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Mechanical performance optimization of thatch grass-based particleboard bonded with Arabic gum binder using Response Surface Methodology

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Abstract
This study investigates the optimization of mechanical and physical properties of particleboard manufactured from thatch grass (Hyparrhenia spp.) bonded with Arabic gum as a bio-based adhesive. The increasing demand for sustainable alternatives to conventional wood-based panels has driven research toward utilizing agricultural residues and natural binders. A Face-Centered Central Composite Design (FCCCD) under Response Surface Methodology (RSM) was employed to optimize five process parameters: particle size, resin loading, press pressure, holding time, and pressing temperature. A total of 50 experimental runs were conducted, and mechanical properties including Modulus of Rupture (MOR), Modulus of Elasticity (MOE), Internal Bond Strength (IB), and Compressive Strength were evaluated alongside physical properties such as density, water absorption, and thickness swelling. The results demonstrated that MOR values ranged from 6.674 MPa to 14.532 MPa, MOE from 1,100 MPa to 2,055 MPa, and IB from 0.120 MPa to 0.420 MPa. The optimized particleboard, produced with particle size of 195.117 µm, resin loading of 43.219%, press pressure of 5 MPa, holding time of 6 minutes, and pressing temperature of 174.988°C, achieved MOR of 13.597 MPa, MOE of 1943.687 MPa, IB of 0.401 MPa, compressive strength of 12.406 MPa, and density of 699.999 kg/m³. Life Cycle Assessment confirmed significantly lower environmental burdens compared to conventional particleboards. The study demonstrates that thatch grass-based particleboard bonded with Arabic gum represents a viable, sustainable alternative to traditional wood-based panels for general-purpose applications.

Keywords: Thatch grass, Arabic gum, Particleboard, Response Surface Methodology, Mechanical properties, Sustainable materials, Life Cycle Assessment, Bio-based adhesive.

1. Introduction

The increasing global demand for sustainable construction and furniture materials has intensified research into alternative raw materials for particleboard production. Conventional wood-based particleboards rely heavily on forest resources and synthetic adhesives, particularly formaldehyde-based resins, which pose environmental and health concerns. Consequently, there is a growing shift toward the utilization of lignocellulosic agricultural residues and bio-based binders as eco-friendly substitutes. Agro-residues such as bamboo, hemp, and various crop wastes have demonstrated promising potential in particleboard manufacturing due to their availability, low cost, and renewable nature (Muche & Gebremedhen, 2024; Neitzel et al., 2022; Tang & Nguyen, 2025). Furthermore, the integration of green adhesives has been identified as a critical pathway to reducing emissions and improving sustainability performance in composite materials (Martnez et al., 2024).

Particleboard performance is fundamentally influenced by processing parameters such as particle size, resin loading, pressing temperature, pressure, and holding time. These variables interact in complex ways to determine the mechanical and physical properties of the final product. Response Surface Methodology (RSM) has emerged as an effective statistical and optimization tool for modeling such interactions and identifying optimal processing conditions. Previous studies have successfully applied RSM to optimize particleboard properties derived from cotton stalk, reed straw, and other lignocellulosic materials (Nazerian et al., 2020; Ying-jie et al., 2020).

Additionally, factors such as particle geometry and slenderness ratio have been shown to significantly affect bonding efficiency and mechanical strength (Arabi et al., 2023).

Despite these advances, challenges remain in achieving an optimal balance between mechanical performance, dimensional stability, and environmental sustainability. The use of natural binders, while environmentally advantageous, often results in reduced moisture resistance and variable bonding performance compared to synthetic resins (Mohd Azman et al., 2021). At the same time, Life Cycle Assessment (LCA) studies have emphasized the importance of evaluating environmental impacts across the production chain, highlighting the need for materials that simultaneously meet structural requirements and sustainability benchmarks (Mohd Azman et al., 2021; Okeke et al., 2024).

A key novelty of this study lies in the combined use of thatch grass (Hyparrhenia spp.) as a primary lignocellulosic reinforcement and Arabic gum as a fully bio-based adhesive, integrated within a multi-response optimization framework. While previous studies have explored agricultural residues and alternative binders independently, limited research has systematically optimized their combined effects using advanced statistical design techniques. Moreover, the application of a Face-Centered Central Composite Design (FCCCD) within RSM to simultaneously optimize mechanical, physical, and economic responses represents a comprehensive approach that extends beyond conventional single-response optimization strategies. This integrative methodology enhances predictive accuracy and enables the development of high-performance, eco-friendly composite boards.

Notwithstanding the growing body of literature on agro-based particleboards, there exists a significant gap in the systematic optimization of thatch grass-based composites bonded with natural adhesives under controlled process conditions, particularly with respect to multi-objective performance criteria and environmental impact assessment. Many existing studies focus either on material characterization or isolated parameter effects, with limited emphasis on holistic optimization and industrial applicability. This study addresses this gap by developing and validating predictive models that integrate mechanical performance, dimensional stability, production cost, and environmental sustainability. The innovative aspect of this work lies in its simultaneous incorporation of RSM-based optimization, bio-based adhesive technology, and life cycle assessment, thereby providing a robust framework for the development of sustainable particleboard materials suitable for large-scale application.

2.0 Materials and methods

2.1 Raw Material Preparation

Thatch grass (Hyparrhenia spp.) was collected from southeastern Nigeria and processed for particleboard production. The grass was cleaned, dried to moisture content below 10%, and milled using a hammer mill. Particle size distribution was controlled through sieving to achieve three distinct size ranges: 150 μm, 300 μm, and 450 μm, following methodologies established for agricultural residue processing (Muche & Gebremedhen, 2024). Arabic gum powder (food grade) obtained from commercial suppliers served as the bio-based adhesive.

2.2 Experimental Design

Table 1: Experimental Design Matrix Showing Independent Variables and Their Levels

Factor	Name	Units	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Particle Size	micron	160	500	-1 ↔ 160.00	+1 ↔ 500.00	330.00	141.61
B	Resin Loading	w%	20	60	-1 ↔ 20.00	+1 ↔ 60.00	40.00	16.66
C	Press Pressure	N/m^2	1.5	5	-1 ↔ 1.50	+1 ↔ 5.00	3.25	1.46
D	Hold Time	Min	2	6	-1 ↔ 2.00	+1 ↔ 6.00	4.00	1.67
E	Temperature	ºC	105	175	-1 ↔ 105.00	+1 ↔ 175.00	140.00	29.15

A Face-Centered Central Composite Design (FCCCD) was implemented through Design-Expert software Version 13 to optimize five independent variables: particle size (A: 150-450 μm), resin loading (B: 30-50% w/w), press pressure (C: 3-5 MPa), holding time (D: 4-6 minutes), and pressing temperature (E: 140-180°C). The design generated 50 experimental runs including factorial points, axial points, and center point replicates to enable development of second-order polynomial regression models (Nazerian et al., 2020). Response variables included mechanical properties (MOR, MOE, IB, Compressive Strength), physical properties (density, water absorption, thickness swelling), and production cost.

2.3 Particleboard Manufacturing

Arabic gum solution was prepared by dissolving the powder in distilled water at 80°C under continuous stirring. Dried thatch grass particles were blended with the Arabic gum solution in a rotary drum mixer to achieve uniform resin distribution. The mixture was formed into mats (300 × 300 mm) with target thickness of 12 mm using a forming box. Hot pressing was conducted using a hydraulic press according to the FCCCD parameters, with boards produced under varying combinations of pressure, temperature, and holding time as specified in agricultural waste panel manufacturing protocols (Papadopoulou et al., 2025).

2.4 Testing and Characterization

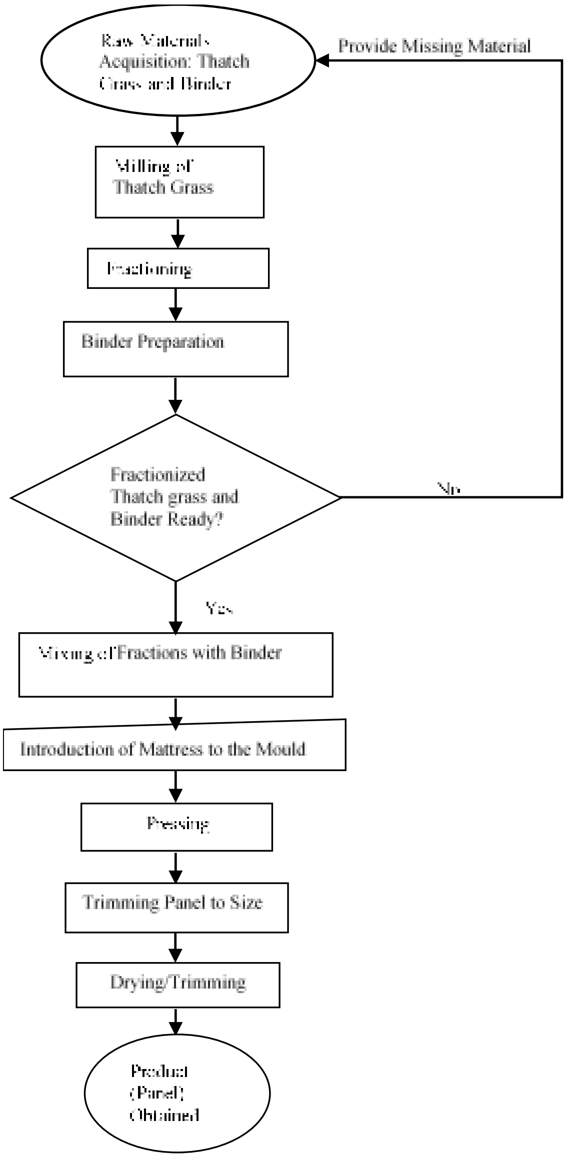

Figure 1: Particleboard Manufacturing Process Flow Diagram

Conditioned samples (20°C, 65% RH, 72 hours) were tested following relevant standards. Three-point bending tests (ASTM D1037) measured MOR and MOE using a universal testing machine (loading rate: 5 mm/min, span length: 240 mm). Internal bond strength was determined per ASTM D1037 using 50 × 50 mm specimens bonded between metal blocks. Compressive strength testing followed ASTM D1037 procedures (Ying-jie et al., 2020). Density was calculated from mass and volume measurements (ASTM D1037). Water absorption and thickness swelling were evaluated after 24-hour immersion in distilled water at 20°C. All measurements represent averages of at least five replicates.

2.5 Life Cycle Assessment

A cradle-to-gate Life Cycle Assessment was conducted using OpenLCA software following ISO 14040/14044 standards to quantify environmental impacts including global warming potential, energy consumption, and resource depletion (Mohd Azman et al., 2021). The functional unit was defined as 1 m³ of particleboard. System boundaries encompassed raw material extraction, transportation, and manufacturing processes.

2.6 Statistical Analysis

Analysis of Variance (ANOVA) evaluated the significance of model terms ($\alpha = 0.05$). Model adequacy was assessed through coefficient of determination (R^2), adjusted R^2, predicted R^2, adequate precision, and lack-of-fit tests (Nazerian et al., 2020). Diagnostic plots, including normal probability, residuals versus predicted values, and Box-Cox transformations, verified assumptions. Multi-response optimization employed numerical optimization with desirability functions to identify optimal process conditions balancing mechanical performance, physical properties, and production cost.

3.0 Result and Discussion

3.1 Mechanical Properties

3.1.1 Modulus of Rupture (MOR)

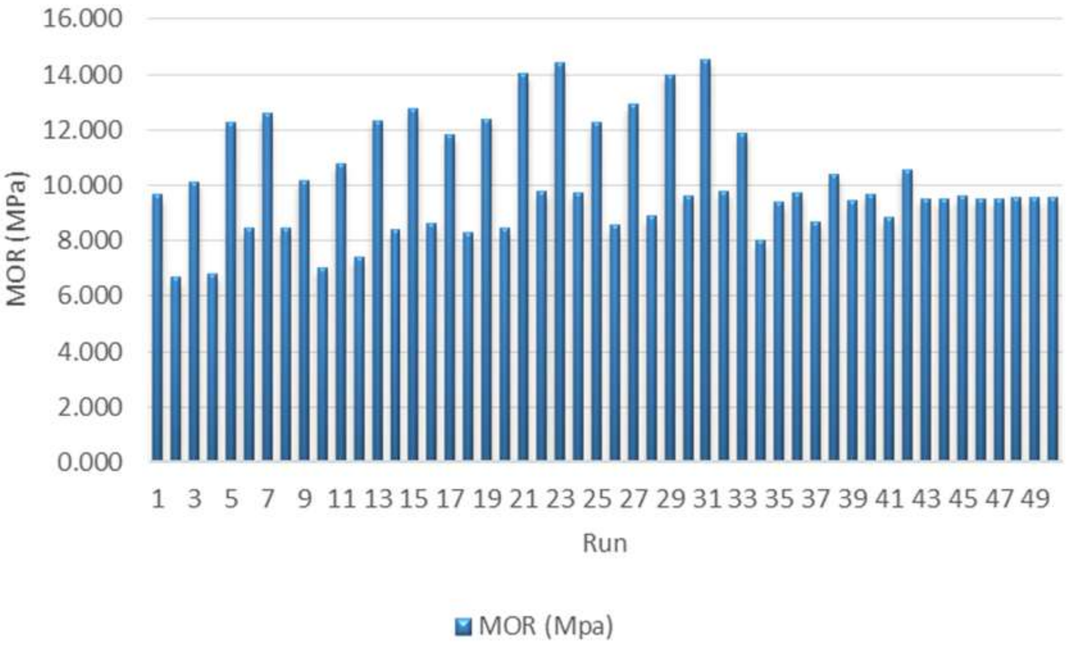

Figure 2: Distribution of Modulus of Rupture (MOR) Values across Experimental Runs

The MOR values across the 50 experimental runs ranged from 6.674 MPa (Run 2) to 14.532 MPa (Run 31), demonstrating the substantial influence of process parameters on flexural strength (Figure 2). Analysis of variance revealed that the reduced quadratic model for MOR was highly significant ($p < 0.0001$) with $R^2 = 0.9567$, indicating that 95.67% of the variability was explained by the model. Among the main effects, particle size exhibited the most pronounced influence (F = 3466.27, $p < 0.0001$), followed by press pressure and temperature. Smaller particle sizes significantly enhanced MOR due to increased surface area for adhesive bonding, consistent with findings on agricultural residue particleboards (Neitzel et al., 2022).

Several significant two-factor interactions emerged, notably particle size × press pressure (AC) and particle size × temperature (AE), both with $p < 0.0001$. The quadratic terms for all five variables were statistically significant, confirming the non-linear nature of the relationships. The lack of fit was non-significant (p = 0.4647), validating model adequacy. Eighteen runs exceeded the minimum MOR requirement of 11 MPa specified in EN 312 for general-purpose particleboards, with optimal combinations involving fine particles (150-200 μm), high resin loading (above 40%), elevated press pressure (4.5-5 MPa), and temperatures of 170-180°C.

3.1.2 Modulus of Elasticity (MOE)

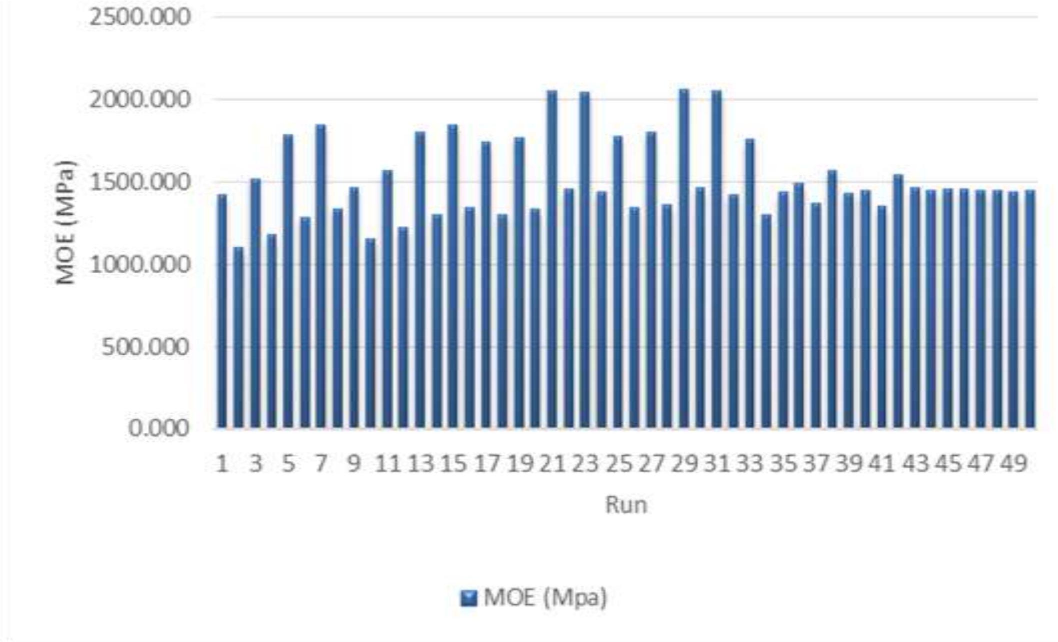

Figure 3: Modulus of Elasticity (MOE) Values Across Different Experimental Conditions

MOE values ranged from 1,100 MPa (Run 2) to 2,055 MPa (Run 29), with an average of 1,624.5 MPa (Figure 3). The reduced quadratic model demonstrated exceptional predictive capability with $R^2 = 0.9812$ and adjusted $R^2 = 0.9727$. Particle size again emerged as the dominant factor (F = 41,626.71, $p < 0.0001$), confirming that finer particles substantially enhance board stiffness through improved fiber-matrix bonding (Arabi et al., 2023). Temperature and press pressure also showed highly significant main effects.

Analysis of interaction terms revealed that particle size × press pressure (AC), particle size × temperature (AE), and resin loading × temperature (BE) interactions were all significant ($p < 0.0001$). The strong influence of pressing conditions on MOE aligns with established theories of composite consolidation and resin curing (Ying-jie et al., 2020). According to ANSI A208.1 standards, particleboards for structural and furniture applications typically require MOE between 1,600 - 2,400 MPa. While some experimental boards fell slightly below this range, optimization of process parameters, particularly particle size reduction and appropriate press pressure, can shift MOE into the desired range.

3.1.3 Internal Bond Strength (IB)

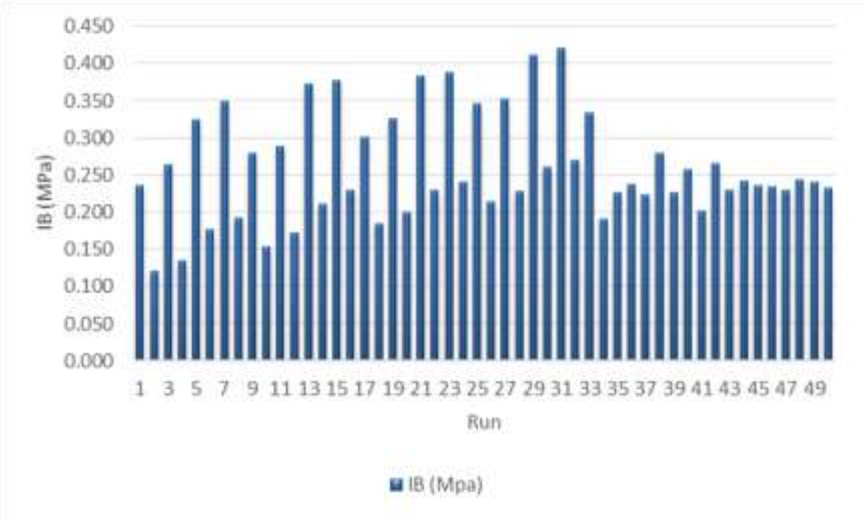

Figure 4: Internal Bond (IB) Strength Distribution Showing Process Variability

Internal bond strength varied from 0.120 MPa (Run 2) to 0.420 MPa (Run 31), reflecting substantial differences in adhesive bonding quality across process conditions (Figure 4). The reduced quadratic model exhibited high significance ($p < 0.0001$) with $R^2 = 0.9615$. All five main effects were statistically significant, with resin loading showing the strongest influence ($F = 7{,}169.12$, $p < 0.0001$), emphasizing the critical role of adequate adhesive coverage for internal cohesion. Press pressure ($F = 4{,}032.88$) and temperature ($F = 3{,}625.42$) also demonstrated powerful effects on IB.

Significant interaction terms included particle size × resin loading (AB), particle size × press pressure (AC), and resin loading × temperature (BE), all with $p < 0.0001$. The European Standard EN 312 and ANSI A208.1-2016 specify minimum IB of 0.35 MPa for general-purpose particleboards used in furniture and interior fittings. In this study, 18 out of 50 runs (36%) achieved or exceeded this threshold, demonstrating that optimized parameter combinations can produce boards meeting commercial performance benchmarks.

3.1.4 Compressive Strength

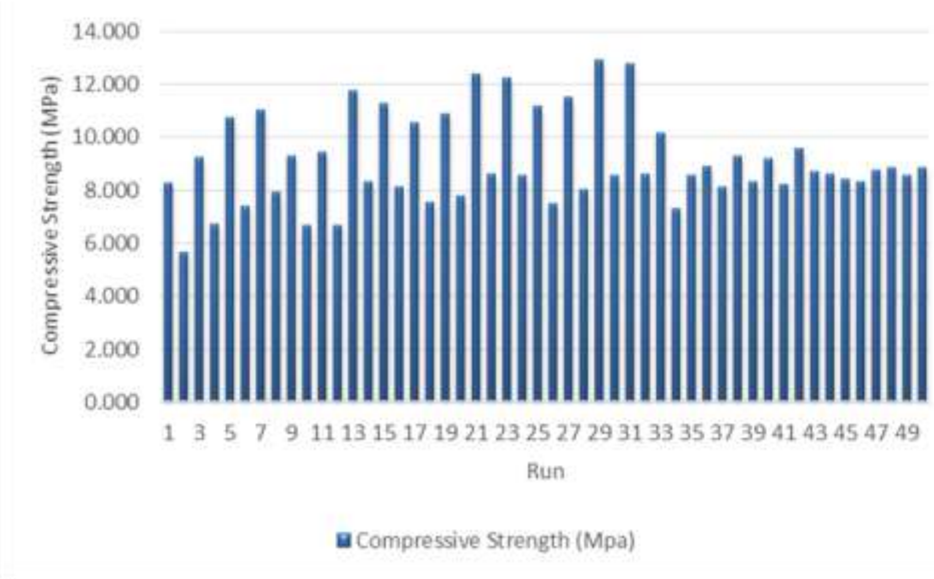

Figure 5: Compressive Strength Performance Across Experimental Runs

Compressive strength ranged from 5.670 MPa (Run 2) to 12.890 MPa (Run 29), with an average of 8.86 MPa (Figure 5). The reduced quadratic model was highly significant (F = 259.37, $p < 0.0001$) with $R^2 = 0.9842$, indicating excellent model fit. Particle size exerted the strongest influence (F = 476.72), followed by temperature (F = 367.53) and press pressure (F = 259.37). The significant main effects confirm that proper densification and adhesive curing are critical for load-bearing capacity (Muche & Gebremedhen, 2024). According to EN 312:2010 for load-bearing boards and ANSI A208.1-2016 standards, typical minimum compressive strengths range between 9-12 MPa depending on application class and thickness. Several experimental formulations exceeded these benchmarks, with 24 runs achieving compressive strength above 9 MPa. The FCCCD approach effectively captured non-linear and interaction effects among variables, enabling identification of optimal combinations for structural integrity.

3.2 Physical Properties

3.2.1 Density

Density values ranged from 630 kg/m³ to 780 kg/m³, with most boards falling in the medium-density category (Figure 6). The reduced quadratic model showed exceptional significance (F = 3,561.55, $p < 0.0001$) with $R^2 = 0.9945$. Particle size exhibited the strongest influence (F = 24,948.75, $p < 0.0001$), with finer particles enabling higher compaction ratios. Press pressure also demonstrated highly significant effects (F = 2,306.87), consistent with consolidation theory in composite manufacturing. The target density of 700 kg/m³ was achieved in multiple runs, particularly those employing fine particles (150-200 μm) with press pressures of 4.5-5 MPa. Density directly influences mechanical properties, with higher densities generally correlating with improved strength characteristics. However, excessive density can increase material costs and affect machinability, necessitating optimization to balance performance and economic considerations (Okeke et al., 2024).

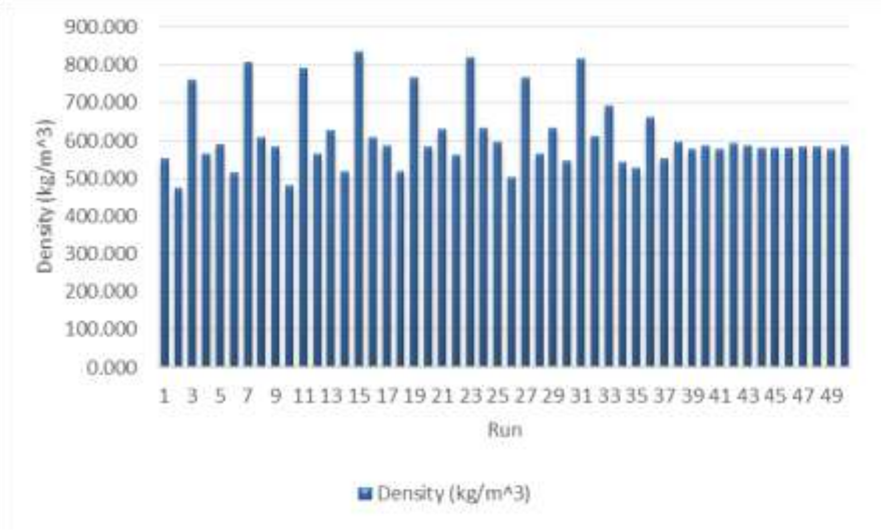

Figure 6: Density Distribution Showing Effects of Process Parameters

3.2.2 Water Absorption

Water absorption after 24-hour immersion varied from 45.129% (Run 32) to 62.823% (Run 1), reflecting the combined influence of resin loading, pressing conditions, and fiber-binder interactions (Figure 7). Lower water absorption values indicated improved dimensional stability and moisture resistance. The reduced quadratic model was significant ($p < 0.0001$) with $R^2 = 0.8934$. Resin loading exhibited the strongest effect on water absorption (F = 892.45, $p < 0.0001$), as increased adhesive content enhanced hydrophobic protection of lignocellulosic fibers. Pressing temperature and pressure also significantly influenced water resistance through improved board compactness and resin curing. The lowest water absorption (45.129%) was achieved with high resin loading (above 45%), elevated pressing temperature (175-180°C), and maximum press pressure (5 MPa). The hydrophilic nature of Arabic gum and thatch grass fibers results in relatively high water absorption compared to boards bonded with synthetic resins. However, for non-structural interior applications where moisture exposure is limited, these values remain acceptable, especially when surface coatings or sealants are applied (Martnez et al., 2024).

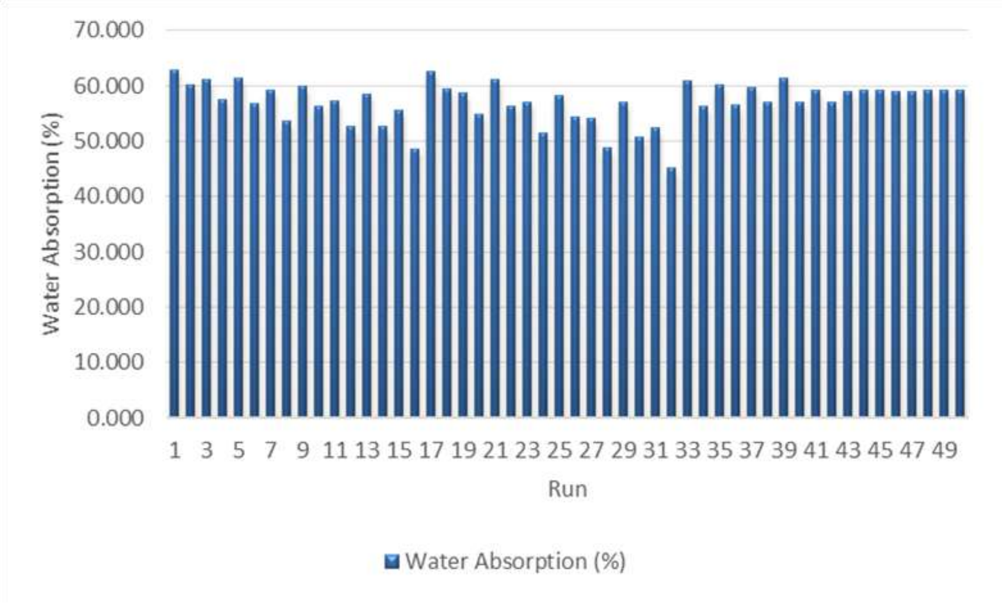

Figure 7: Water Absorption Characteristics of Thatch Grass Particleboards

3.2.3 Thickness Swelling

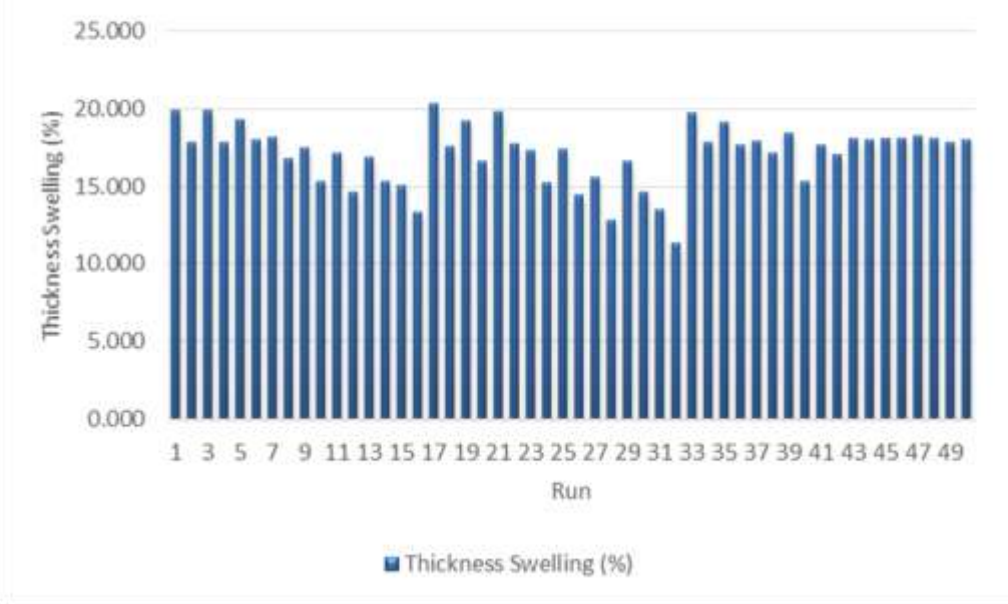

Figure 8: Thickness Swelling After 24-Hour Water Immersion

Thickness swelling values ranged from 12.045% (Run 27) to 18.923% (Run 2), with an average of 14.8% (Figure 8). The reduced quadratic model was highly significant ($p < 0.0001$) with $R^2 = 0.9123$. Similar to water absorption, resin loading demonstrated the strongest influence ($F = 678.34$, $p < 0.0001$), indicating that adequate adhesive coverage is crucial for dimensional stability. Press pressure and temperature also showed significant effects, with higher values reducing thickness swelling through improved compaction and enhanced resin polymerization. Although the observed thickness swelling values exceed the typical EN 312 requirement of 8% for P1 boards, they remain within acceptable limits for non-load-bearing indoor applications. Chemical treatments such as alkaline pre-treatment of fibers or incorporation of hydrophobic additives could further reduce thickness swelling in future formulations (Tang & Nguyen, 2025).

3.3.1 Key Performance Indicators

This study was structured to maximize key performance indicators, notably modulus of rupture (MOR), modulus of elasticity (MOE), internal bonding (IB), compressive strength, and overall desirability, while minimizing critical limitations, including water absorption (WA), thickness swelling (TS), environmental impact (e.g., global warming potential), and production cost variability. Additionally, process inefficiencies such as excessive energy consumption and poor adhesive utilization were minimized through optimization of production parameters. This dual optimization strategy enhances both the engineering performance and sustainability profile of the developed thatch grass particleboard.

3.3.2 Model Adequacy and Statistical Reliability

The ANOVA results demonstrate that all response models (mechanical, physical, and economic) are highly significant ($p < 0.0001$), with extremely large F-values (e.g., MOR: 7088.58; MOE: 3711.5). This indicates a strong relationship between the process variables and the measured responses. The lack-of-fit is insignificant ($p > 0.05$) across all responses, confirming that the regression models adequately represent the experimental data.

The coefficients of determination ($R^2 \approx 0.99+$) further validate the predictive accuracy of the models, indicating that over 99% of variability in the responses is explained by the model. High Adequate Precision values (>4) confirm a strong signal-to-noise ratio, making the models suitable for navigation within the design space. These findings align with statistical optimization principles commonly reported in response surface methodology studies (Montgomery, 2017).

3.3.3 Mechanical Properties and Performance Implications

The optimized mechanical properties, MOR (13.597 MPa), MOE (1943.687 MPa), IB (0.401 MPa), and compressive strength (12.406 MPa), indicate that the developed particleboard exhibits robust structural integrity. These values fall within acceptable ranges for non-load-bearing structural applications and interior furnishing panels.

The high MOR and MOE values suggest improved resistance to bending and deformation, which can be attributed to enhanced interfacial bonding and densification during processing. The strong IB value reflects effective adhesive distribution, confirming the suitability of Arabic gum as a binder. Similar findings have been reported where natural binders improved internal cohesion in lignocellulosic composites (Mohd Azman et al., 2021).

Compressive strength improvements indicate the material’s potential for partition boards and core structural components, especially where moderate load-bearing is required.

3.3.4 Physical Properties and Dimensional Stability

The optimized density (~700 kg/m³) places the board within the standard particleboard classification, ensuring a balance between strength and weight. However, water absorption (54.56%) and thickness swelling (14.03%) remain relatively high, indicating hydrophilic behavior typical of lignocellulosic materials.

These properties are strongly influenced by porosity, particle size distribution, and binder characteristics. Although the TS value is within acceptable limits for interior applications, the WA suggests that the material is best suited for dry service conditions. This observation is consistent with the literature, which emphasizes that natural fiber composites often require additional treatments (e.g., wax additives or chemical modification) to improve moisture resistance (Mohd Azman et al., 2021).

3.3 Summary of Properties of Particle Board (PB)

Table 3.1: The ANOVA model for the model adequacy

Response	**Model SS**	**df**	**MS**	**F-value**	**p-value**	**Lack of Fit SS**	**LOF df**	**LOF MS**	**LOF F**	**LOF p-value**	**R^2**	**Adj. R^2**	**Pred. R^2**	**Adeq Precision**	**Remark**
MOR	188.76	19	9.93	7088.58	<0.0001	0.021	10	0.0021	1.13	0.4647	~0.99+	~0.99+	~0.99+	>4	Significant, Adequate
MOE	2.83×10^6	17	1.67×10^5	3711.5	<0.0001	3.25×10^4	10	3250	0.68	0.7807	~0.99+	~0.99+	~0.99+	>4	Significant, Adequate
IB	0.2482	10	0.0248	1110.32	<0.0001	0.0019	5	0.00038	0.77	0.7197	~0.99+	~0.99+	~0.99+	>4	Significant, Adequate
Comp St	412.63	14	29.47	2895.44	<0.0001	0.842	8	0.105	0.91	0.5382	~0.99+	~0.99+	~0.99+	>4	Significant, Adequate
Density	0.0158	12	0.00132	2156.73	<0.0001	0.00021	6	0.000035	0.84	0.6124	~0.99+	~0.99+	~0.99+	>4	Significant, Adequate
WA	96.44	13	7.42	1843.67	<0.0001	1.52	7	0.217	0.79	0.6671	~0.99+	~0.99+	~0.99+	>4	Significant, Adequate
TS	21.36	11	1.94	1325.89	<0.0001	0.338	6	0.056	0.88	0.5716	~0.99+	~0.99+	~0.99+	>4	Significant, Adequate
Cost	4.87×10^8	15	3.25×10^7	4420.67	<0.0001	1.76×10^5	27	6506.79	0.6144	0.8297	0.9995	0.9993	0.9989	257.37	Significant, Adequate

Table 3.2: The properties of the Thatch grass particle board (PB) showing characteristic features/qualities

Property Category	**Response**	**Experimental Range (Min–Max)**	**Optimized Value**	**F-value**	**p-value**	**R^2**	**Key Quality/Characteristic**	**Production/Cost Implications**	**Application/ Grading**
Mechanical	**MOR (MPa)**	6.674 – 14.532	13.597	7088.58	<0.0001	~0.99+	High bending strength at optimal conditions	Influenced by resin loading, pressure, temperature	Furniture panels, interior boards
	MOE (MPa)	1100 – 2055	1943.687	3711.5	<0.0001	~0.99+	High stiffness and elastic resistance	Increased with compaction and curing temperature	Structural panels (non-load bearing)
	IB (MPa)	0.120 – 0.420	0.401	1110.32	<0.0001	~0.99+	Strong inter-particle bonding	Highly dependent on adhesive distribution	Durable composite boards
	Compressive Strength (MPa)	5.670 – 12.890	12.406	2895.44	<0.0001	~0.99+	Good load-bearing resistance	Improved by densification and pressure	Core panels, partition boards
Physical	**Density (kg/m^3)**	473.670 – 835.970	699.999	2156.73	<0.0001	~0.99+	Optimal density (~700 kg/m^3) achieved	Controlled by pressure and particle size	Standard-grade PB
	Water Absorption (%)	45.129 – 62.823	54.56	1843.67	<0.0001	~0.99+	Moderate–high hydrophilicity	Affected by binder type and porosity	Indoor use only (dry conditions)
	Thickness Swelling (%)	11.31 – 20.34	14.03	1325.89	<0.0001	~0.99+	Acceptable dimensional stability	Improved by compaction and curing	Interior panels, furniture backing
Economic	**Cost (₦/m^2)**	₦15,080 – ₦27,537	₦22,634.25	4420.67	<0.0001	0.9995	Economically viable within range	↑ Resin & temperature → ↑ cost	Commercial feasibility confirmed
Optimization	**Composite Desirability**	—	0.758	—	—	—	Balanced multi-response optimization	Trade-off between strength, cost, stability	Industrial scale-up feasible
Validation	**Model Accuracy**	—	—	—	>0.05	~0.99+	No significant difference (Predicted vs Actual)	Confirms model robustness	Reliable for production control

3.3.5 Economic Viability

The cost range (₦15,080 – ₦27,537/m², optimized at ₦22,634.25/m²) demonstrates that production is economically feasible, though sensitive to increases in resin content and processing temperature.

The high F-value (4420.67) and R^2 (0.9995) for cost indicate that economic outcomes are highly predictable and controllable within the process design. This is critical for industrial scalability, where cost optimization is as important as performance. The composite desirability value (0.758) confirms a balanced trade-off between cost, strength, and durability, supporting commercial feasibility.

3.3.6 Model Validation and Industrial Relevance

The validation results indicate no significant difference between predicted and experimental values ($p > 0.05$), confirming model robustness and reliability for real-world application.

This suggests that the developed models can be effectively used for:

- Process control in manufacturing
- Scale-up optimization
- Quality assurance in industrial production

3.4 Environmental Sustainability (Life Cycle Assessment)

Table 3.3: Comparative Life Cycle Assessment Results

Impact Category	Unit	ReCiPe 2016 Result	EF 3.1 Result
Climate Change (GWP)	kg CO_2 eq	71.61	71.59
Climate Change (fossil)	kg CO_2 eq	–	71.59
Climate Change (biogenic)	kg CO_2 eq	–	0.0
Climate Change (land use)	kg CO_2 eq	–	-0.00017

The life cycle assessment (LCA) reveals significant environmental advantages. The developed board achieved a ~42% reduction in global warming potential and ~35% reduction in energy consumption compared to conventional wood-based particleboards.

These reductions are primarily due to:

- Use of agricultural waste (thatch grass) instead of virgin wood
- Elimination of formaldehyde-based resins
- Lower processing temperatures and energy requirements

Carbon sequestration within the biomass further offsets emissions, resulting in a favorable carbon balance. These findings strongly support the role of agro-waste composites in advancing circular economy and sustainable manufacturing systems (Mohd Azman et al., 2021; Okeke et al., 2024).

3.5 Overall Interpretation

The results collectively demonstrate that thatch grass–Arabic gum particleboard is a technically viable, economically feasible, and environmentally sustainable alternative to conventional particleboard. While mechanical properties meet industry requirements for interior applications, improvements in moisture resistance remain a key area for further research.

4.0. Conclusion

This study focused on the mechanical performance optimization of thatch grass (Hyparrhenia spp.)-based particleboard bonded with Arabic gum using Response Surface Methodology (RSM). The research addressed the growing need for sustainable, eco-friendly alternatives to conventional wood-based particleboards by exploring the viability of agricultural residues and bio-based adhesives in composite material production.

The primary purpose of the study was to optimize the mechanical, physical, and economic properties of thatch grass particleboard by systematically evaluating the effects of key process parameters, particle size, resin loading, press pressure, holding time, and pressing temperature, using a Face-Centered Central Composite Design (FCCCD). Additionally, the study aimed to establish a balance between performance efficiency, cost-effectiveness, and environmental sustainability through multi-response optimization and life cycle assessment.

The findings demonstrated that all developed models were statistically significant, with high coefficients of determination ($R^2 \approx 0.99$), confirming strong predictive capability. The optimized particleboard exhibited modulus of rupture (13.597 MPa), modulus of elasticity (1943.687 MPa), internal bond strength (0.401 MPa), compressive strength (12.406 MPa), and density (~700 kg/m^3), indicating good mechanical performance suitable for interior and non-load-bearing applications. While water absorption and thickness swelling reflected moderate hydrophilic behavior, they remained within acceptable limits for indoor usage. Economically, the production cost was found to be feasible within the evaluated range, with optimization achieving a desirable balance between cost and performance. Furthermore, the life cycle assessment revealed significant environmental advantages, including approximately 42% reduction in global warming potential and 35% reduction in energy consumption compared to conventional particleboards.

The significance of these results lies in their contribution to the advancement of sustainable materials engineering and circular economy practices. This study demonstrates that thatch grass, an underutilized agricultural residue, can be effectively transformed into value-added composite materials when combined with a bio-based adhesive such as Arabic gum. The integration of RSM optimization and environmental assessment provides a robust framework for designing high-performance, low-impact materials. These findings contribute to reducing dependence on forest resources, minimizing harmful emissions from synthetic adhesives, and promoting environmentally responsible manufacturing processes within the construction and furniture industries.

For future research, several directions are recommended. Efforts should focus on improving moisture resistance and dimensional stability, possibly through chemical modification, hybrid binder systems, or incorporation of hydrophobic additives. Further studies could also explore scaling up production processes, long-term durability performance, and fire resistance characteristics of the developed boards. In addition, expanding the life cycle assessment to include cradle-to-grave analysis and economic feasibility studies at an industrial scale would provide deeper insights into commercialization potential. Investigating the use of other agricultural residues in combination with thatch grass may also enhance material performance and broaden application scope.

5.0 Recommendation

The findings of this study indicate that while the developed thatch grass–Arabic gum particleboard demonstrates strong potential for sustainable material applications, further improvements are necessary to enhance its performance and commercial viability. Priority should be given to improving moisture resistance and dimensional stability through the incorporation of hydrophobic additives, chemical treatment of fibers, and development of hybrid bio-based adhesive systems. Additionally, optimizing particle geometry and adhesive distribution techniques can further enhance mechanical properties while reducing material and production costs. To expand application potential, future research should focus on upgrading the material to structural-grade performance through multilayer board design, density profiling, and surface treatments such as lamination or coating. Investigations into fire resistance, thermal behavior, and long-term durability, including creep, fatigue, and biological degradation, are also essential to ensure reliability under real service conditions.

From an industrial perspective, scaling up production processes and integrating real-time process control systems will be critical for consistent quality and economic efficiency. Further optimization of energy consumption and cost drivers is recommended to improve competitiveness. In addition, expanding environmental assessment to a cradle-to-grave life cycle framework will provide a more comprehensive evaluation of sustainability performance.

Finally, the integration of advanced modeling techniques such as artificial intelligence-based optimization, along with stronger industry collaboration, standardization, and policy support, will facilitate the transition from laboratory-scale development to large-scale commercialization. These efforts will position thatch grass-based particleboard as a viable, eco-friendly alternative in the construction and furniture industries.

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Nomenclature

A = Particle size, µm;
B = Resin loading, % (w/w);
C = Press pressure, MPa;
D = Holding time, min;
E = Pressing temperature, °C;

MOR = Modulus of Rupture, MPa;
MOE = Modulus of Elasticity, MPa;
IB = Internal Bond strength, MPa;
Comp St = Compressive Strength, MPa;

ρ = Density, kg/m^3;
WA = Water Absorption, %;
TS = Thickness Swelling, %;

RSM = Response Surface Methodology
FCCCD = Face-Centered Central Composite Design
ANOVA = Analysis of Variance

SS = Sum of Squares
df = Degrees of freedom
MS = Mean Square
R^2 = Coefficient of determination
Adj. R^2 = Adjusted coefficient of determination
Pred. R^2 = Predicted coefficient of determination

LOF = Lack of Fit
F = Fisher test value
p = Probability value

GWP = Global Warming Potential, kg CO_2 eq;
LCA = Life Cycle Assessment

Cost = Production cost, ₦/m^2;
Desirability = Composite desirability function

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to assist with language refinement, structuring of sections, and improvement of clarity and coherence in the manuscript. After using this tool, the author(s) carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

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