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Lignocellulosic Characterisation of Thatch Grass Sourced from Southeastern States of Nigeria for Particleboard Manufacturing

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Abstract

The shift from thatch grass, a traditional roofing material, to modern materials in Nigeria has led to the underutilisation of the plentiful thatch grass species, raising concerns about environmental risks like bushfires. This study explores an innovative solution by repurposing species of thatch grass as an eco-friendly material for particleboard Manufacturing, which supports United Nations Sustainable Development Goals. The research includes an in-depth lignocellulosic analysis, examining components such as lignin, cellulose, hemicellulose, extractive content, and pH. Advanced techniques, including TAPPI methods, were employed for accurate determination. The lignin content for thatch grass samples ranged from a minimum of 20.998% to a maximum of 26.591%. Cellulose content exhibited variations, ranging from 40.873% to 45.086%. Hemicellulose content displayed variability, ranging from 20.556% to 27.349%. Extractive values fell within the range of 4.624% to 6.083%. The pH values for all samples remained within the range of 6.52 to 7.00. The results indicate that thatch grass species exhibit favourable lignin, cellulose, and hemicellulose contents within ranges suitable for particleboard Manufacturing. Extractive values and pH levels are consistent and meet industry standards. The results highlight the emerging possibilities of thatch grass species as a sustainable and environmentally friendly material for particleboard manufacturing in Nigeria, fostering eco-conscious practices and promoting a circular economy approach.

Keywords: Thatch grass, Particleboard, Lignocellulosic characterisation, United Nations Sustainable Development Goals (SDGs), Bush burning, Nigeria.

1. Introduction

The vast landscapes of Nigeria and other regions in Africa are adorned with thatch grass species, traditionally used for thatching roofs (Hyparrhenia, n.d., Para. 1). Thatch Grass species have been pushed to the margins because of the advent and rise of modern materials. These materials include asbestos, zinc and corrugated aluminum sheets, (Hyparrhenia, n.d., Para. 2; Types of roofing sheets, 2023). The transition to modern roofing materials has reduced the functional importance of these abundant grasses and increased the risk of their contribution to wildfires, posing significant threats to local ecosystems (US national-scale study, n.d.).

The ramifications of this transition extend far beyond the architectural landscape, unleashing the menace of bush burning, a perilous threat with profound negative impacts on the environment, public infrastructure, agricultural output, and the fabric of human life and livelihoods (Godwin & Chukwu, 2024). This study introduces an innovative approach that utilises thatch grass as an eco-friendly material for producing particleboard. This transformative strategy promotes environmentally friendly manufacturing practices and paves the way for new opportunities in sustainable construction. This proposal aligns with the Sustainable Development Goals (SDGs) of United Nations, especially those that advocate for responsible consumption and production (UNDP, 2018).

Particleboard, a pivotal engineered wood product extensively employed in furniture and house interior facilities, faces a soaring demand in Nigeria (Hassan and Awopetu, 2019). The drivers behind this demand are multifaceted, ranging from the quest for a fine surface finish to the pursuit of lightweight and cost-effective alternatives to other engineered wood products such as plywood (Abdulkareem & Adeniyi, 2016). Notably, the particleboards available in the Nigerian market are primarily sourced through imports (Types of Roofing Sheets, 2023).

Thatch grass stands out as a viable alternative for particleboard manufacture, offering unique advantages such as lower density and more significant renewable potential than traditional wood waste (Nwandana et al., 2023; Thatching, n.d.). The production of particleboard from thatch grass as suggested, has the potential to transform the industry, offering significant benefits such as decreased reliance on wood waste, the consequent reduction in raw material costs and the price of the final product and as superior product quality with an improved strength-to-weight ratio,.

This study embarks on a journey of lignocellulosic characterisation of thatch grass material, utilising advanced techniques to quantify critical components and chemical properties. By delving into the intricacies of this naturally abundant resource, we aspire to provide invaluable insights that pave the way for sustainable utilisation, fostering a harmonious coexistence between human needs and ecological preservation (US national-scale study, n.d., para 2).

2.0 Material and Methods

This study aimed to investigate the lignocellulosic characterisation of thatch grass species obtained from the five Southeastern states of Nigeria for the manufacture of particleboard. Samples of thatch grass were gathered from various locations across the five Southeastern states.

Figure 1: Thatch Grass Growing in a Ugbonabo, Enugu State, Nigeria

2.1 Precautions, Safety and Accuracy

Precaution, safety, and accuracy are essential in every engineering and scientific investigation. Operating a muffler furnace at temperatures as high as 900°C requires strict adherence to precautions that will ensure the safety of the work environment and prevention of accidents. Essential precautions taken to ensure safety include:

- **Use of (PPE) Personal Protective Equipment:** Ensuring all personnel wear appropriate protective gear.

- **Training and Equipment Knowledge:** We conducted training and familiarisation with the equipment before operation.
- **Workplace Ventilation:** Maintained proper airflow to prevent the buildup of hazardous fumes.
- **Fire Safety Measures:** Fire extinguishers and other fire safety equipment were readily available.
- **Emergency Preparedness:** Procedures for handling emergencies were communicated to all team members and personnel.
- **Temperature Monitoring:** Equipment in use was regularly checked to ensure it was operating at acceptable conditions.
- **Equipment Maintenance:** Routine maintenance was carried out to ensure quality service delivery and avoid unexpected failure.
- **Handling of Materials:** All materials were handled to avoid damage to persons, the environment, machines, and the materials themselves.
- **Clear Communication:** Communication channels were **e**stablished to ensure an adequate flow of information among team members.
- **Protective Barriers:** Barriers were used to cordon high-temperature areas to minimise direct exposure to heat.
- **First Aid Readiness:** A well-equipped first aid kit was provided.

For accuracy in lignocellulosic characterisation and pH measurement, the following procedures were implemented:

1. **Sample Preparation:** A homogenous and representative sample was prepared to ensure consistency.
2. **Analytical Techniques:** The lignin, cellulose, hemicellulose, and extractive values were analysed using appropriate analytical methods.
3. **Instrument Calibration:** Instruments were regularly calibrated and validated using certified reference materials.
4. **Quality Control/Quality Assurance:** Quality control sample was included in each batch so as to obtain quality assurance.
5. **Environmental Controls:** To ensure moisture content and other components were not influenced negatively, humidity and temperature were checked regularly within the time of preparation of sample and analysis, as these factors.
6. **Triplicate Analyses:** Subsets of tests were analysed in triplicate to ensure consistency and precision.
7. **pH Measurement:** pH instruments were calibrated using standard reference materials, with temperature monitored to ensure accurate results. Samples were handled carefully to avoid contamination that could affect pH readings.

All data were meticulously recorded, ensuring reliability and precision in the findings.

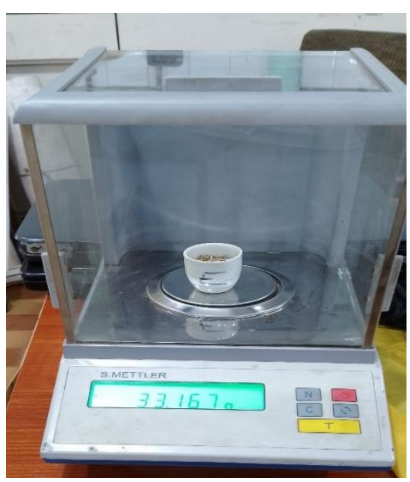

Figure 2: Analytical weighing balance with the sample weighed in a crucible

2.2.1 Lignin Content Investigation

Lignin was carried out according to TAPPI testing method T222 (1988) (Gou et al., 2018). Examining lignin content in wood or wood-based materials is a crucial step in assessing the composition of the material (Khan et al., 2018; Onyeonagu & Eze, 2013; Sluiter et al., 2008). TAPPI Test Method T222-88 is a standard method developed by the Technical Association of the Pulp and Paper Industry (TAPPI) to determine acid-insoluble lignin in wood and pulp. Here is a general outline of the process: TAPPI testing method T222-88: Determination of Acid-Insoluble Lignin in Wood and Pulp (Janiszewska et al., 2022).

First, 2g of sample was weighed, transferred into a crucible, and recorded as $\mathbf{W_1}$ (Okafor et al., 2022). Then, mix 3ml of 72% H_2S0_4 and stir for 1 minute. Then, the crucibles were placed in a water bath controlled to 30^0C and hydrolysed for 2 hours. Then, the sample was stirred at intervals of 15 minutes to ensure we obtained complete wetting and mixing. The hydrolysed sample was made up to 100ml with distilled water. The crucible and contents were dried in an oven at 105^0C for 2 hours, then removed and cooled in a desiccator and recorded as $\mathbf{W_2}$. Then, the crucible and contents were removed from the oven, placed in a muffle furnace, and ignited at 575^0C for at least 3 hours; then, it was removed and placed in a desiccator to cool. It was then weighed and recorded as $\mathbf{W_3}$.

Calculation:

$$\text{Acid} - \text{Insoluble Lignin} = \frac{\text{Weight of Residue (g)}}{\text{Weight of Sample (g)}} \text{x } 100$$

$$\%\ \text{Lignin} = \frac{W_2 - W_3}{W_1} \text{x } 100$$

Where,

- W_1 is the total solid sample (initial weight of the sample).
- W_2 is the weight of the residue after the lignin determination process.
- W_3 is the weight of the ash (if any) that may be present in the residue.

So, the numerator ($W_2 - W_3$) represents the weight of the lignin in the sample. When divided by the total solid weight W1 and multiplied by 100, the lignin content is given as a percentage of the original sample.

2.2.2 Cellulose Content Determination

Cellulose content was determined using the Crampton and Mayrand method 1978 (Khan et al., 2018; Onyeonagu & Eze, 2013; Sluiter et al., 2008; Okafor et al., 2022). About 0.2 to 0.3g of the sample was weighed and placed into a glass centrifuge tube of 50 ml that contained 5 ml of water. It was then mounted on a centrifuge, spun at a speed of 1500rpm for 10 minutes, and decanted the supernatant. Then the sample was re-suspended in 100ml of the volumetric flask containing 12.5ml glacial acetic acid and 2.5ml of concentrated nitric acid and digested in a boiling water bath for 20mins at a temperature of 60^0C, and then we collected the supernatant. The supernatant was carefully moved to a Gooch crucible, and its weight was noted as $\mathbf{W_1}$. It was then washed sequentially with hot alcohol, 10 ml of 90% benzene, and 10 ml of 60% ether. Afterwards, it was dried and weighed again, recorded as $\mathbf{W_2}$. The sample was ashed in a muffle furnace at 500°C for 2 hours, cooled in a desiccator, and its final weight was recorded as $\mathbf{W_3}$.

$$\%\ \text{Cellulose Content} = \frac{\text{Weight of Residue (g)}}{\text{Weight of Sample (g)}} \text{x } 100$$

$$\%\ \text{Cellulose Content} = \frac{W_2 - W_3}{W_1} \text{x } 100$$

W_2= weight of dried sample
W_3 = weight of ash content
W_1 = weight of sample

2.2.3 Hemicellulose Content Determination

Hemicellulose content was measured according to the Crampton and Mayrand method in 1978 (Khan et al., 2018; Onyeonagu & Eze, 2013; Sluiter et al., 2008; Okafor et al., 2022).

- About 1g to 2g of the sample was weighed and placed in a 20x150mm test tube, recorded as $\mathbf{W_1}$, the initial sample weight.
- 15ml of 72% H_2S0_4 was added and stirred for 1minute until the sample is thoroughly wetted.
- The sample was then transferred into a 1000ml Erlenmeyer flask and diluted to 500ml deionised water. The flask was placed on the heating manifold and attached to the reflux condenser. It was then gently boiled and refluxed for 4 hours at 80^0C. At the end of 4 hours, the condenser was rinsed with a small amount of deionised water before disassembling the reflux apparatus.
- The hydrolysed solution was placed on the crucibles. The weight of the collected filtrate was measured. The crucible and contents were dried at 105^0C for 2 hours.
- The crucible and its contents were then cooled in a desiccator and recorded as $\mathbf{W_2}$, the weight of the crucible. The crucible was then placed in the muffle furnace and ignited at 575^0C for at least 3 hours until all the carbon was eliminated. It was then removed from the furnace and cooled in a desiccator, and the weight was recorded as $\mathbf{W_3}$.

The hemicellulose content was determined using the method described by Crampton and Maynard 1978, (Khan et al., 2018; Onyeonagu & Eze, 2013; and Sluiter et al., 2008).

- A sample weighing 1g to 2g was measured and placed into a 20x150 mm test tube, and its weight was recorded as $\mathbf{W_1}$.
- 15 ml of 72% H_2SO_4 was added to the sample and stirred for one minute to ensure thorough wetting.
- The mixture was transferred into a 1000ml Erlenmeyer flask and diluted to 500ml using deionised water. The flask was then on a heating manifold and connected to a reflux condenser. The solution was gently boiled and refluxed for 4 hours at 80°C. After refluxing, the condenser was rinsed with a small volume of deionised water before dismantling the reflux setup.
- The hydrolysed solution was filtered through crucibles, and the filtrate's weight was measured. The crucible and its contents were dried at 105°C for 2 hours.
- The dried crucible was cooled in a desiccator, and its weight, including the contents, was recorded as $\mathbf{W_2}$. Subsequently, it was placed in a muffle furnace and ignited at 575°C for at least 3 hours to eliminate all carbon residues.
- Finally, the crucible was removed from the furnace and cooled in a desiccator, and the final weight was recorded as $\mathbf{W_3}$.

Figure 3: Muffler furnace with Tong for removing hot samples

Calculations

$$\% \textbf{ Hemicellulose } = \frac{W_2 - W_3}{W_1} \text{x } 100$$

2.2.4 Extractive Value Determination

To conduct an alcohol-soluble extractive test on a thatch grass material, one will need specific materials and equipment to ensure accurate and reliable results (Sluiter, 2008). Here is a list of the common materials and equipment for an alcohol-soluble extractive test:

A powdered sample weighing approximately 2 to 5 g was accurately measured and recorded as $\mathbf{W_1}$. The sample was macerated in 100 ml of alcohol within a sealed flask for 24 hours, with frequent shaking during the first 6 hours and then allowed to stand undisturbed for the remaining 18 hours. The mixture was filtered promptly, ensuring minimal solvent loss.

Next, 25 ml of the filtrate was evaporated to dryness in a pre-weighed, flat-bottomed shallow dish. The weight of the dish with the dried contents was recorded as $\mathbf{W_2}$. The dried material was further heated at 105°C until a constant weight was achieved, and the final weight was noted as $\mathbf{W_3}$.

The percentage of alcohol-soluble extractives was calculated relative to the air-dried sample using the formula provided.

$$\% \text{ Extrative Value} = \frac{\text{Weight of Extractive (g)}}{\text{Initial Sample Weight (g)}} \text{x } 100 = \frac{W_2 - W_3}{W_1} \text{ x } 100$$

Figure 3: Set of samples in a crucible after weighing

2.2.5 Determination of pH

This procedure is typically followed when the pH of a material is examined (Onyeonagu & Eze, 2013):

- 10g of thatch grass sample was Weighed out
- The sample weighed was placed into a glass container, and approximately 100ml of distilled water was added
- The mixture was then stirred thoroughly and allowed to stand for 1 hour
- The mixture was filtered, and the pH was measured, read out, and recorded

2.3 Limitations

During the testing of thatch grass, the following limitations were encountered:

a. **Sample Variability:** Thatch grass showed some characteristics that suggest that they are different with regards to the geographic location, season, climate, and soil conditions. To account for this variability in nature, samples were collected in multiple of five from different locations and seasons.

b. **Standardisation Issues:** The need for standardised testing methods for thatch grass presented challenges. However, testing protocols designed for wood resources were applied as a substitute.

3.0 Result and Discussion

The findings were derived from the average values calculated based on tests performed on three thatch grass samples collected from five different locations across the five states in Southeastern Nigeria. By calculating the mean, a representative and consolidated result for the studied parameter or property was achieved. This approach helps reduce the impact of location-based variations, providing a more holistic understanding of the characteristics of thatch grass samples from the Southeastern region (Khan et al., 2018).

Table 1: Lignin Content

Sample	% Lignin = [(W2-W0-W3)/W1-W0]*100				
	ABIA	**ANAMBRA**	**EBONYI**	**ENUGU**	**IMO**
A	23.754	21.814	22.588	22.643	23.406
B	22.096	23.765	24.124	26.591	24.933
C	26.014	21.687	25.406	23.197	25.950
D	25.555	25.963	21.632	22.273	22.476
E	22.326	22.523	25.668	20.998	21.922
Average	**23.949**	**23.1504**	**23.8836**	**23.1404**	**23.7374**

Table 1 presents the lignin content measurements from different thatch grass samples sourced from various states (AB, AN, EB, EN, and IM). Each row represents a specific sample (A, B, C, D, E), and the columns represent various measurements and calculations related to the lignin content determination process. The lignin content is expressed as a percentage.

Table 1 above shows that most of the samples fall within the suggested range of 20% to 30%, indicating that these agro-based materials are generally suitable for particleboard Manufacturing. The minimum Lignin Content obtained is 20.998%, while the maximum is 26.591%. Each sample has variability in lignin content across different states (AB, AN, EB, EN, IM). These results highlight the influence of location and the state of origin on lignin composition. Manufacturers can use this data to make informed decisions about selecting agro-based materials, considering lignin content variations based on location, sample, and state. The data emphasises the importance of quality control measures in ensuring consistency in lignin content, especially when sourcing materials from different states. The variability in lignin content provides opportunities for manufacturers to optimise particleboard properties by adjusting processing parameters or blending materials.

Table 2: Cellulose Content

Sample	% Cellulose = [(W2-W3)/W1]*100				
	ABIA	**ANAMBRA**	**EBONYI**	**ENUGU**	**IMO**
A	42.451	43.860	42.373	43.168	43.365
B	43.976	43.473	43.966	43.701	42.035
C	42.030	41.706	40.873	41.483	43.058
D	43.196	42.320	45.086	40.981	43.012
E	44.424	43.346	40.958	44.415	40.879
Average	**43.2154**	**42.941**	**42.6512**	**42.7496**	**42.4698**

Table 2 outlines the cellulose content analysis, expressed as a percentage, for samples originating from different states (AB, AN, EB, EN, IM), each analysed with specific samples labelled A, B, C, D, and E. This data provides insights into the cellulose content variations across different states and specific samples, offering a comprehensive view of the cellulose composition in the analysed samples.

The observed cellulose content values generally fall within the standard guideline range of 40% to 50%, indicating that the thatch grass material is within the typical cellulose content range for particleboard Manufacturing. The minimum Cellulose Content obtained is 40.87306, while the maximum is 45.0862. There is variability in cellulose content among different samples. Manufacturers may explore adjusting processing parameters or blending materials to achieve the desired cellulose content for optimising particleboard properties.

Table 3: Hemicellulose Content

Sample	**% Hemicellulose = [(W2-W3)/W1]*100**				
	ABIA	**ANAMBRA**	**EBONYI**	**ENUGU**	**IMO**
A	24.814	21.962	22.021	25.700	23.354
B	24.297	21.738	25.905	24.354	23.158
C	21.645	22.253	23.488	23.470	26.168
D	20.958	23.121	26.558	22.411	20.556
E	21.420	27.349	26.547	25.572	21.336
Average	**22.6268**	**23.2846**	**24.9038**	**24.3014**	**22.9144**

Table 3 presents the hemicellulose content analysis for thatch grass samples (A, B, C, D, E) and states (AB, AN, EB, EN, IM). The values, expressed in percentage, depict the hemicellulose content for each combination of samples and states. This data provides valuable insights into the variation of hemicellulose composition among different states and samples, offering a comprehensive overview of the hemicellulose content in the analysed samples.

The observed hemicellulose content values fall within and around the typical range of 20% to 35%, indicating that the thatch grass material has hemicellulose content within the standard range for particleboard Manufacturing. The minimum Hemi-Cellulose Content obtained is 20.556%, while the maximum is 27.349%. There is variability in hemicellulose content among different samples. This variability suggests that the state of origin may influence hemicellulose composition. The observed variations underscore the importance of quality control measures to ensure consistency and reliability in hemicellulose content, especially when sourcing thatch grass material from different states. Hemicellulose content is a crucial factor affecting particleboard bonding and physical properties. The observed variability may impact the overall characteristics of the resulting particleboard. Manufacturers may explore adjusting processing parameters or blending materials to achieve the desired hemicellulose content for optimising particleboard properties.

Table 4: Extractive Value

Sample	**% Extractive Value = ((W2-W0)/(W1-W0))*100**				
	ABIA	**ANAMBRA**	**EBONYI**	**ENUGU**	**IMO**
A	5.926	4.851	5.886	5.578	5.450
B	4.906	4.624	5.167	5.584	4.990
C	5.531	5.216	5.721	5.566	6.011
D	5.469	5.328	5.302	6.083	5.609
E	4.985	5.534	5.631	5.358	5.497
Average	**5.3634**	**5.1106**	**5.5414**	**5.6338**	**5.5114**

Table 4 provides the extractive value analysis for different thatch grass samples (A, B, C, D, E) across various states (AB, AN, EB, EN, IM). Expressed in percentage, the values in the table depict the extractive value for each combination of sample and state. This data offers insights into the extractive characteristics of the samples from different states, providing a comparative analysis of the extractive value among the various combinations.

The observed extractive values for thatch grass material generally fall within the typical range for wood-based materials used in particleboard manufacturing (3% to 8%). The minimum Extractive Value obtained is 4.624106, while the maximum is 6.082896. Extractive values show relatively consistent trends across different samples and states, with values falling within a narrow range. Although there is some variability in extractive values, it is moderate, suggesting that the thatch grass material may have a relatively consistent composition across different samples and states. Extractive values within the general range are generally favourable for particleboard Manufacturing. However, it is essential to consider the specific requirements of the particleboard and how extractive content may influence bonding properties. The consistent extractive values indicate that the material may have a uniform composition. Quality control measures can ensure consistency in extractive content, contributing to the reliability of particleboard Manufacturing. Manufacturers may explore adjusting processing parameters or blending materials to achieve desired extractive content and optimise particleboard properties. While the extractive values are within the general range, further research may be conducted to understand the specific types of extractives present and their potential impact on particleboard characteristics.

Table 5: pH Values

Sample	**pH of Samples**				
	ABIA	**ANAMBRA**	**EBONYI**	**ENUGU**	**IMO**
A	6.700	6.640	6.710	6.810	6.600
B	6.610	6.810	6.600	6.520	6.670
C	6.530	6.750	6.920	6.590	7.000
D	6.610	6.850	6.770	6.830	6.580
E	6.740	6.790	6.620	6.920	6.830
Average	**6.638**	**6.768**	**6.724**	**6.734**	**6.736**

Table 5 presents the pH results for different samples (A, B, C, D, E) across various states (AB, AN, EB, EN, IM). The pH values, representing the acidity or alkalinity of the samples, provide crucial information about the chemical nature of the substances analysed. The pH values for each combination of sample and state are outlined in the table. This data facilitates a comparative analysis of the pH levels among samples sourced from different states, offering insights into the variations in acidity or alkalinity across the analysed specimens.

The pH values for all samples fall within the range of 4.5 to 7.5, typically considered suitable for particleboard Manufacturing. The minimum pH Value obtained is 6.520, while the maximum is 7.000. However, all values remain within the acceptable range, suggesting a relatively consistent pH characteristic of the thatch grass material. The pH of the material is an essential factor in adhesive performance during particleboard Manufacturing. The observed pH values indicate conditions favourable for bonding with typical wood adhesives. The consistent pH values are positive for quality control, as they suggest uniformity in the thatch grass material. Manufacturers may use these values as a reference for maintaining product consistency. Manufacturers should be mindful of processing conditions that may influence pH, such as temperature and moisture content, to ensure stability and consistency in the material properties. The observed pH values suggest that the thatch grass material is adaptable to standard particleboard manufacturing processes without significant adjustments.

4.0 Conclusion

The study presents a comprehensive analysis of thatch grass samples sourced from five different States in Nigeria (AB, AN, EB, EN, IM) with a focus on lignocellulosic characterisation for potential application in particleboard Manufacturing. The results from the lignin content test, cellulose content test, hemicellulose content test, extractive value content test, and pH Value analyses provide valuable insights into the suitability of thatch grass for particleboard Manufacturing. Overall, the lignocellulosic characterisation of thatch grass supports its potential as a sustainable alternative for particleboard manufacturing in Nigeria. The study supports the United Nations Sustainable Development Goals (SDGs) by encouraging responsible production and consumption practices. The findings contribute to the broader discourse on utilising locally abundant resources for eco-friendly construction materials, addressing environmental concerns, and promoting economic sustainability.

5.0 Recommendation

Developing and standardising production protocols that optimise its unique lignocellulosic properties is crucial to ensuring durability and industrial performance. Advanced mechanical testing, such as tensile strength and elasticity evaluations, should be conducted to meet industry standards. Considering the geographical and climatic variations across the five studied states, localised sourcing strategies should be adopted to enhance material quality while reducing transportation costs and environmental impact. A comprehensive life cycle assessment is essential to highlight the environmental benefits, including reduced deforestation and carbon footprints compared to conventional wood-based particleboards. Collaboration with policymakers can help integrate thatch grass boards into national construction standards, complemented by incentives to encourage adoption by industries and artisans. Further research should explore these particleboards' thermal, acoustic, and fire-resistant properties while experimenting with hybrid materials, such as blends of thatch grass with other agricultural residues or recycled materials, to expand their versatility and applications. These actions will bridge the gap between research and real-world implementation, driving sustainability and innovation in construction.

Definition of Terms

ASTM = ASTM International (formerly American Society for Testing and Materials)
SDGs = Sustainable Development Goals.
W_1 = Weight of crucible
W_2 = Weight of dried sample and crucible
W_3 = Weight of Residue and crucible
AB = Abia State
AN = Anambra State
EB = Ebonyi State
EN = Enugu State
IM = Imo State
A = Samples A
B = Samples B
C = Samples C
D = Samples D
E = Samples E

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