Recycled Polypropylene as Binder for Composite Particleboards Produced from Groundnut Shells and Waste Glass Fibres

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Received: 16-JULY-2026; Reviewed: 25-SEPT-2026; Accepted: 30-SEPT-2026
https://dx.doi.org/10.46792/fuoyejet.v11i3.1627

ORIGINAL RESEARCH

Abstract—Timber-based particleboard production continues to place heavy pressure on forest resources, while agricultural and industrial wastes such as groundnut shells, waste polypropylene, and glass fibers keep accumulating with little productive use. Turning these residues into viable construction materials offers a practical way to cutting down on deforestation and giving waste a second life. This study evaluated the physical, mechanical, and microstructural properties of composite particleboards produced from groundnut shells (GS), recycled polypropylene (PL), and waste glass fibers (GF) at mixing ratios of 50:40:10, 60:30:10, and 70:20:10 (GS:PL:GF). The composite boards were fabricated through hot-press moulding and assessed for modulus of rupture (MOR), modulus of elasticity (MOE), water absorption, thickness swelling, and microstructural characteristics. Results showed that MOR decreased with increasing groundnut shell content, while MOE increased, reaching a maximum value of 5,234.64 N/mm² for the 70:20:10 formulation. While MOR values fell below typical general-purpose particleboard requirements (EN 312, ANSI A208.1), MOE values exceeded the minimum thresholds of both standards, indicating strong potential for non-structural, stiffness-driven applications. The 50:40:10 composite exhibited the best dimensional stability, recording the lowest water absorption and thickness swelling values due to the higher polypropylene content. SEM showed a denser, well-bonded structure in the 70:20:10 formulation, explaining its higher stiffness though its lower polypropylene content also meant more water absorption and swelling than the 50:40:10 mix. XRD confirmed a semi-crystalline structure across all composites, with crystallinity increasing alongside groundnut shell content. ANOVA showed significant differences in MOR, MOE, and water absorption among the formulations ($p \leq 0.05$). The findings demonstrate that groundnut shells, waste glass fibers, and recycled polypropylene can be effectively utilized to produce sustainable composite particleboards with competitive mechanical and physical performance, offering a viable alternative to conventional wood-based boards.

Keywords— Agricultural waste, Composite particleboard, Glass fiber, Groundnut shells, Recycled polypropylene, Sustainable composites.

1 INTRODUCTION

Global demand for timber-based products has intensified due to population growth and urbanization, exerting severe pressure on forest resources and accelerating deforestation, biodiversity loss, and greenhouse gas emissions (Lee et al., 2022). A transition to alternative, waste-derived raw materials is therefore urgently needed. Particleboards which are composite panels manufactured by bonding lignocellulosic particles under heat and pressure, offer a viable pathway, promoting circular economy principles while reducing solid waste disposal burdens (Okeke et al., 2024). Groundnut shells represent a largely untapped agro-industrial residue. Global production exceeds 45 million metric tons annually, with shells constituting 30–35% of pod weight (Bodor et al., 2024). In Nigeria, shells are typically burnt or discarded openly. Waste glass fibers, generated from fiberglass manufacturing and end-of-life composites, present disposal challenges due to non-biodegradability. Polypropylene waste, generated in large volumes from packaging and insulation, can be repurposed as a synthetic thermoplastic binder, eliminating the need for formaldehyde-based adhesives (Bodor et al., 2024).

Agro-residue particleboards show performance that varies widely with binder type and content; for instance, rice husk boards bonded with phenol-formaldehyde achieved MOR of 10.1–21.5 N/mm² and MOE of 1,253–2,624 N/mm² at medium density, meeting ANSI A208.1 commercial-grade requirements (Ciannamea et al., 2017). Glass fiber reinforcement, as used in this study, is similarly expected to improve load transfer and restrict crack propagation within the matrix, as observed in other fiber-reinforced agro-composites (Kumar et al., 2023), though its effect within a groundnut shell-polypropylene system remains unexplored.

The accumulation of groundnut shells, polypropylene packaging waste, and glass fibers constitutes a growing environmental burden. (Astari et al., 2024). While studies have explored rice husks, corn cobs, sawdust, and bagasse for particleboard production, limited studies have examined the combined use of groundnut shells, waste glass fibers, and polypropylene waste. Astari et al. (2024), and Ojo et al. (2025) demonstrated that integrating biobased or recycled binders with lignocellulosic particles can significantly enhance engineered panel performance; however, the synergistic effects of this

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Section E- CIVIL ENGINEERING & RELATED SCIENCES

Can be cited as:

Oke J. O., and Ojo M. O. (2026). Recycled Polypropylene as Binder for Composite Particleboards Produced from Groundnut Shells and Waste Glass Fibres. FUOYE Journal of Engineering and Technology (FUOYE**JET**), **11(3), 557-561.** https://dx.doi.org/10.46792/fuoyejet.v11i3.1627

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specific three-component system remain unexplored. This study therefore evaluates the physical, mechanical, and microstructural performance of composite particleboards from these three waste streams as a contribution to sustainable construction materials development.

Specifically, the study aims to: (1) determine the effect of mixing ratio on the mechanical properties (MOR and MOE) of the composite boards; (2) evaluate the physical properties, namely water absorption and thickness swelling, across different formulations; (3) examine the microstructural and crystalline characteristics of the composites using SEM and XRD; and (4) compare the performance of the developed boards against existing particleboard standards (ANSI A208.1 and EN 312).

2 MATERIALS AND METHODS

2.1 Materials Collection and Preparation

Groundnut shells were sourced from local agro-processing centers (Fig. 2.1a). The shells were washed, sun-dried for several days, oven-drying (105°C for 24 hours). Dried shells were milled and sieved to obtain particle sizes between 0.5 mm and 2.0 mm, suitable for particleboard production.

Waste glass fibers (Fig. 2.1b) were collected from discarded fiberglass products, cleaned, and chopped into short strands (5–15 mm). Polypropylene waste (PP) was sourced from post-consumer plastic packaging, shredded into small flakes, and pre-treated by washing and drying to remove contaminants (Fig 2.1c).

(a) Groundnut shells (b) waste glass Fibre (c)Polypropylene waste

Fig. 2.1(a-c): Prepared materials

2.2 Experimental Design

Composite boards were prepared with varying proportions (Table 1) of groundnut shells (GS), glass fibers (GF), and polypropylene waste (PP). A factorial mix design was adopted, with groundnut shells serving as the primary lignocellulosic material and polypropylene acting as the binder. Glass fibers were introduced as reinforcement. Three mix ratios were formulated (e.g., 70:20:10, 60:30:10, and 50:40:10 by weight for groundnut shells, polypropylene, and glass fibers, respectively).

Table 1. Composite Particleboard Production

Sample ID	GS (%)	PP (%)	GF (%)
GS50PP40GF10	50	40	10
GS60PP30GF10	60	30	10
GS70PP20GF10	70	20	10

2.3 Board Production Process

Raw materials were blended according to designated proportions. Polypropylene was thermally pre-treated at 170 -180 °C to enhance binding. Mixtures were placed in a 300 mm × 300 mm stainless steel mold and hot-pressed at 180 °C, 3-4 MPa, for 10–15 minutes, consistent across all replicates to ensure uniform consolidation. Two board panels were produced per mixing ratio, from which three specimens each were cut for mechanical testing, giving a total of six replicate specimens per formulation. Boards were conditioned for 7 days at 20 ± 2 °C and 65 ± 5% relative humidity before testing

2.4 Physical Properties Testing

The physical properties of the produced particleboards were evaluated in accordance with the ASTM D1037 (2020) Standard Test Methods for Evaluating the Properties of Wood-Base Fiber and Particle Panel Materials. These properties include water absorption and thickness swelling.

2.5 Mechanical Properties Testing

Modulus of rupture (MOR) and modulus of elasticity (MOE) were determined by three-point bending per ASTM D1037 (2020) and EN 310 (1993).

2.6 Microstructural Analysis

Microstructural characterization was carried out using Scanning Electron Microscopy (SEM) to observe particle dispersion, interfacial bonding, and fracture morphology. Additionally, X-ray Diffraction (XRD) analysis was performed to investigate the crystalline phases and structural composition of the composite boards.

2.7 Comparative Evaluation

The performances of the produced particleboards were compared with conventional wood-based particleboards using available benchmark data from ANSI A208.1 (2022) and EN 312 (2010) standards. Statistical analysis (ANOVA) was employed to determine the significance of differences in physical and mechanical properties among the different formulations and the control samples.

3 RESULTS AND DISCUSSIONS

3.1 Mechanical and physical properties of Groundnut shell–glass fiber plastic composite

Table 2 presents the mean mechanical and physical properties of the GS/PL/GF composite boards. Pooled mean values were 4,355.47 N/mm² for MOE and 6.14 N/mm² for MOR. Mixing proportion significantly influenced both mechanical properties, with ANOVA confirming significant differences at the 5% level (Table 2).

MOR decreased with increasing groundnut shell content (Fig 3.1), declining from 6.88 N/mm² at 50:40:10 to 5.24 N/mm² at 70:20:10. The reduction may be associated with changes in reinforcement

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distribution and load-transfer efficiency within the composite matrix. This is consistent with Ajayi et al. (2020). Conversely, MOE increased with groundnut shell content (Fig 3.2), peaking at 5,234.64 N/mm² for 70:20:10, reflecting the contribution of the lignocellulosic phase to composite stiffness, in agreement with Bourchak et al. (2023). DMRT results (Table 2) confirm that 70:20:10 achieved the highest MOE and was significantly different from both other proportions, while MOR was highest for 50:40:10.

Compared against EN 312 (2010) requirements for general-purpose particleboards (MOR ≥ 11 N/mm², MOE ≥ 1,800 N/mm²), all three formulations fell short of the MOR threshold but comfortably exceeded the MOE requirement. Similarly, under ANSI A208.1 (2022), MOR values met the minimum for low-density (LD) grade boards but fell below the thresholds for medium-density (M-1/M-2) grades, while MOE values exceeded all grade requirements. This suggests the developed composites are better suited to stiffness-driven, non-structural applications rather than high-bending-load uses.

Table 2. Mean values (with DMRT groupings) for mechanical and physical properties of Groundnut shell – glass fiber plastic composite boards

Property	50:40:10	60:30:10	70:20:10	Total
MOR (N/mm²)	6.88±0.07[a]	6.32±0.13[b]	5.24±0.21[c]	6.14±0.43
MOE (N/mm²)	3653.43±172.16[c]	4178.35±251.69[b]	5234.64±276.12[a]	4355.47±447.72
WA 24 h (%)	0.51±0.11[a]	1.15±0.39[b]	3.22±0.53[c]	1.63±1.15
WA 48 h (%)	1.05±0.33[a]	1.65±0.71[b]	3.79±0.63[c]	2.16±1.23
WA 72 h (%)	1.54±0.53[a]	2.67±0.65[b]	3.54±0.42[c]	2.58±1.08
TS 24 h (%)	2.57±0.62	3.07±0.54	3.27±1.52	2.97±1.26
TS 48 h (%)	3.47±0.65	4.15±0.72	4.24±0.85	3.95±0.12
TS 72 h (%)	4.13±0.52	5.28±0.44	5.39±0.39	4.93±0.15

Each value represents the mean of six replicated samples. Superscript letters (a, b, c) denote DMRT groupings for MOR, MOE, and water absorption; shared letters within a row indicate no significant difference (P > 0.05). Thickness swelling did not differ significantly among formulations at any exposure period (see Table 3).

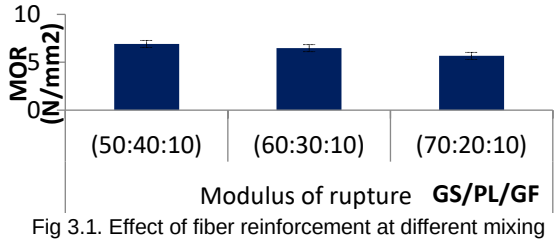

Fig 3.1. Effect of fiber reinforcement at different mixing proportions on MOR

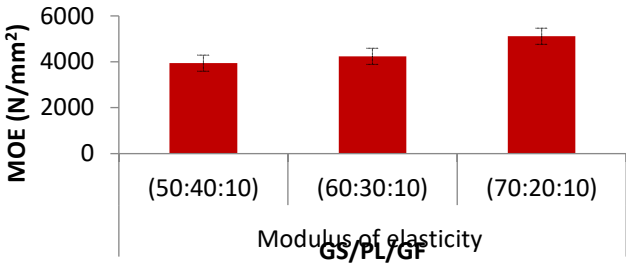

Fig 3.2. Effect of fiber reinforcement at different proportions on MOE

3.2 Physical Properties (Water Absorption and Thickness Swelling)

Mixing proportion significantly influenced water absorption at all exposure periods. The 50:40:10 formulation recorded the lowest water absorption (Tables 2 and 4) and the least thickness swelling across all periods, attributable to the higher polypropylene content encapsulating fibrous components and restricting moisture ingress. This is consistent with Chen et al. (2025), who demonstrated that the hydrophobic nature of polypropylene limits hydroxyl group accessibility, reducing water uptake and swelling. Water absorption and thickness swelling both increased with exposure duration and with increasing groundnut shell proportion (Fig 3.3 and 3.4). It is noted that the mean water absorption for the 70:20:10 formulation appeared to decline marginally between 48 and 72 hours (3.79% to 3.54%); however, given the overlapping standard deviations at both time points (±0.63% and ±0.42%, respectively), this is attributed to specimen-to-specimen variability rather than an actual reversal of moisture uptake, and does not affect the overall increasing trend observed across formulations and exposure periods.

DMRT (Table 2) confirmed that 50:40:10 was not significantly different from 60:30:10 at 24 hours but was significantly different at 48 and 72 hours. Thickness swelling did not differ significantly among formulations at any exposure period (24, 48, or 72 hours), although the difference at 72 hours approached significance (p = 0.073).

Table 3. ANOVA Summary for All Measured Properties

Property	F-value	p-value	Significance
MOE	10.39	0.03	Significant*
MOR	189.23	0.02	Significant*
Water Absorption (24 h)	96.33	< 0.001	Significant*
Water Absorption (48 h)	58.00	< 0.001	Significant*
Water Absorption (72 h)	22.08	< 0.001	Significant*
Thickness Swelling (24 h)	0.668	0.426	Not significant
Thickness Swelling (48 h)	2.084	0.532	Not significant
Thickness Swelling (72 h)	3.125	0.073	Not significant

3.3 Scanning Electron Microscopy (SEM) Analysis

SEM micrographs (Fig 3.5 (a-c)) revealed progressive changes in microstructural morphology with increasing groundnut shell content. The

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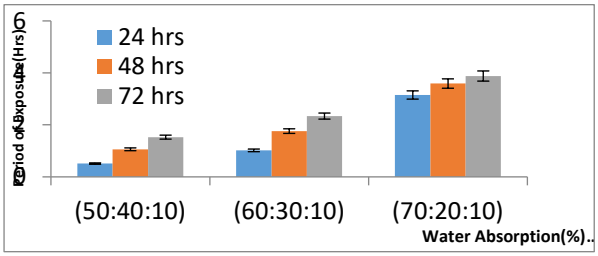


Fig 3.3. Effect of Water Absorption (WA) on Groundnut shell – glass fiber plastic composite boards at different mixing proportion.

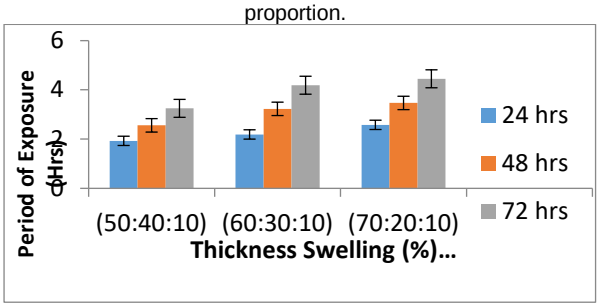
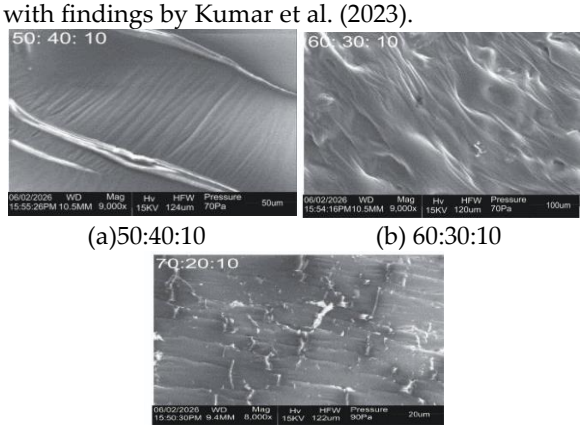


Fig 3.4. Effect of TS on Groundnut shell – glass fiber plastic composite boards at different mixing proportions

50:40:10 composite (Fig 3.5a) exhibited a slightly porous internal structure with small voids and weak interfacial bonding between reinforcement particles and the polypropylene matrix. Such voids indicate insufficient wetting of natural fillers by the polymer, which reduces effective stress transfer and promotes moisture ingress through capillary action, consistent with findings by Kumar et al. (2023).



(a)50:40:10 (b) 60:30:10

(c) 70:20:10

Fig 3.5(a-c). Microstructural Morphology of GS/PL/GF

The 60:30:10 formulation (Fig 3.5b) showed a more distributed porosity with moderate matrix-filler interaction; while pore size was more uniform, disconnected matrix regions still contributed to potential water absorption pathways and reduced dimensional stability (Kumar et al., 2022).

The 70:20:10 formulation (Fig 3.5c) demonstrated a significantly more compact morphology, with the matrix well-encapsulated around reinforcement fibers, minimal visible voids, and a continuous phase distribution. This improved interfacial adhesion and matrix-reinforcement continuity supports superior load transfer and limits crack propagation, contributing to its higher stiffness (Thippanna et al., 2024).

The greater structural compactness in 70:20:10 thus explains its superior stiffness (MOE), with the fibrous groundnut shell structure contributing to a more homogeneous, ductile blend (Darekar and Goyal, 2025). However, this compactness did not translate into improved moisture resistance, as 70:20:10 recorded the highest water absorption and thickness swelling among the three formulations - indicating that dimensional stability in this composite system is governed more by polypropylene content (which encapsulates fibers and limits moisture ingress) than by matrix compactness alone.

3.4 X-Ray Diffraction (XRD) Analysis of Composite boards

XRD patterns of all three formulations (Fig 3.6) exhibited characteristic broad diffraction peaks centered near $2\theta \approx 22°$, corresponding to the (002) plane of cellulose and confirming a semi-crystalline structure in each composite. A progressive increase in peak intensity was observed from 50:40:10 to 70:20:10, indicating higher relative cellulose crystallinity with increasing groundnut shell content. Crystalline cellulose domains contribute to stiffness, load-bearing capacity, and improved intermolecular hydrogen bonding, thereby enhancing MOE (Ahirwar et al., 2024). The 70:20:10 formulation accordingly exhibited greater crystallinity and higher MOE. In contrast, the substantial amorphous fractions, arising from lignin, hemicellulose, and residual polypropylene, reduce rigidity, promote moisture sorption, and contribute to thickness swelling and dimensional instability (Ahirwar et al., 2024). The 50:40:10 sample, with relatively lower crystallinity but higher PP content, demonstrated superior MOR and dimensional stability, reflecting the dominant role of the polymer encapsulation rather than crystalline order in moisture resistance at this proportion. Overall, XRD results indicate that increasing cellulose crystallinity progressively shifts composite behavior toward improved stiffness at the expense of moisture resistance, while adequate polymer encapsulation at lower GS ratios remains the primary mechanism for dimensional stability.

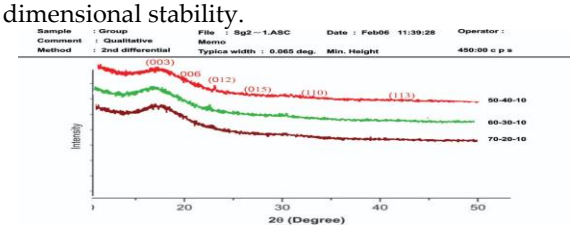


Fig 3.6. XRD analysis for the three mixing proportions (GS/PL/GF)

4 Conclusion and Recommendation

The following conclusions are drawn from the findings of this study:

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1. Mixing proportion significantly governed all measured composite properties. MOR decreased with increasing groundnut shell content while MOE increased correspondingly. ANOVA confirmed significant differences in MOR, MOE, and water absorption at the 5% probability level, establishing mixing proportion as a critical performance determinant.
2. The 50:40:10 formulation exhibited superior dimensional stability, recording the lowest water absorption and least thickness swelling across all exposure period. This formulation is most suitable for moisture-sensitive applications.
3. The 70:20:10 formulation demonstrated the most compact SEM morphology with minimal voids and superior XRD crystallinity.

Overall, groundnut shells, waste glass fibers, and recycled polypropylene waste can be effectively combined to produce composite particleboards with acceptable physical, mechanical, and microstructural performance, offering a sustainable, waste-valorizing alternative to conventional wood-based boards in alignment with SDGs 12, 13, and 15. Based on these findings, the 50:40:10 formulation is recommended for applications where moisture resistance and dimensional stability are critical, such as humid or exterior-adjacent environments. Conversely, the 70:20:10 formulation is recommended where stiffness and load-bearing capacity are prioritized over moisture exposure. The optimal formulation therefore depends on the intended application, and manufacturers should select the mixing ratio according to the specific performance requirements of the end use.

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