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Experimental Study on the Development of Particle Board Using Local Materials

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Abstract
The escalating demand for sustainable materials necessitates the development of high-performance bio-composites derived from agricultural wastes. This study explores the effects of varying proportions of melon husk, groundnut shell powder, and bone powder on the mechanical and water absorption properties of bio-composites using melamine formaldehyde as the binding matrix. Nine formulated samples (S1 - S9) were analyzed for mechanical strength, most importantly tensile strength and flexural strength, and also, water absorption. Results showed that Sample S6 containing 100 % melon husk hada lower tensile strength of 21.62 MPa and flexural strength of 36.89 MPa while Sample S7 made with 100 % groundnut husk had a tensile strength of 14.23 MPa and flexural strength of 30.31 MPa. However, Sample S5 with a hybrid formulation of 20 % melon husk, 70 % groundnut husk and 15 % bone powder gave the highest tensile strength of 28.96 MPa and flexural strength of 46.66 MPa. Using Grey Relational Analysis over the nine samples, considering nine properties in all, S5 was found to have the optimal composition with a Grey Relational Grade (GRG) of 7.32. All samples recorded high mechanical values well above the required threshold for woodwork and furniture and therefore, may be explored as alternative materials for structural applications.

Keywords: *Particle board from waste, Bio-composites from agriculture, Sustainable building materials, Agricultural waste utilization, Grey Relational Analysis.*

1.0 Introduction

The increasing demand for wood-based products has led to widespread deforestation and environmental degradation, particularly in tropical regions like Nigeria [1]. The Nigerian government has implemented policies to promote sustainable forest management and reduce the country's reliance on wood imports [2]. However, the demand for wood-based products continues to rise, driven by population growth, urbanization, and economic development [3]. In response to this challenge, researchers have been exploring the use of alternative materials for wood-based products, including particleboard [4].

Particleboard is a type of engineered wood product made from wood particles or fibers bonded together with an adhesive [5]. It is widely used in furniture, construction, and packaging applications [6]. However, the production of particleboard is heavily reliant on wood, which is becoming increasingly scarce and expensive [7]. In Nigeria, the demand for particleboard is high, driven by the growing construction and furniture industries [8]. However, the country's particleboard industry is heavily reliant on imported wood, which is expensive and unsustainable [9].

One potential solution to this problem is the development of particleboard using local, non-wood materials. Several studies have investigated the use of agricultural waste materials, such as wheat straw, rice husks, and sugarcane bagasse, for particleboard production [10]. These materials have been shown to have good physical and mechanical properties, making them suitable for use in particleboard production [11].

In Nigeria, melon seed husks, groundnut shells and animal bones are abundant agricultural waste materials that have the potential to be used as alternatives to wood in particleboard production [12]. Melon seed husks have been shown to have good physical and mechanical properties, making them suitable for use in particleboard production. Groundnut shells have also been shown to have good physical and mechanical properties, and have been used as a filler material in particleboard production [13]. Animal bones can improve density, enhance mechanical properties (tensile strength, impact strength, flexural strength), increase water resistance and reduce formaldehyde emission.

1.1 Background

The escalating global demand for cost-effective and sustainable construction materials has driven the development of particle boards from agricultural residues. Traditional wood-based composites contribute significantly to deforestation and biodiversity loss [1]. In contrast, agro-waste—specifically melon seed husks and groundnut shells—is abundant in tropical regions, yet largely underutilized, often leading to

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environmental disposal challenges [2]. Furthermore, the integration of animal bone waste from the meat industry offers a unique opportunity to incorporate hydroxyapatite-rich fillers, which can enhance the structural density of bio-composites [3].

Melamine formaldehyde (MF) remains a primary choice for a binding matrix due to its superior moisture resistance and adhesive strength compared to urea-formaldehyde [4]. However, the mechanical limitations of individual agro-fibers often require hybridization to meet industrial standards for load-bearing applications. Recent studies have shown that while groundnut shell-reinforced composites offer decent thermal insulation, they frequently suffer from low flexural strength [6].

Research by Olowo and Kumar (2023) noted that melon husk fibers increase ductility but significantly raise the water absorption rate of the matrix [7]. This study addresses these gaps by evaluating a ternary hybrid system. By combining the fibrous strength of groundnut shells, the ductility of melon husks, and the rigid reinforcement of bone powder, this research identifies an optimal formulation that mitigates the inherent weaknesses of the individual components.

2.0 Material and methods

2.1 Materials procurement and preparation

The materials used in this study included melon husk powder, groundnut shell powder, and cow bone powder as fillers, while melamine formaldehyde (2,4,6-triamino-1,3,5-triazine) served as the matrix and was manufactured by Mubychem Group (India) bought at Samaru market Zaria Kaduna State.

Groundnut shells and melon seed husks were collected from vendors at Mangorori Market, Samaru, Zaria, while cow bones were obtained from Zango Abattoir in Samaru, Zaria, Kaduna State. The collected cow bones were cleaned by removing all attached meat, fat, and connective tissues with a knife, then thoroughly rinsed with borehole water. They were sun-dried for seven days and subsequently ground into powder using a grain mill.

Similarly, the groundnut shells and melon seed husks were cleaned and dried, after which stones, dirt, and spoiled materials were removed. They were washed with clean borehole water to eliminate dust, sun-dried for five days, and then ground into powder using a grain mill.

Equipment

S/N	Equipment	Manufacturer/Model No.	Source
1	Compression Moulding Machine	Wenzhou Zhiguang Machine Ltd, China (Model: 0557)	NILEST[1]
2	Universal Testing Machine	D-100KN (SN:190536)	ABU[2]
3	Resil Impact Tester	CEAST Resil Family (6957.0000)	NILEST[1]
4	Universal Material Testing Machine	Norwood Instruments Ltd (Cat. Nr. 261)	ABU[2]
5	Digital Weighing Balance	Mettler Instruments Ltd (Model no: AE200)	NILEST[1]

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2.2 Research design

The study utilized a hybrid experimental architecture to evaluate the ternary bio-composite system. This structural approach ensures that every sample (S1–S9) serves a specific statistical purpose in identifying the interaction between the Melamine Formaldehyde matrix and the varying filler concentrations.

2.2.1. Simplex Lattice Layout

The Simplex Lattice Design was employed to manage the "sum-to-one" constraint inherent in mixture experiments ($X_1 + X_2 + X_3 = 100\%$).

i. (S6, S7): These samples define the boundary limits. By testing 100% concentrations of melon husk and groundnut shell, the study establishes the baseline mechanical properties of single-filler systems.

ii. (S3, S9): These formulations probe the interaction between two components while excluding the third. S9 (Melon/Bone) and S3 (Groundnut/Bone) reveal how the addition of animal bone powder modifies the properties of a single agricultural fiber.

iii. (S1, S2, S4, S5, S8): These represent ternary blends where all three fillers interact simultaneously. This is where the complex synergistic effects (such as the high performance of S5) are discovered.

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Table 1: Simplex Lattice Design

Sample	**Melon Husk Powder (M) (%)**	**Groundnut Shell Powder (G) (%)**	**Bone Powder (B) (%)**
S1	20	75	5
S2	75	20	5
S3	0	85	15
S4	70	20	10
S5	20	70	10
S6	100	0	0
S7	0	100	0
S8	45	45	10
S9	85	0	15

2.2.2 Optimisation: Grey Relational Analysis (GRA)

GRA is a decision-making method used when multiple performance criteria conflict with each other. In this case, particleboard is produced from agricultural waste (melon seed husks, groundnut shells, animal bones) for improved strength and durability. But improving one property might worsen another. GRA facilitates optimization.

2.2.2.1. Classification of Performance Criteria

Nine properties are identified. Some are better when higher, others when lower:

Category	Properties
Higher-the-Better	Tensile Strength, Tensile Modulus, Elongation, Flexural Strength, Flexural Modulus, Time of Ignition
Lower-the-Better	Water Absorbed, Swelling Thickness, Flame Duration

This classification is crucial for normalization.

2.2.2.2. Normalization of Data

All values are scaled between 0 and 1 to facilitate fair comparison.

i. For HB: Higher values get closer to 1.
ii. For LB: Lower values get closer to 1.

This gives you a normalized table where each sample's performance is expressed on a common scale.

For the smaller the better criterion,

Normalised value = $\frac{\max y_{i(k)} - y_{i(k)}}{\max y_i(k) - \min y_{i(k)}}$

For the larger the better,

Normalised value = $\frac{y_{i(k)} - min y_{i(k)}}{\max y_i(k) - \min y_{i(k)}}$

2.2.2.3. Calculate Deviation from Ideal

The ideal value for every property is 1 (perfect performance). How far each sample is from this ideal is calculated as above. Smaller deviations mean better performance.

$$\text{Maximum of respective normalized values} - \text{Corresponding normalized value}$$

2.2.2.4. Compute Grey Relational Coefficients (GRC)

This step transforms the deviation into a relational score:

This formula ensures that values closer to 1 are better. You now have a table of GRCs for each property and sample.

$$\frac{\text{minimum of respective deviation sequences} - \xi * \text{maximum of respective deviation sequence}}{\text{corresponding value} + \xi * \text{maximum of respective deviation sequence}}$$

2.2.2.5. Calculate Grey Relational Grade (GRG)

This is the average of all 9 GRCs for each sample:

$\frac{1}{n}\sum_{k=1}^{n}\xi_i$

The higher the GRG, the better the overall performance across all properties.

2.3 Mechanical Analysis

2.3.1Tensile Strength

The tensile strength was carried out accordance with ASTM D-638 [20]. A dumbbell shaped samples were subjected to a tensile force and tensile strength, tensile modulus percentage elongation at beak for each sample were calculated and recorded automatically by the machine and the results were on the certificate.

2.3.2 Impact Strength

The impact test was carried out according to the standard specified ASTM D-156 [21].The specimen was cut and prepared to dimensions64 mm x 12.7 mm x 3.2mm and 45^{o} notched was inserted at the middle of the test specimens from all the produced composite samples.The impact energy test was carried out using Izod Impact Tester (Resilimpactor testing machine). The specimen was clamped vertically on the jaw of the machine and hammer of weight 1500 N was released from an inclined angle 150°. The impact energy for corresponding tested specimen was taken and recorded. Impact strength was calculated and recorded accordingly using equation 3.2

Average Impact Energy = $\frac{1st+2nd+3rd}{3}$ (J) …………………………………… (Eq.) [21]

Impact Strength =$\frac{Average\ Impact\ Energy}{Sample\ Thickness}$ (J/mm) ……………………………............ (E.q) [21]Sample thickness = 3.2 mm

2.3.3 Flexural Strength

The flexural strength test on the blends was carried out in accordance with ASTM D-790 [22]. The specimen measuring 100 mm x 25 mm x 3.2 mm was placed on a support span horizontally at 80 mm gauge length and a steady load was applied to the center by the loading nose producing three-point bending until the sample specimen failed. The maximum load (N) and the corresponding deflection (mm) were recorded accordingly as the sample specimen failed. The flexural strength and flexural modulus were calculated using equation……….

Flexural Strength = $3FL/2bd^2$ (MPa) …………………………………………… (Eq……) [22]

Flexural Modulus = $FL^3/4bd^3D$ (MPa) …………………………………………… (Eq…..) [22]

Where,
F = Maximum Load at break
L = distance between the support spans at both edge of the specimen = 80mm
b = Sample width = 25mm
d = Sample thickness = 3.2 mm

2.4 Water absorption test

The water absorption test on particleboard is typically carried out to evaluate its dimensional stability and resistance to moisture ASTM D-1037 [23].

The samples was cut and prepared to dimensions 100 mm x 100 mm x 3.7mm, the samples are condition to constant weight at a controlled temperature and humidity, the dry sampleswere weighing accurately and thickness was taking using a digital weigh balance and digital vernier caliper and data taken were recorded.

The samples were fully immersed in water at room temperature, they are completely submerged without touching container sides, and the immersion time was 24 hours. After 24 hours the samples were removed from water and the surface moisture were quickly and carefully damp with a dry clothto avoid loss of absorbed water, the wet samples were immediately weighedto determine the increased in weight and thickness due to absorbed water.Percentage increased in weight and thicknesswas calculated and record.

3.0 Results and discussion

3.1 Effects on Tensile Strength

Tensile strength is crucial in evaluating a material's ability to withstand tensile forces. The results as presented in figure. 3.1 reveal that Sample S5 had the highest tensile strength of 28.96 MPa among other samples. This could be attributed to the synergistic effect (groundnut shell 70 % and bone powder 10 %) of the sample composition, because groundnut shell is rich in lingo-cellulosic content which might have offered good reinforcement, while bone powder most likely improved the stiffness and filler-matrix bonding due to its mineral content which is primarily hydroxyapatite [1]. Additionally, the moderate presence of melon husk 20 % ensures fiber distribution without compromising matrix continuity.

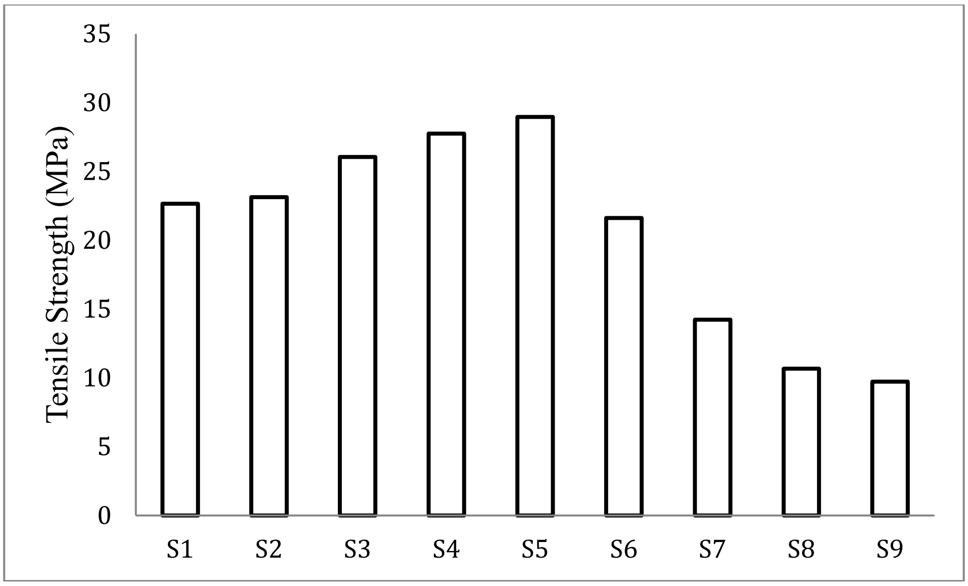

Figure.3.1**:** Effect of hybrid bio-fillers on the tensile strength on melamine formaldehydebio-composites

However, samplesS6 with 100 % melon husk and S7 with 100 % groundnut shell both showed lower tensile strength of 21.62 MPaand 14.23 MPa respectively. Thisconfirms that hybridization improves mechanical strength of particle boards as already reported in earlier works.

3.1.2 Tensile modulus Test Results

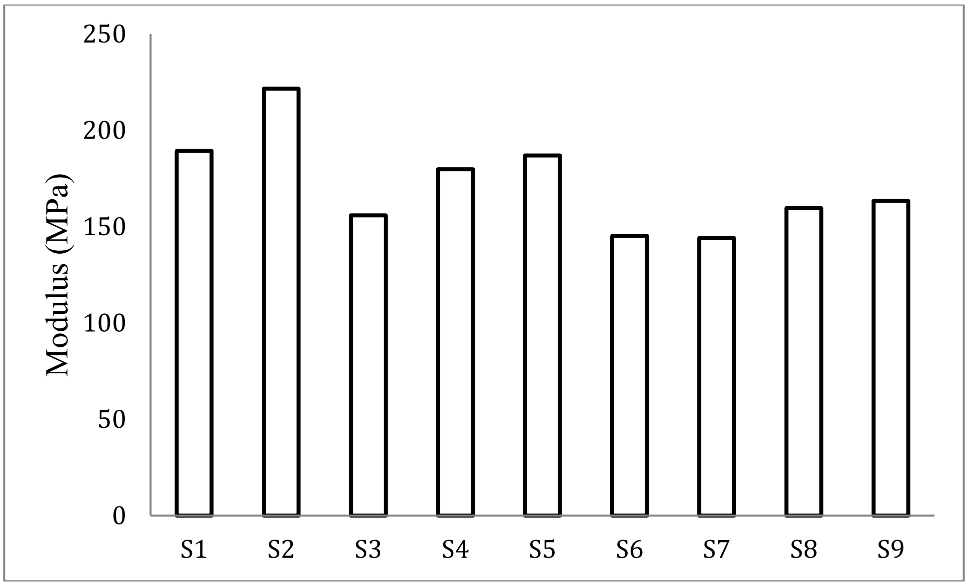

Figure.3.2**:** Effect of hybrid bio-fillers on the tensile modulus on melamine formaldehydebio-composites

Figure.3.2 indicates the tensile modulus results for the tested samples. Tensile modulus describes how stiff a material is under axial loading. Sample S2 formulated with 75 % groundnut shell, 20 % melon husk, and 5 % bone powder exhibited the highest tensile modulus of 221.66 MPa. This indicates that higher proportions of groundnut shell significantly contribute to rigidity. The low to moderate presence of bone powder further enhances stiffness, likely through its fine particulate reinforcement and load distribution capabilities [3].

Conversely, mono-filler Samples S6 and S7 shown the lowest moduli of 145.18 MPa and 144.08 MPa respectively. Sample S6 with 100% melon husk, likely exhibits lower stiffness due to the husk's relatively lower mechanical integrity and fiber fragmentation while sample S7 low modulus is unexpected because it contains reasonable quantity of groundnut shell powder. Consequently, these results suggest that lack of bone powder and potential particle agglomeration may reduce effective stress transfer.

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3.1.3 Flexural Strength Test Results

Flexural strength assesses material ability to resist bending stress. From the results represented in figure.3.3, sample S5 again outperformed other produced samples with flexural strength of 46.66 MPa, reaffirming the effective interaction between melon husk, groundnut shell, and bone powder. Similarly, Samples S4 and S3 also showed good flexural performance of 45.32 MPa and 43.34 MPa respectively, with moderate to high groundnut shell and bone powder content.

Sample S9 had the lowest flexural strength of 20.62 MPa, correlating with poor tensile results obtained from the sample. This reinforces the conclusion that high melon husk content weakens the composite structurally. Sample S7 also underperformed in flexural strength of 30.31 MPa, indicating that while groundnut shell improves modulus, it does not guarantee strength without supportive materials.

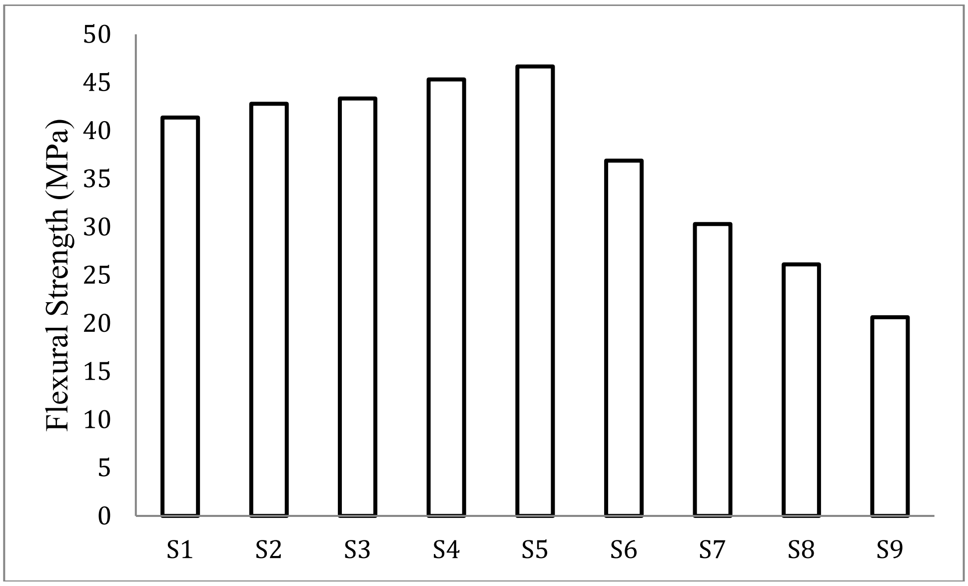

Figure 3.3: Effect of hybrid bio-fillers on the flexural strength on melamine formaldehyde bio-composites

3.1.4 Flexural Modulus Test Results

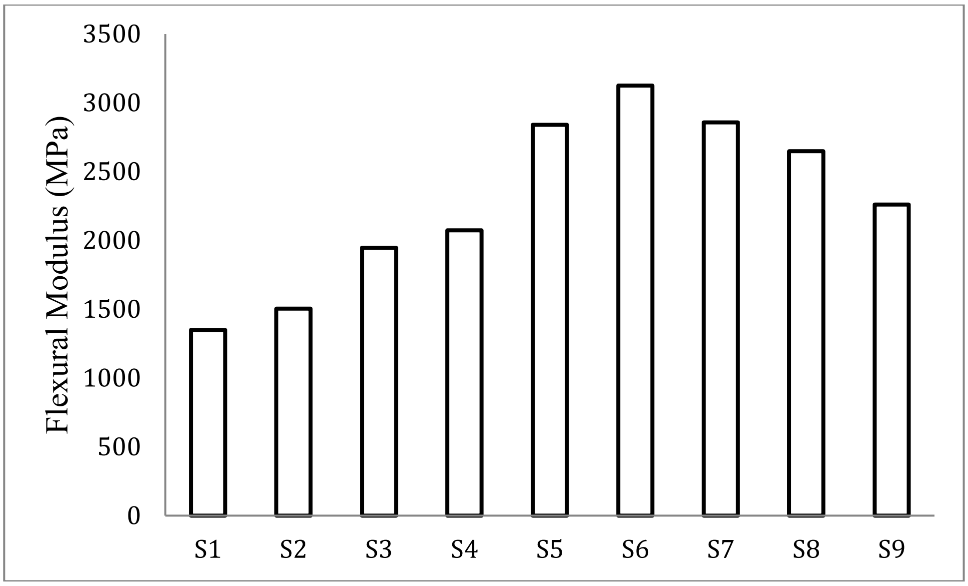

Figure 3.4: Effect of hybrid bio-fillers on the flexural modulus on melamine formaldehyde bio-composites

Flexural modulus reflects material stiffness under bending. The flexural modulus for the tested samples is represented in Figure.3.4. Sample S6 recorded the highest flexural modulus value of 3125.41 MPa, despite having poor tensile properties. This result may be due to the structural alignment of melon husk particles during curing, forming a rigid matrix that resists bending deformation, but is brittle under tension. Sample S9 again performed poorly with flexural modulus of 2260.35 MPa, confirming that excessive melon husk, even with bone powder doesn't guarantee improved performance. The highest modulus in S6, coupled with low strength, reflects a classic trade-off between stiffness and brittleness.

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3.1.5 Water Absorption Test Results

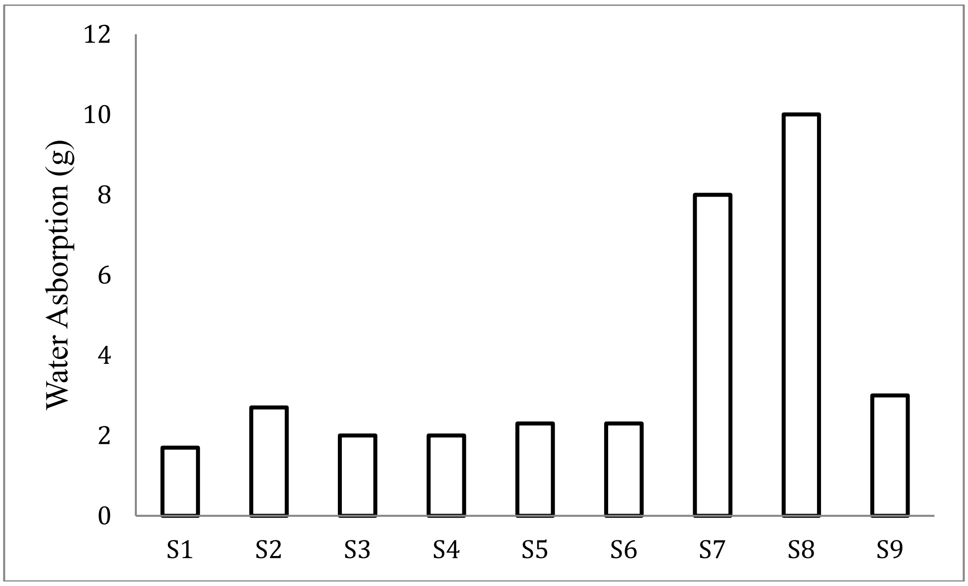

Figure 3.5**:** Effect of hybrid bio-fillers on the water absorption on melamine formaldehydebio-composites

Figure.3.5 is the water absorption results of the produced composite samples. Water absorption is a critical durability parameter. From the results, all samples exhibited relatively low water absorption except Samples S7 and S8. Bone powder likely helped in reducing porosity and forming a more water-impermeable matrix [4].S7 lacked bone powder, and S8 had equal ratio of groundnut shell and melon husk, both of which are hydrophilic. Their porous structure and poor filler–matrix bonding likely created capillary pathways for water intake. The high-water resistance demonstrated by S6 is unexpected and will be further explored.

3.1.6 Swelling Thickness

The swelling thickness of the samples, which indicates their dimensional stability when absorbed water, varied from 0.02 mm to 0.60 mm as shown in Figure.3.6. Samples S1 and S2 which contained only 5% bone powder, showed no measurable swelling highlighting the role of bone powder in stabilizing the structure under wet condition. Conversely, sample S7 which composed entirely of groundnut shell with no bone powder exhibited the highest swelling thickness at 0.60 mm.

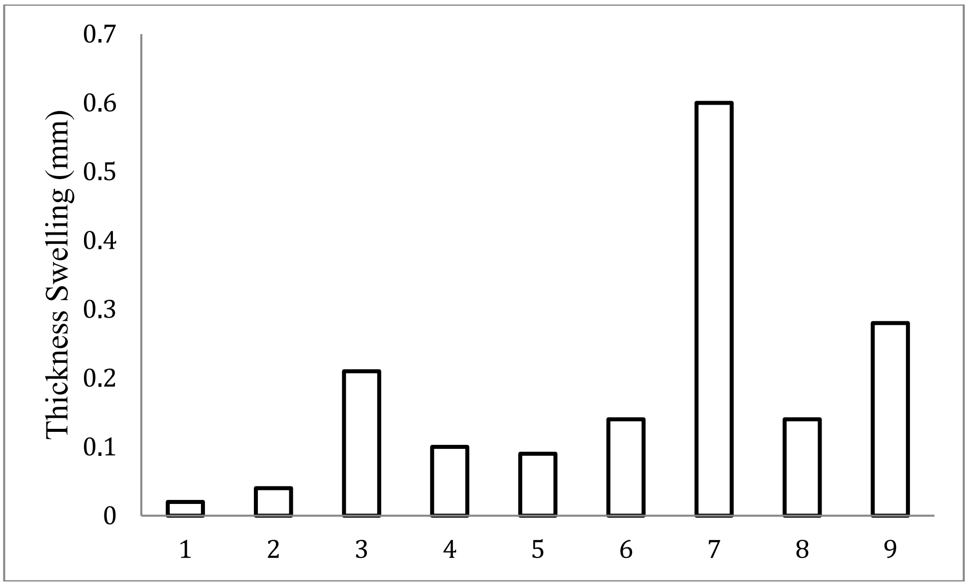

Figure.3.6: Effect of hybrid bio-fillers on the swelling thickness of melamine formaldehydebio-composites

This suggests that groundnut shell alone lacks the water resistance required to resist structural deformation. Similarly, sample S9 with 85% melon husk, 15 % bone powder and S3 with 85% groundnut

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shell, 15 % bone powder exhibited moderate swelling of 0.28 mm and 0.21 mm respectively. This indicates that while bone powder contributes to improved structural integrity under wet conditions, its effect is diminished when the organic content is excessively high [5].

3.2 Results of Optimization

GRA is a decision-making method used when multiple performance criteria conflict with each other. In this study, optimization is carried out on nine samples considering nine properties for particleboard produced from agricultural wastes (melon seed husks, groundnut shells, animal bones).

Table 1: Normalized Data

Sample	Tensile Strength	Tensile Modulus	Elongation	Flexural Strength	Flexural Modulus	Water Absorbed	Swelling Thickness	Time of Ignition	Flame Duration
S1	0.672	0.582	0.497	0.749	0.000	1.000	1.000	1.000	0.000
S2	0.697	1.000	0.528	0.794	0.088	0.896	0.966	0.013	0.356
S3	0.849	0.153	0.353	0.812	0.384	0.962	0.672	0.038	0.694
S4	0.937	0.461	0.734	0.880	0.465	0.962	0.862	0.885	0.664
S5	1.000	0.553	0.814	0.925	0.975	0.936	0.879	0.141	0.299
S6	0.618	0.014	0.884	0.595	1.000	0.936	0.793	0.038	0.674
S7	0.234	0.000	0.631	0.371	0.986	0.269	0.000	0.167	1.000
S8	0.049	0.201	0.400	0.223	0.847	0.000	0.793	0.090	0.568
S9	0.000	0.249	0.000	0.000	0.590	0.885	0.552	0.000	0.596

Table 2: Grey Relational Coefficients (GRC)

Sample	Tensile Strength	Tensile Modulus	Elongation	Flexural Strength	Flexural Modulus	Water Absorbed	Swelling Thickness	Time of Ignition	Flame Duration
S1	0.604	0.545	0.499	0.666	0.333	1.000	1.000	1.000	0.333
S2	0.623	1.000	0.514	0.708	0.352	0.827	0.937	0.336	0.437
S3	0.768	0.371	0.436	0.726	0.448	0.928	0.603	0.342	0.620
S4	0.888	0.481	0.652	0.806	0.483	0.928	0.758	0.813	0.598
S5	1.000	0.528	0.729	0.870	0.951	0.886	0.806	0.368	0.416
S6	0.567	0.337	0.812	0.552	1.000	0.886	0.705	0.342	0.606
S7	0.395	0.333	0.576	0.443	0.973	0.406	0.333	0.375	1.000
S8	0.345	0.385	0.455	0.392	0.766	0.333	0.705	0.355	0.536
S9	0.333	0.400	0.333	0.333	0.550	0.813	0.526	0.333	0.553

Table 3: Grey Relational Grades (GRG) and Rankings

Sample	GRG	Rank	Composition (Melon Husk : Groundnut Shell : Bone)
S5	0.732	1	20% : 70% : 10%
S4	0.730	2	70% : 20% : 10%
S1	0.668	3	20% : 75% : 5%
S6	0.667	4	100% : 0% : 0%
S2	0.641	5	75% : 20% : 5%
S3	0.586	6	0% : 85% : 15%
S7	0.516	7	0% : 100% : 0%
S8	0.458	8	45% : 45% : 10%
S9	0.453	9	85% : 0% : 15%

Why S5 Is Optimal

S5 has the highest GRG (0.732), meaning it performs best overall. Here's why:

i. **Mechanical Strength**: High tensile and flexural values.
ii. **Durability**: Low water absorption and swelling.
iii. **Fire Resistance**: Decent ignition time and flame duration.
iv. **Balanced Composition**: 10% bone improves fire resistance without hurting strength or durability.

Insights from Other Samples

i. **High Bone Content (S3, S9)**: Improves fire resistance but weakens strength and increases swelling.

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ii. **Pure Materials (S6, S7)**: Excel in one area but fail in others. For example, S6 has great flexural modulus but poor tensile strength.
iii. **Balanced Mixes (S4, S5)**: Hit the sweet spot—strong, durable, and fire-resistant.

Practical Implications

S5's composition (20% melon husk, 70% groundnut shell, 10% bone) is not just optimal technically—it's also sustainable:

i. Uses agricultural waste efficiently.
ii. Reduces reliance on synthetic binders.
iii. Offers a viable solution for eco-friendly construction materials.

4.0 Conclusion

The study demonstrates that the mechanical and water resistance properties of melamine formaldehyde-based bio-composites are significantly influenced by the synergistic interaction and specific proportions of agricultural fillers. A balanced formulation of groundnut shell and bone powder, characterized by a minimized melon husk concentration, yielded the most favorable performance across all structural and durability parameters.

The research identifies Sample S5, composed of 20% melon husk, 70% groundnut shell, and 10% bone powder, as the optimal formulation. This specific blend achieved the highest recorded tensile strength of 28.96 MPa and flexural strength of 46.66 MPa, alongside an elongation of 8.93%. These results confirm that groundnut shell provides the primary structural reinforcement and stiffness, while the 10% bone powder addition enhances the matrix density and moisture resistance.

In contrast, Sample S9, which contained an excessive concentration of 85% melon husk and 15% bone powder with no groundnut shell, exhibited the poorest mechanical performance, yielding a tensile strength of only 9.73 MPa and a flexural strength of 20.62 MPa. Excessive melon husk content reduces the bonding efficiency within the melamine formaldehyde matrix and increases interfacial porosity, thereby compromising the overall durability of the composite. Furthermore, Sample S6, composed of 100% melon husk, demonstrated high flexural stiffness but suffered from poor tensile properties and highwater absorption, highlighting the limitations of utilizing melon husk as a standalone filler.

Water absorption was significantly minimized in samples with balanced compositions and bone powder reinforcement. Samples S1 (1.7g) and S3 (2.0g) exhibited superior moisture resistance compared to other formulations. Conversely, Sample S8 (10.0g) and Sample S7 (8.0g) showed poor resistance to moisture, suggesting that high hydrophilic filler content without calibrated bone powder reinforcement leads to structural degradation and swelling under wet conditions.

The incorporation of bone powder functioned as a strategic flame retardant, effectively increasing ignition time and reducing flame duration. Samples S1 and S4 demonstrated the most stable fire behavior. The high mineral content in bone powder creates a thermal barrier that protects the combustible melon and groundnut fibers from rapid thermal degradation and structural deformation.

Despite the success of the Simplex-Taguchi optimization, certain limitations suggest avenues for further research. Future studies should focus on conducting formaldehyde emission analysis to ensure compliance with indoor air quality standards and exploring chemical surface modifications, such as alkalization, to improve the interfacial bonding of melon husks at higher loadings. Additionally, long-term durability assessments, including creep tests and fungal resistance studies, are recommended to determine the service life of these bio-composites in diverse environmental conditions.

Further Studies: Relevance and Limitations

To enhance the industrial applicability and scientific depth of this research, the following areas are proposed for future investigation:

1. A primary limitation observed in this study was the degradation of mechanical strength in samples with high melon husk concentrations (e.g., S9 at 9.73 MPa). Future research should explore the effects of chemical surface modifications, such as alkalization (mercerization) or silane coupling treatments, on the fibers. Such treatments could reduce the hydrophilic nature of the agricultural waste, thereby improving the interfacial adhesion between the fillers and the melamine formaldehyde matrix.
2. While melamine formaldehyde provides excellent moisture resistance, its potential for formaldehyde outgassing remains a critical concern for indoor applications. Further studies must include Formaldehyde Emission Tests (using the desiccator or chamber method) to ensure the developed particle boards comply with international standards such as E1 or E0 classifications. This is vital for showcasing the relevance of the boards in sustainable housing and interior design.

3. Long-term Durability and Biodegradation This study focused on immediate physical and mechanical characterization. However, the long-term performance of bio-composites in tropical climates is governed by their resistance to biological decay. Future work should involve:

i. Fungal Resistance Tests: Assessing the vulnerability of the protein-rich bone powder and fibrous husks to termites and mold.
ii. Accelerated Aging: Exposing the boards to cyclic UV radiation and humidity to determine the service life and structural stability over time.

4. Thermal Insulation and Acoustic Properties Beyond structural strength, the relevance of these boards can be expanded by investigating their thermal conductivity and sound absorption coefficients. Given the porous nature of melon husk and groundnut shells, these composites may serve as effective insulators in "Green Building" designs, reducing energy consumption for cooling in tropical regions.

5. Life Cycle Assessment (LCA) To provide a comprehensive argument for the sustainability of this ternary blend, a formal Life Cycle Assessment is required. This would quantify the carbon footprint reduction achieved by diverting melon husks and bone waste from landfills compared to the environmental cost of resin production and board manufacturing.

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