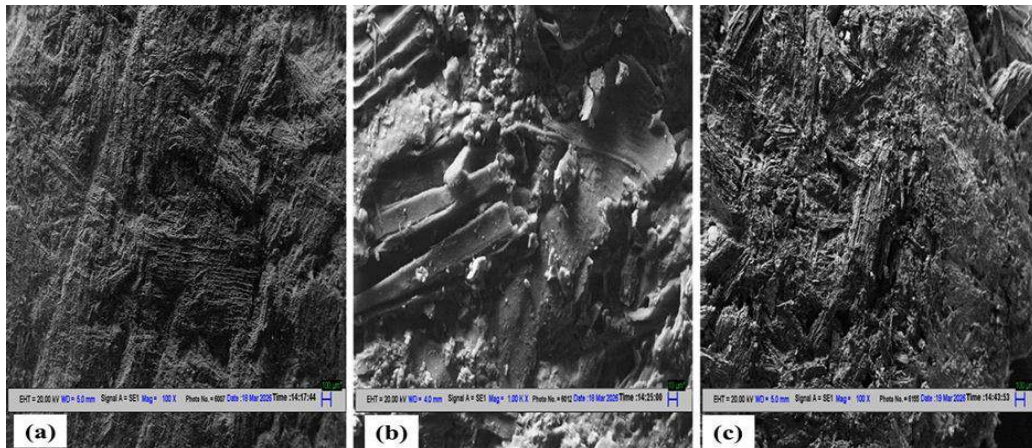


Figure 6: SEM analysis for (a) 10% bio-binder, (b) 20% bio-binder, (c) 30% bio-binder

Conclusions

This study demonstrated the potential of *Detarium senegalense* seed powder as a sustainable, renewable, and formaldehyde-free bio-binder for particleboard production using a low-energy cold-pressing process. FTIR spectroscopy results revealed the presence of functional groups associated with polysaccharides and proteins that can promote interparticle adhesion and matrix formation without the use of synthetic resins. The physical and mechanical properties of the boards were highly dependent on the bio-binder content: increasing the binder concentration generally improved particle consolidation, density, flexural strength, and stiffness. The 30 wt% formulation exhibited the most favorable overall properties, with a density of $872.78 \pm 80.70 \text{ kg/m}^3$, water absorption of $59.43 \pm 5.90\%$, flexural strength of $7.36 \pm 0.01 \text{ MPa}$, and elastic modulus of $2189.73 \pm 0.04 \text{ MPa}$. Scanning electron microscope observations further confirmed improved particle-binder interactions and reduced voids at higher binder contents, although localized binder agglomeration and microcracks were observed at 30 wt%. Despite the encouraging mechanical properties, the relatively high water

absorption indicates that moisture sensitivity remains a key limitation. Therefore, further research should focus on binder modification, crosslinking, or hydrophobic treatment to improve moisture resistance and durability. Overall, the obtained results demonstrate the potential of this underutilized tropical seed resource as a bio-based adhesive for wood composites and contribute to the development of formaldehyde-free renewable materials for sustainable construction and the circular bio-economy.

Conflict of Interest Statement

The authors declare no known competing financial or personal interests.

Data Availability Statement

The authors declare that all data presented in this article are included.

Acknowledgements

The authors would like to thank Sharda University, Greater Noida, India, for providing equipment and technical support for this study, particularly in the internal combustion engine laboratory.

Author Contributions

All authors contributed to the design, experimental design, data analysis, data interpretation, and manuscript writing and editing. All authors read and approved the final version of the manuscript.

References

- [1] S. Essid, V. J. Hegde, A. Mahieu, L. Bizet, N. Leblanc, and A. Saouab, "Comparison of the properties of flax shives based particleboards prepared using binders of bio-based lignin and partially bio-based epoxy resin," *Int. J. Adhes. Adhes.*, vol. 109, p. 102915, Sep. 2021, doi: 10.1016/j.ijadhadh.2021.102915.
- [2] A. Mahieu, A. Vivet, C. Poilane, and N. Leblanc, "Performance of particleboards based on annual plant byproducts bound with bio-adhesives," *Int. J. Adhes. Adhes.*, vol. 107, p. 102847, Jun. 2021, doi: 10.1016/j.ijadhadh.2021.102847.

- [3] H. Orelma, A. Tanaka, M. Vuoriluoto, A. Khakalo, and A. Korpela, “Manufacture of all-wood sawdust-based particle board using ionic liquid-facilitated fusion process,” *Wood Sci. Technol.*, vol. 55, no. 2, pp. 331–349, Mar. 2021, doi: 10.1007/s00226-021-01265-x.
- [4] X. Huang, H. Su, P. Hu, Y. Ye, and D. Wang, “Efficient separation and extraction of guaiacol and its derivatives from bio-oils based on a heterogeneous extraction technique,” *Separation Purification Technology*, vol. 356, p. 129739, 2025.
- [5] B. Arias-Cárdenas, A. M. Lacasta, L. Haurie, S. Duarte, M. Duarte, and P. Faria, “Biological colonisation in bio-materials and composites with different bio-binder combinations,” *Construction Materials*, vol. 492, p. 142980, Sep. 2025, doi: 10.1016/j.conbuildmat.2025.142980.
- [6] A. ElHassan, B. Abu-Jdayil, and W. Ahmed, “Thermal and mechanical characteristics of natural fiber-reinforced composites using bio-binder as sustainable insulation materials,” *International Journal of Thermofluids*, vol. 30, p. 101507, Nov. 2025, doi: 10.1016/j.ijft.2025.101507.
- [7] A. Boussetta *et al.*, “Formulation and Characterization of Chitin-Starch Bio-Based Wood Adhesive for the Manufacturing of Formaldehyde-Free Composite Particleboards,” *Waste Biomass Valorization*, vol. 14, no. 11, pp. 3671–3687, Nov. 2023, doi: 10.1007/s12649-023-02091-x.
- [8] J. Dasiewicz and G. Kowaluk, “Characteristics of high-density fibreboard produced with the use of rice starch as a binder,” *Annals of WULS For. Wood Technol.*, vol. 122, pp. 169–181, Jun. 2023, doi: 10.5604/01.3001.0053.9299.
- [9] O. D. Fagbemi and B. Sithole, “Evaluation of waste chicken feather protein hydrolysate as a bio-based binder for particleboard production,” *Current Research in Green Sustainable Chemistry*, vol. 4, p. 100168, 2021, doi: 10.1016/j.crgsc.2021.100168.
- [10] P. Mensah, R. R. De Melo, E. A. De Oliveira Paula, A. S. Pimenta, J. De Moura, and F. Rusch, “Eco-Friendly Particleboards Produced with Banana Tree (*Musa paradisiaca*) Pseudostem Fibers Bonded with Cassava Starch and Urea-Formaldehyde Adhesives,” *Journal of Renewable Materials*, vol. 13, no. 7, pp. 1475–1489, 2025, doi: 10.32604/jrm.2025.02025-0047.
- [11] A. Nehra, D. Biswas, V. Siracusa, and S. Roy, “Natural Gum-Based Functional Bioactive Films and Coatings: A Review,” *International Journal of Molecular Sciences*, vol. 24, no. 1, p. 485, Dec. 2022, doi: 10.3390/ijms24010485.
- [12] M. Mili *et al.*, “Novel lignin as NATURAL-BIODEGRADABLE binder for various sectors—A review,” *Journal of Applied Polymer Science*, vol. 139, no. 15, p. 51951, Apr. 2022, doi: 10.1002/app.51951.

- [13] S. O. Nwozo, T. L. Adebawale, and B. E. Oyinloye, “Defatted Detarium senegalense seed-based diet alters lipid profile, antioxidants level and sperm morphology in male albino rats,” *Int. J. Biol. Chem. Sci.*, vol. 10, no. 3, p. 928, Dec. 2016, doi: 10.4314/ijbcs.v10i3.2.
- [14] A. A. Sowemimo *et al.*, “Chemical composition, antimicrobial activity, proximate analysis and mineral content of the seed of Detarium senegalense JF Gmelin,” *Afr. J. Biotechnol.*, vol. 10, no. 48, pp. 9875–9879, Aug. 2013, doi: 10.5897/AJB11.1416.
- [15] Q. Wang, P. R. Ellis, S. B. Ross-Murphy, and J. S. Grant Reid, “A new polysaccharide from a traditional Nigerian plant food: Detarium senegalense Gmelin,” *Carbohydr. Res.*, vol. 284, no. 2, pp. 229–239, Apr. 1996, doi: 10.1016/0008-6215(96)00021-3.
- [16] A. S. Imam and K. Sarangapani, “Chemical extraction and characterization of Detarium senegalense seed oil as a potential biodiesel feedstock,” *Res.*, vol. 9, no. 101795, p. 6, 2026.
- [17] J. Santos *et al.*, “Grape Canes (*Vitis vinifera* L.) Applications on Packaging and Particleboard Industry: New Bioadhesive Based on Grape Extracts and Citric Acid,” *Polymers*, vol. 14, no. 6, p. 1137, Mar. 2022, doi: 10.3390/polym14061137.
- [18] G. A. Nevara, S. K. Syed Muhammad, N. Zawawi, N. A. Mustapha, and R. Karim, “Physicochemical and functional properties of carbohydrate–protein gum extracted from kenaf (*Hibiscus cannabinus* L.) seed,” *Int. J. Food Sci. Technol.*, vol. 57, no. 1, pp. 258–267, Jan. 2022, doi: 10.1111/ijfs.15421.
- [19] J. Santos *et al.*, “Grape Canes (*Vitis vinifera* L.) Applications on Packaging and Particleboard Industry: New Bioadhesive Based on Grape Extracts and Citric Acid,” *Polymers*, vol. 14, no. 6, p. 1137, Mar. 2022, doi: 10.3390/polym14061137.