



Research Article

Physical Properties and Dimensional Stability of Starch-Bonded Mixed-Species Particleboards from Selected Tropical Hardwoods

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ABSTRACT

This study examined how species composition and particle size influence the physical performance of starch-bonded particleboards made from tropical sawmill residues. Mixed furnish from *Gmelina arborea*, *Tectona grandis*, *Khaya senegalensis* and *Daniellia oliveri* was prepared at three blending ratios (25:25:25:25, 40:20:20:20 and 55:15:15:15) and particle sizes (1.70, 2.36 and 3.35 mm). Data were analysed using ANOVA, Pearson correlation, and multiple regression. Board density was 0.41–0.45 g/cm³ across all treatments, indicating tough mat consolidation under constant pressing conditions despite changes in species proportion and granulometry. Shatter index decreased from 26–38% in boards with equal or moderate *K. senegalensis* content to 5–9% in boards dominated by *K. senegalensis*, while shatter resistance increased from 62–74% to 91–95%. Strong, significant correlations among responses at different particle sizes ($r \approx 0.94$ – 0.97) showed that performance trends at one sieve class were closely mirrored at the others, and regression modelling indicated that particle-size parameters explained over 80% of the variance in a composite response measure ($R^2 = 0.807$). Density showed only a weak relationship with impact behaviour, while shatter index and shatter resistance were nearly perfect inverses ($r = 0.999$), indicating they function as a tightly coupled pair for assessing toughness. A multiple regression model incorporating density and both shatter metrics explained 56.4% of the variability in board performance, highlighting impact-related properties as the dominant predictors. Increasing *K. senegalensis* content and optimising particle-size distribution provides a practical strategy for producing durable, fully bio-based particleboards from under-utilised hardwood residues.

Keywords: Dimensional stability; *Khaya senegalensis*; Mixed hardwood; Particleboard; Physical properties; Starch binder

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INTRODUCTION

Industrial wood processing in tropical regions generates large volumes of sawdust and offcuts that are often under-utilised or openly burnt, contributing to local air pollution and inefficient resource use (Adegoke *et al.*, 2022). In West and Central Africa in general and Nigeria in particular, hardwoods such as *Gmelina arborea*, *Tectona grandis*, *Khaya senegalensis* and *Daniellia oliveri* occupy an important niche in construction and furniture

markets, yet their residues remain largely unmanaged along the value chain (Abdulrahman *et al.*, 2006). Transforming these residues into engineered composites, particularly particleboards, has been identified as a promising strategy to relieve pressure on natural forests, reduce waste, and support circular bioeconomy goals (Rossi *et al.* 2025). At the same time, global regulations restricting formaldehyde emissions from conventional urea-formaldehyde adhesives have intensified

interest in bio-based binders and low-volatile organic compound (VOC) wood composites, especially for interior applications (Betené *et al.*, 2023; Yano *et al.*, 2020; Kubanni *et al.*, 2025).

A growing body of work demonstrates that non-wood biomass and agro-industrial by-products can be successfully valorised in particleboard manufacture. Studies have reported the use of oil-palm biomasses, sugarcane bagasse, fruit shells and other agricultural residues to produce boards with acceptable or even enhanced density, water resistance and mechanical properties (Ramlee *et al.* 2019). Recent investigations on particleboards made from tropical fruit shells have shown that hybridising different shell types and controlling particle size can markedly improve dimensional stability (water absorption, thickness swelling) and internal bond strength, with some formulations meeting European standard for particleboard specifications (EN 312) requirements for general-purpose boards (Tupciauskas *et al.*, 2026). These advances highlight the potential of mixed-species or hybrid systems in tailoring board performance to specific applications. However, much less attention has been paid to mixed-species particleboards derived from tropical hardwood sawdust, especially in West African contexts where species availability, residue quality and processing conditions differ substantially from temperate systems (Betené *et al.*, 2023; Zakaria *et al.*, 2021; Yano *et al.*, 2020).

Parallel to the diversification of raw materials, starch and other biopolymers have emerged as viable binders for wood-based composites. Laboratory-scale studies on starch-bonded particleboards have shown that cassava or other starches can produce low-density boards with surprisingly good physico-mechanical performance, supported by foamed structures that fill inter-particle voids and enhance stress transfer (Mensah *et al.* 2024). Starch offers several advantages: it is widely available, inexpensive, compatible with a range of lignocellulosic substrates, and free from formaldehyde emissions. Yet, the application of starch as a sole binder in mixed tropical hardwood furnish remains underexplored, and questions remain about how species composition and particle-size distribution interact to control fundamental physical properties such as density and impact-related durability (Monteiro *et al.*, 2019; Betené *et al.*, 2023). Dimensional stability and physical integrity under handling and service conditions are critical for particleboard acceptance in building and furniture sectors. Prior research on wood-cement and

resin-bonded particleboards emphasises that density, porosity and microstructure strongly influence water uptake, swelling and mechanical performance (Żabowski *et al.*, 2024). Papadopoulos and co-workers, and subsequent studies on tropical wood-cement boards, have shown that manipulating wood-to-binder ratios and face layer configurations can significantly alter thickness swelling and water absorption behaviour, with direct consequences for durability. More recently, shell-based particleboards have demonstrated that finer particles often yield higher densities, lower water sensitivity and better dimensional stability, whereas coarse particles can introduce voids and heterogeneous stress fields (Betené *et al.*, 2023). These insights suggest that, in bio-based systems, both species-level chemistry (extractives, density, fibre structure) and particle-size distribution play decisive roles in determining board performance (Betené *et al.*, 2023; Da Silva *et al.*, 2021).

Against this backdrop, mixed-species particleboards produced from tropical hardwood sawdust and bonded with starch present a compelling yet insufficiently studied alternative. Combining species such as *G. arborea*, *T. grandis*, *K. senegalensis* and *D. oliveri* in controlled ratios offers opportunities to exploit complementary properties density, grain structure, and impact resistance while stabilising supply from heterogeneous sawmill streams. However, designing such boards for reliable dimensional stability and impact resistance requires a clear understanding of how species composition and particle size jointly affect density, shatter index and shatter resistance under realistic processing conditions.

The study systematically evaluating the physical properties and dimensional stability of starch-bonded mixed-species particleboards manufactured from sawdust of four common tropical hardwoods at three mixing ratios and three particle sizes.

MATERIALS AND METHODS

Study Area

The Board production and test was carried out at the Department of Civil Engineering Materials and Concrete Laboratory, College of Engineering, Joseph Sarwuan Tarka University, Makurdi (JOSTUM) located at 7.73°–7.78° N latitude and 8.52°–8.62° E longitude North Bank Makurdi, Benue State, Nigeria.

Collection of materials

Sawdust used in this study was obtained from routine sawing operations at UAC Road sawmill in Lafia, Nasarawa State, Nigeria. The species selected

Gmelina arborea, *Tectona grandis*, *Khaya senegalensis* and *Daniellia oliveri* are commonly used hardwoods in local construction and furniture, ensuring that the resulting boards reflect realistic resource conditions. To minimise contamination from other timber species and floor debris, Tampolean sheets were placed directly beneath the band-saw outlet, so that only fresh, species-specific sawdust was collected. Starch used as a natural binder was sourced from a starch-processing facility in North Bank, Makurdi, and purchased as a dry powder from the local market, reflecting materials readily available to small-scale manufacturers.

Materials preparation

Sawdust from each species was gently spread in thin layers and air-dried under shelter until it reached a stable moisture content suitable for bonding. The aim was to reduce free moisture without subjecting particles to elevated temperatures that might alter their surface chemistry. Dried sawdust was then manually sieved into three particle-size classes (1.70, 2.36 and 3.35 mm), using standard metal sieves (Plates 1). Sieving had a dual purpose: it produced controlled particle-size distributions for the experiment and removed extraneous materials such as small metal fragments, plastics and oversized wood chips.



Plate 1: Sieves used to filter sawdust

Starch binder was prepared immediately before board formation. A 20 g portion of starch was first dispersed in 25 g of cold water to avoid lumping and then gradually introduced into 25 g of boiling water with continuous stirring. This yielded a smooth, homogeneous paste of moderate viscosity designed to coat particles uniformly and promote adhesion without excessive runoff.

Experimental design

The investigation of physical properties and dimensional stability followed a $4 \times 3 \times 3$ factorial arrangement in a completely randomised design. Factor A was wood species (four hardwoods), factor B was particle size (1.70, 2.36 and 3.35 mm), and factor C was the species mixing. Sawdust (Plate 2) was sieved into 1.70, 2.36, and 3.35 mm fractions and blended into three ratios: 25:25:25:25, 40:20:20:20, and 55:15:15:15 (Table 1). Boards were produced using 100 g furnish and starch binder under a pressure of 120 kN/mm². The experiment followed a $4 \times 3 \times 3$ factorial arrangement in a completely randomized design with four replications and was carried out at the Department of Civil Engineering Materials and Concrete Laboratory, College of Engineering (JOSTUM).



Plate 2: Sawdust particle sizes

Table 1: Species mixing ratios and replication structure

Species composition (%)	<i>K. senegalensis</i> (%)	<i>D. oliveri</i> (%)	<i>T. grandis</i> (%)	Replications per sieve size
25:25:25:25	25	25	25	R1–R4
40:20:20:20	40	20	20	R1–R4
55:15:15:15	55	15	15	R1–R4

Board production process

The particleboards (Plate 3) were manufactured by uniformly blending the sawdust particles with the starch-based adhesive, followed by manual mat formation in a mould. The mat was then hot-pressed under controlled temperature and pressure to consolidate the particles and facilitate starch

gelatinization, thereby forming a rigid bonded panel. The boards were subsequently cooled, conditioned, and trimmed to the required dimensions before testing, following the procedure described by Monteiro *et al.* (2019) with slight modifications. The overall procedure is described in the flowchart in Figure 1 below.



Figure 1: Process Cycle for sawdust Preparation and Particleboard Production



Plate 3: Produced boards arranged for curing

Determination of physical properties of Boards

Physical properties evaluated included were Density, Shatter index and Shatter resistance Standard procedures (ASTM D1037, Tembe *et al.*, 2014) were used.

Determination of board density

Board density was evaluated 10 days after demoulding, following Tembe *et al.* (2014). The oven-dry weight of each board was measured using a digital

weighing balance, while length, width and thickness were measured with a calliper at two positions to determine volume. Density was calculated as:

$$\text{Density} = \frac{W}{V} \quad \dots\dots\dots (1)$$

Where W is the oven-dry weight of the board (kg) and V is the volume (m^3) (Tembe *et al.*, 2014).

Determination of shatter index

Board durability was assessed using the shatter index test as described by Tembe *et al.* (2014). Boards were repeatedly dropped from a height of 2 m onto a solid base, and the mass retained after impact was recorded. Percentage weight loss was computed as (Sengar *et al.*, 2012; Tembe *et al.*, 2014):

$$\text{Percentage weight loss} = \frac{W_{\text{initial}} - W_{\text{retained}}}{W_{\text{initial}}} \times 100 \dots (2)$$

Where W_{initial} is the initial mass of the specimen and W_{retained} is the mass retained after dropping.

Determination of shatter resistance

Shatter resistance, used as an index of impact durability, was obtained from the percentage weight loss as (Sengar *et al.*, 2012; Tembe *et al.*, 2014):

$$\text{Shatter resistance} = 100 - \text{Percentage weight loss} \dots (3)$$

Data analysis

Data were analysed using ANOVA, Duncan's multiple range test, Pearson correlation, and multiple regression.

RESULTS

The result of the study revealed across all mixtures and sieve sizes, board density remained tightly constrained between 0.41 and 0.45 g/cm³, indicating that mat consolidation and bulk compaction were stable under fixed pressing conditions. In contrast, impact-related metrics were highly sensitive to composition. Shatter index decreased from approximately 26–38% in boards with equal or moderate *Khaya senegalensis* content to 5–9% in boards dominated by *K. senegalensis*, while shatter resistance increased from roughly 62–74% to 91–95%. These shifts establish elevated *K. senegalensis* proportion as a dominant driver of impact durability, whereas particle-size variation in the 1.70–3.35 mm range exerts only a secondary influence (Table 2).

This correlation matrix (Table 3) examines the coherence of particleboard responses across three particle-size classes (1.70, 2.36 and 3.35 mm). The result show very high, positive correlation coefficients ($r = 0.944\text{--}0.968$, $p < 0.01$) between all

sieve sizes this was indication that boards performing well at one particle size tend to perform equally well at the others.

This regression model quantifies how far particle size distribution alone can explain variation in board response. Using the three sieve classes (1.70, 2.36 and 3.35 mm) as predictors, the model achieved a high multiple correlation ($R = 0.898$) and strong explanatory power ($R^2 = 0.807$; adjusted $R^2 = 0.789$), with a relatively low standard error (1.350). The highly significant F-statistic [$F(3,32) = 44.57$, $p < 0.001$] demonstrates that refining the particle-size profile is a statistically powerful means of tuning performance in starch-bonded mixed hardwood composites (Table 4).

This correlation analysis disentangles the relationships among density, shatter index and shatter resistance in mixed-species starch-bonded boards. Density exhibits only weak, non-significant associations with shatter index ($r = -0.289$) and shatter resistance ($r = 0.284$), confirming that mass per unit volume is largely decoupled from impact durability in this composite system. In contrast, shatter index and shatter resistance display an almost perfect inverse relationship ($r = -0.999$, $p < 0.01$), indicating that they are complementary descriptors of a single underlying toughness domain (Table 5).

This regression model explores how density, shatter index and shatter resistance jointly control overall board performance. The combined physical properties yielded a moderate-to-strong multiple correlation ($R = 0.751$) and accounted for 56.4% of the variance in the response ($R^2 = 0.564$; adjusted $R^2 = 0.523$), with a standard error of 1.809. The model exhibited a highly significant F-statistic [$F(3,32) = 13.77$, $p < 0.001$], demonstrating that these properties provide a substantially better prediction than an intercept-only baseline. Given the near-perfect inverse relationship between shatter index and resistance, the regression results underscore impact metrics as the dominant drivers of performance, while density plays a secondary, stabilising role (Table 6).

Table 2: Influence of particle size and species composition on density, shatter index and shatter resistance

Species composition (%)	Particle size (mm)	Density (g/cm ³) (Mean ± SD)	Shatter index (%) (Mean ± SD)	Shatter resistance (%) (Mean ± SD)
25:25:25:25	1.70	0.41 ± 0.02 ^a	37.81 ± 11.01 ^b	61.99 ± 11.20 ^a
	2.36	0.41 ± 0.01 ^a	30.06 ± 10.57 ^b	69.94 ± 10.57 ^a
	3.35	0.42 ± 0.03 ^a	32.69 ± 16.81 ^b	67.11 ± 16.65 ^a
40:20:20:20	1.70	0.45 ± 0.01 ^b	25.90 ± 8.78 ^b	74.10 ± 8.78 ^a
	2.36	0.41 ± 0.03 ^a	31.47 ± 9.82 ^b	69.53 ± 9.66 ^a
	3.35	0.41 ± 0.01 ^a	28.87 ± 3.79 ^b	71.13 ± 3.79 ^a
55:15:15:15	1.70	0.43 ± 0.02 ^{ab}	8.70 ± 4.55 ^a	91.31 ± 4.55 ^b
	2.36	0.42 ± 0.01 ^{ab}	5.25 ± 2.82 ^a	94.75 ± 2.82 ^b
	3.35	0.42 ± 0.02 ^{ab}	8.43 ± 3.74 ^a	91.58 ± 3.74 ^b

Table 3: Pearson correlation matrix among responses of particleboards at different particle sizes

Variable	Sieve size 1.70 mm	Sieve size 2.36 mm	Sieve size 3.35 mm
Sieve size 1.70	1.000	0.968**	0.961**
Sieve size 2.36	0.968**	1.000	0.944**
Sieve size 3.35	0.961**	0.944**	1.000

**Correlation is significant at the 0.01 level (2-tailed).

Table 4: Multiple regression summary for the effect of particle size (sieve classes) on particleboard response

Model	R	R Square	Adjusted Square	R	Std. error of the estimate	R Square change	F change	df1	df2	Sig. change	F
1	0.898	0.807	0.789		1.350	0.807	44.570	3	32	0.000	

Predictors: (Constant), Sieve size 3.35, Sieve size 2.36, Sieve size 1.70)

Table 5: Pearson correlation matrix among physical properties of mixed-species particleboards

Variable	Density (g/cm ³)	Shatter index (%)	Shatter resistance (%)
Density (g/cm ³)	1.000	-0.289	0.284
Shatter index (%)	-0.289	1.000	-0.999**
Shatter resistance (%)	0.284	-0.999**	1.000

**Correlation is significant at the 0.01 level (2-tailed).

Table 6: Multiple regression summary for physical properties (density, shatter index, shatter resistance) on particleboard response

Model	R	R Square	Adjusted Square	R	Std. error of the estimate	R Square change	F change	df1	df2	Sig. change	F
1	0.751	0.564	0.523		1.809	0.564	13.774	3	32	0.000	

Predictors: (Constant), Shatter resistance (%), Density (g/cm³), Shatter index (%)

DISCUSSION

A central finding of this study was that species composition, particularly the increased proportion of *Khaya senegalensis*, strongly influenced impact-related performance while board density remained relatively constant. Boards containing equal or moderate proportions of *K. senegalensis* (25:25:25:25 and 40:20:20:20) recorded relatively high shatter indices and moderate shatter resistance, whereas the board dominated by *K. senegalensis* (5:15:15:15) exhibited a much lower shatter index and substantially higher resistance to impact. This suggests that impact performance was influenced not only by density but also by the intrinsic anatomical,

physical and mechanical characteristics of the wood species and their interaction within the starch-bonded matrix. Similar observations were reported by Amiamdamhen *et al.* (2021), who found that varying the proportions of *Ceiba pentandra* and *Gmelina arborea* significantly affected the physical and mechanical properties of cement-bonded particleboards. Adelusi *et al.* (2019) likewise reported that different mixing ratios of *C. pentandra* and *G. arborea* influenced modulus of rupture, modulus of elasticity, water absorption and thickness swelling, demonstrating that species proportion can be deliberately manipulated to obtain desirable board properties. Further evidence was provided by Aina *et al.* (2023), who showed that mixing ratios among

Gmelina arborea, *Azelia africana* and *Triplochiton scleroxylon* significantly influenced the physico-mechanical properties of cement-bonded particleboards. These findings support the present observation that increasing the proportion of *K. senegalensis* can improve impact resistance even when density remains within a relatively narrow range.

The improved impact resistance observed at the highest *K. senegalensis* proportion may be associated with differences in wood density, fibre characteristics, anatomical structure, particle geometry and stress-transfer capacity within the composite. Rather than behaving as a homogeneous material, the mixed species furnish provides particles with different mechanical characteristics, which can influence crack initiation, crack propagation and energy dissipation during impact. This agrees with Olorunnisola (2018), who emphasized the importance of wood selection and material characteristics in designing tropical wood-based composites. Recent research by Pędzik *et al.* (2024) also demonstrated that residues generated from wood-product manufacturing can be successfully converted into particleboards with useful engineering properties, supporting the potential for value addition to heterogeneous wood residues. Consequently, the present results suggest that heterogeneous Nigerian sawmill residues can be strategically blended rather than treated simply as an undifferentiated waste stream.

Within the tested particle-size range of 1.70–3.35 mm, particle size had a secondary but non-negligible effect compared with species composition. The relatively stable density across the sieve classes indicates that particle size did not substantially change the mass-to-volume relationship of the boards, although it influenced the arrangement and interaction of particles within the board. Mehrvan *et al.* (2024) similarly demonstrated that particle size significantly affects particleboard properties, including internal bond strength, modulus of rupture, modulus of elasticity, water absorption and thickness swelling. This indicates that particle size influences the contact area between particles, void distribution and adhesive coverage, thereby affecting stress transfer through the board. In addition, Sanni *et al.* (2022) reported that particle characteristics, material proportions and processing conditions are important determinants of the physical and mechanical properties of composite particleboards produced from Nigerian agro-waste materials. More recent Nigerian evidence from Okoli *et al.* (2026) further

indicates that sawdust–rice husk blending ratios and adhesive type can significantly influence particleboard performance, reinforcing the importance of optimizing both material composition and binder system. Thus, although species composition was the stronger determinant of impact performance in the present study, particle size remains an important processing variable that can be optimized alongside species ratio. The findings demonstrate that increasing the proportion of *K. senegalensis*, while controlling particle size and starch distribution, can provide a practical approach for producing lightweight particleboards with improved resistance to impact and fragmentation from heterogeneous Nigerian sawmill residues.

The weak correlations between density and shatter index/shatter resistance indicate that impact durability can be improved without substantially increasing board density, suggesting that bonding quality, particle architecture and species composition also influence impact performance. This agrees with Abubakar *et al.* (2025), who demonstrated the potential of waste-polystyrene adhesive for producing sustainable particleboards from rice-husk residues. Abdul Muhaimin *et al.* (2025) similarly reported that modification of starch adhesive with citric acid improved the mechanical properties of bamboo particleboards, particularly MOR and internal bond strength. Furthermore, Engehausen *et al.* (2025) established that particle size and adhesive distribution independently influence MOR, MOE and internal bond strength, confirming that board performance is not governed by density alone. Monteiro *et al.* (2019) also demonstrated that starch-based adhesives can produce low-density particleboards with useful bonding performance. These findings provide a plausible explanation for the present results, where boards with comparable densities exhibited different levels of shatter resistance. Therefore, optimizing species composition, particle architecture and starch–wood bonding may improve impact resistance while maintaining the lightweight characteristics of the boards.

The density of the boards produced in this study ranged from 0.41–0.45 g/cm³ (410–450 kg/m³), indicating that lightweight panels can be produced from sawmill residues using starch as a binder. This finding is comparable to Monteiro *et al.* (2019), who reported a density of approximately 0.405 g/cm³ for low-density wood particleboards bonded with sour cassava starch. Their study demonstrated that starch could enhance particle consolidation by filling spaces

between wood particles. Similarly, Mensah *et al.* (2024) reported that cassava starch can effectively function as a renewable adhesive in particleboard production. The relatively low density observed in the present study may be attributed to differences in wood species, particle size, particle geometry, particle packing and pressing conditions. These factors influence the degree of particle consolidation and the amount of void space within the board. The results therefore suggest that careful management of species composition and particle architecture is important in controlling board density and performance. The use of starch as an adhesive also reduces dependence on conventional synthetic adhesives such as urea-formaldehyde. Mensah *et al.* (2024) noted that cassava starch has potential as a sustainable alternative to UF adhesive in particleboard manufacturing. The use of sawmill residues further promotes waste valorisation by converting wood-processing residues into useful composite products. The lightweight boards may therefore be suitable for non-structural applications such as ceiling panels, partitions and furniture components, where reduced weight is desirable. However, density alone cannot confirm the physical robustness of the boards. Their suitability should also be evaluated using modules of rupture, modules of elasticity, internal bond strength, water absorption and thickness swelling. Monteiro *et al.* (2019) demonstrated that low-density starch-bonded boards could achieve useful mechanical performance despite their relatively low density. Thus, the present density range demonstrates the feasibility of producing lightweight starch-bonded boards from sawmill residues.

CONCLUSION

The study shows that density remained stable across all species combinations and particle sizes, indicating that the pressing conditions and starch binder consistently produced well-compacted boards regardless of how the furnish was configured. At the same time, impact-related properties were clearly governed by species composition, with boards containing higher proportions of *K. senegalensis* displaying substantially improved resistance to shattering compared with mixes where this species was less dominant. Results obtained at different sieve sizes tracked each other closely, and modelling confirmed that particle-size distribution captures much of the variation in board behaviour, while density itself plays only a minor role in explaining differences in toughness. Shatter index and shatter

resistance exhibited an inverse relationship, making them complementary metrics for evaluating the impact performance of tropical hardwood residue-based panels. Together, these parameters provide a robust and comprehensive assessment of the panels' resistance to impact-induced damage. These findings indicate that lightweight starch-bonded particleboards can be designed from tropical hardwood residues with good dimensional stability and impact resistance by optimising species composition particularly the proportion of *K. senegalensis* and using controlled particle-size distributions rather than relying on higher density or synthetic resins.

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