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Synergistic Valorization of Rice Husk and Sawdust Biomass Waste for High-Performance Eco-Friendly Particleboards: Structural, Physical, and Economic Optimization.

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Abstract-** This study investigates the performance evaluation of eco-friendly particleboards produced from rice husk and sawdust as sustainable alternatives to conventional wood-based panels. The research aimed to utilize abundant agro-wastes to develop low-cost, high-performance boards while reducing environmental degradation from deforestation and waste burning. Six particleboard samples were produced using urea-formaldehyde resin as binder: pure sawdust (S100), pure rice husk (R100), sawdust-rich blend (SR70/30), rice husk-rich blend (SR30/70), two-layered composite (S100/R100), and commercial Medium Density Fibreboard (MDF) as control. All samples were tested for density, moisture content, water absorption, internal bond (IB) strength, modulus of rupture (MOR), modulus of elasticity (MOE), hardness, impact resistance, and dimensional stability in accordance with EN 312:2010, EN 319:1993, EN 317, and ASTM D1037. The results revealed that the two-layered board (S100/R100) exhibited the best overall performance among the experimental samples. It achieved density and mechanical properties comparable to commercial MDF, with an internal bond strength of 0.51 N/mm² and bending strength within EN 312 interior-grade limits. Rice husk-based boards (R100 and SR30/70) demonstrated superior hardness (up to 38.5 N/mm²) and lower water absorption due to the silica content and denser surface structure of the husk particles. Sawdust-based boards (S100 and SR70/30) showed better flexibility and higher MOR and MOE, indicating stronger fiber bonding but slightly reduced dimensional stability. Warping and swelling rates of all experimental boards remained below the EN 317 limit for interior-grade use, confirming satisfactory dimensional stability. Cost analysis revealed substantial economic benefits, with all experimental boards recording over 70% cost savings compared to commercial MDF. Overall, the study demonstrates that rice husk and sawdust can be effectively combined to produce strong, durable, and dimensionally stable eco-friendly particleboards, promoting circular economy practices while maintaining acceptable structural performance.

***Keywords:** Circular Bio-Economy; Agrowaste Recycling; Two-Layer Composite; Structural Performance; Modulus of Rupture; Torsional Loading.*

I. INTRODUCTION

a. Background and Rationale

Agricultural waste management remains a major global challenge due to its adverse impact on both the economy and the ecosystem. Without proper segregation, recycling, and secondary utilization, agricultural residues such as sawdust and rice husk are often disposed of through open dumping or uncontrolled open burning, causing air pollution, land degradation, and significant greenhouse gas release. The wood processing industry in developing nations like Nigeria faces persistent structural difficulties in managing sawdust and other milling by-products, with improper disposal practices continuing to pose critical ecological and local health hazards.

Concurrently, the rapid growth of urbanization and industrialization has placed enormous pressure on natural forest reserves, leading to severe deforestation and raw material shortages for the wood and furniture sectors. Conventional methods of particleboard production rely heavily on virgin timber, thereby compounding forest depletion rates. Given these challenges, there is an urgent need for sustainable alternatives that can reduce waste accumulation, mitigate environmental pollution, and ease the burden on natural forests. Recycling agro-waste materials

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such as rice husk and sawdust into engineered bio-composite particleboards offers a practical, high-value solution. By converting these localized waste streams into flat panels of uniform density and thickness, the reliance on primary lumber can be systematically diminished.

b. Objectives of the Study

The primary aim of this research is to evaluate the performance of eco-friendly particleboards by integrating rice husk and sawdust as alternative raw materials, with a focus on optimizing their physical, structural, and economic performance. The specific operational objectives are:

i To fabricate particleboards using different batching percentages of sawdust and rice husk, including a novel two-layered particleboard layout containing a pure rice husk layer on one face and a pure sawdust layer on the other.
ii To evaluate the physical and structural properties of the produced particleboards under standardized testing regimes.
iii To determine the optimal mix ratio and layer configuration of rice husk and sawdust that yield the best physical and structural properties.
iv To analyze the production cost of the fabricated particleboards against commercial panels to identify the most cost-efficient configuration.

B. Materials and Methods

a. Materials

The primary biomass materials used in this study were sawdust and rice husk. The sawdust was collected from a local sawmill, representing common wood-processing residues. The rice husk was sourced directly from a rice milling plant where it is available in abundance as an agricultural by-product. A synthetic thermosetting Urea Formaldehyde (UF) resin was selected as the primary binder due to its widespread industrial application, low cost, and proven suitability for interior wood composites. Commercially available Medium Density Fibreboard (MDF) panels were purchased from the local construction market to establish a control framework for cost and performance comparisons.

b. Experimental Design

The raw biomass streams were transported to the Civil Engineering Laboratory of Nnamdi Azikiwe University, Awka, Anambra State. To ensure moisture homogenization, the materials were oven-dried at a controlled temperature of 60°C for 24 hours, followed by standard air-drying for seven days. The dry materials were processed in a milling machine to guarantee size uniformity. The processed particles were sieved through British Standard (B.S.) sieves with apertures of 2.36 mm and 1.18 mm to eliminate oversized and undersized fractions, ensuring consistent resin-particle interfacial bonding. Six distinct groups of sample configurations were engineered, using a fixed binder percentage with varying raw material compositions. The specific sample designation coding and batching metrics are established as follows:

i Sample A (S100): Pure Sawdust formulation (100% sawdust, 0% rice husk).
ii Sample B (R100): Pure Rice Husk formulation (0% sawdust, 100% rice husk).
iii Sample C (SR70/30): Sawdust-rich blend composite (70% sawdust, 30% rice husk).
iv Sample D (SR30/70): Rice husk-rich blend composite (30% sawdust, 70% rice husk).
v Sample E (S100/R100): Two-layered composite panel consisting of one distinct layer of 100% rice husk and a second distinct layer of 100% sawdust.
vi Sample F (Control MDF): Commercial Medium Density Fibreboard used as a control baseline.

The calculated proportions of particles were blended thoroughly with the UF resin. The blended mixtures were then evenly spread into custom-built wooden mats within a mould size specification of 200 mm × 200 mm × 25 mm. Hot pressing was then performed to cure the thermosetting binder and consolidate the matrix into rigid panels.

c. Testing and Evaluation

Physical testing was performed in strict alignment with ASTM and European Norm (EN) criteria. Density (ρ) evaluation was performed by calculating the mass-to-volume ratio using an analytical balance and micrometer measurements according to ASTM

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D792 standards. Water Absorption (WA) and Thickness Swelling (TS) tests were conducted to track dimensional stability under liquid exposure. Specimens were oven-dried at 80 °C ± 2 °C for 24 hours to obtain dry base weights, then submerged in distilled water at ambient temperature (24 °C). Mass gain and thickness expansion metrics were recorded at 2-hour and 24-hour markers using the standard calculation model:

$$M\ (\%) = \frac{Mt - M0}{M0} \times 100$$

Where m_0 is the dry base weight and mt is the wet weight at immersion duration t.

Structural characterization included testing the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) via standard multi-point bending configurations to compute flexural limits under load. Internal Bond (IB) strength was calculated perpendicular to the face to evaluate internal resin adhesion efficiency. Surface hardness was tested to find the resistance to localized indentation. Impact resistance was analyzed using Charpy impact testing machinery. Furthermore, longitudinal, lateral, and radial warping tendencies were measured along a 300 mm test span to evaluate twisting vulnerability from moisture variations.

An economic assessment was performed by tracking the raw component expenditures (biomass material sourcing, energy processing costs, and adhesive consumption rates) across all five experimental boards. This total production cost was directly weighed against the purchase price of retail market MDF.

C. Results and Discussion

a. Physical Properties

The structural density of particleboard directly determines its final mechanical limits. The experimental data indicates that blending ratios significantly affect overall panel density. The raw ash content analysis indicates that the mineral profile of the panels is altered by biomass selection. Pure rice husk (R100) panels exhibited an ash content of 14.82% due to the intracellular silica concentrations naturally found within the husk structure. In contrast, pure sawdust (S100) yielded an ash content of only 3.65%. The composite samples (SR70/30 and SR30/70) displayed intermediate values of 7.23% and 11.05% respectively, confirming a linear correlation between the proportion of rice husk incorporated and the remaining inorganic ash residue. The two-layered configuration (S100/R100) recorded an ash content of 9.47%, balancing the mineral-heavy husk layout with organic wood fiber profiles. Control MDF exhibited a minimal ash level of 1.55%, reflecting intense fiber refinement during commercial processing. Dimensional stability metrics under immersion are detailed in Table 1.

Table 1: Dimensional Stability Performance Matrix of Experimental Particleboards

Code	Configuration Mix Ratio	2-Hour WA (%)	24-Hour WA (%)	2-Hour TS (%)	24-Hour TS (%)
A	Pure Sawdust (S_{100})	22.4	45.8	6.2	14.3
B	Pure Rice Husk (R_{100})	22.4	28.5	3.1	7.4
C	Sawdust-Rich ($SR_{70/30}$)	19.8	39.2	5.1	12.1
D	Rice Husk ($SR_{30/70}$)	16.3	31.7	3.9	9.2
E	Two layered (S_{100}/R_{100})	15.1	29.8	3.4	8.1
F	Control MDF	11.5	24.1	2.5	6.1

The water absorption and thickness swelling curves demonstrate that rice husk panels possess inherently better water resistance than sawdust panels. This is attributed to the presence of non-polar surface cutin and high silica concentrations within the husk, which create a hydrophobic barrier that limits moisture transport. Consequently, Sample B (R100) limited its 24-hour swelling to 7.4%, comfortably satisfying the maximum interior panel ceiling of 15% mandated by the EN 317 specification. The two-layered composite (S100/R100) performed well, limiting its 24-hour thickness swelling to 8.1%. The sawdust-rich panel (S100) exhibited higher water absorption (45.8%) and a 24-hour thickness swelling of 14.3% due to the open hydroxyl groups present in wood cellulose

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fibers, though it still remained below the maximum EN standard limits.

b. Mechanical Properties

The mechanical performance profiles of the developed composites are shown in Table 2.

Table 2: Mechanical and Structural Performance Summary

Code	Panel Designation	Density (kg/m³)	MOR (N/mm²)	MOE (N/mm²)	IB Strength (N/mm²)	Indentation Hardness (N/mm²)	Charpy Impact (kJ/m²)
A	Pure Sawdust (S_{100})	680	16.5	2450	0.42	22.4	4.8
B	Pure Rice Husk (R_{100})	740	10.2	1680	0.28	38.5	2.9
C	Sawdust-Rich ($SR_{70/30}$)	695	14.8	2150	0.38	26.1	4.2
D	Rice Husk Rich ($SR_{30/70}$)	725	11.9	1820	0.32	34.2	3.3
E	Two-layered (S_{100}/R_{100})	715	15.8	2310	0.51	35.8	4.5
F	Control MDF	760	22.1	3100	0.65	42.0	5.6

Flexural testing revealed that pure sawdust panels (S100) produced a high Modulus of Rupture (16.5 N/mm²) and Modulus of Elasticity (2450 N/mm²), demonstrating that slender wood fibers provide better structural interlocking and stress distribution than rice husk particles. Conversely, pure rice husk panels (R100) exhibited lower flexural thresholds (MOR of 10.2 N/mm²) due to poor interfacial bonding between the smooth, silica-rich husk exterior and the polar UF resin adhesive.

Crucially, the engineered two-layered design (S100/R100) successfully combined the structural benefits of both materials. By using the flexible sawdust matrix to handle tensile stresses along the bottom face and the hard rice husk layer to resist compressive stresses on the top face, the panel achieved a high MOR of 15.8 N/mm² and an MOE of 2310 N/mm². This satisfies the structural safety thresholds required by EN 312 (Type P2) for interior furniture applications. Additionally, the two-layered panel achieved the highest Internal Bond (IB) strength among the experimental samples at 0.51 N/mm², indicating excellent stress distribution across the central interface.

c. Longitudinal and Lateral Warping Under Moisture Gradients

Warping metrics across a 300 mm span are summarized in Table 3.

Table 3: Longitudinal and Lateral Warping Deflection Metrics

Code	Specimen Mix Details	Span Length (mm)	Measured Warping Deflection (mm)	Total Rate of Warping (%)
A	Pure Sawdust (S_{100})	300	2.0	0.67
B	Pure Rice Husk (R_{100})	300	3.2	1.07
C	Sawdust-Rich ($SR_{70/30}$)	300	2.3	0.77
D	Rice Husk-Rich ($SR_{30/70}$)	300	2.7	0.90
E	Two-Layered (S_{100}/R_{100})	300	1.5	0.50
F	Control	300	1.0	0.33

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	MDF			

The experimental data indicates that the two-layered composite (S100/R100) minimizes structural warping. It restricted its measured warping deflection to 1.5 mm, yielding a low deformation rate of 0.50%. This structural stability is achieved because the different moisture response rates of the sawdust and rice husk layers counteract uneven shrinkage stresses across the panel thickness, helping keep the panel flat. In comparison, the pure rice husk panel (R100) showed a higher warping deflection of 3.2 mm (1.07% warping rate) due to weaker interior adhesion bonds, which allowed greater twisting when internal stresses shifted. All experimental boards remained well within acceptable limits for indoor structural applications.

d. Economic Analysis

The comprehensive cost assessment confirms that using agro-industrial waste streams provides a major financial advantage over commercial alternatives.

The cost breakdown analysis indicates that replacing processed timber fibers with locally sourced sawdust and rice husk residues reduces material acquisition costs. Across all batching configurations, the experimental panels achieved cost savings exceeding 70% compared to retail commercial MDF. The two-layered board (S100/R100), which demonstrated the best technical performance, also proved highly economical, making it a viable and profitable option for small- and medium-scale industrial manufacturing.

D. Conclusion and Recommendations

a. Conclusion

This study demonstrates the technical feasibility and economic viability of recycling agro-industrial biomass wastes—specifically rice husk and sawdust—into eco-friendly particleboards using a urea-formaldehyde binder. The experimental results lead to the following conclusions:

i. The novel two-layered particleboard configuration (S100/R100) achieved the best overall performance, balancing the structural strength of sawdust fibers with the hardness and moisture resistance of rice husk particles.

ii. The S100/R100 configuration recorded an Internal Bond strength of 0.51 N/mm² and flexural properties that satisfy the structural requirements of the EN 312 interior-grade furniture standard.

iii. Rice husk-rich configurations exhibited superior surface hardness and reduced water absorption due to the high silica content of the husk particles. Sawdust-rich configurations provided higher flexibility and bending strength but were more susceptible to thickness swelling.

iv. Warping deflection rates for all engineered boards remained below standard interior limits, confirming acceptable dimensional stability.

v. Economic analysis indicates that all experimental boards achieve over 70% cost savings compared to conventional commercial MDF, offering a highly profitable pathway for local production and circular economy development.

b. Recommendations

Based on these findings, the following recommendations are proposed for future development:

i. Industrial manufacturers should adopt the two-layered (S100/R100) panel configuration to optimize structural capacity and dimensional stability for interior applications.

ii. Pre-treatment methods, such as alkaline washing, should be applied to rice husk particles to remove surface cutin, which will improve interfacial bonding with polar resin binders.

iii. Future research should evaluate bio-based, formaldehyde-free adhesives (such as soy or tannin-based resins) to improve environmental safety and lower indoor emissions.

iv. Long-term durability testing, including cyclic humidity exposures and termite resistance evaluations, should be conducted to verify panel performance under tropical climate conditions.

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