Scientific Research Publishing

Open Journal of Applied Sciences, 2024, 14, 2460-2470
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Development and Characterization of Particle Boards Based on Sorghum Husk

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How to cite this paper: Gbian, H.T.T., Chabi, E., Doko, V.K., Yarou, K.F.C. and Olodo, E. (2024) Development and Characterization of Particle Boards Based on Sorghum Husk. *Open Journal of Applied Sciences*, **14**, 2460-2470.
https://doi.org/10.4236/ojapps.2024.149162

Received: August 8, 2024
Accepted: September 10, 2024
Published: September 13, 2024

Abstract

This study tackles current environmental challenges by developing innovative and eco-friendly particle boards utilizing sorghum husk, combined with recycled expanded polystyrene (EPS). This dual eco-responsible approach valorizes sorghum husk, often deemed agricultural waste, and repurposes EPS, a plastic waste, thus contributing to CO_2 emission reduction and effective waste management. The manufacturing process involves dissolving recycled polystyrene within a solvent to create a binder, which is then mixed with sorghum husk and cold-pressed into composite boards. The study explores the impact of two particle sizes (fine and coarse) and two different concentrations of the recycled EPS binder. Results demonstrate significant variations in the boards' mechanical properties, displaying a range of Modulus of Rupture (MOR) from 0.84 MPa to 3.85 MPa, and Modulus of Elasticity (MOE) spanning from 658.13 MPa to 1313.25 MPa, influenced by the binder concentration and particle size. These characteristics suggest that the boards can be effectively used in various construction applications, including interior decoration, false ceilings, and potentially for furniture and door manufacturing when combined with appropriate coatings. This study not only exemplifies the valorization of plastic and agricultural wastes but also offers a practical, localized solution to global climate change challenges by promoting sustainable construction materials.

Keywords

Eco-Material, Bio-Sourced Material, Sorghum Husk, Particle Board, Recycled Expanded Polystyrene, Sustainable Construction

1. Introduction

In the current context marked by climate change, the international community, through various summits and agreements [1]-[4], has reached a consensus on the need for a transition towards more sustainable practices, particularly in the construction sector. This sector, known as a major consumer of resources and a significant contributor to greenhouse gas emissions, is at the forefront of sustainability efforts. Therefore, it is crucial to explore and valorize local resources, especially in regions such as Africa where sustainable development is both an urgent necessity and an opportunity for growth. This approach aligns not only with global sustainability goals but also offers the advantage of reducing construction costs and improving access to housing for a rapidly expanding population.

Benin, like many other African countries, faces a unique opportunity to leverage its local resources, particularly in the construction field. Among these resources, agricultural waste such as sorghum husk is an underutilized asset. Typically burned, this waste contributes to increased CO_2 emissions and exacerbates environmental issues. Simultaneously, the proliferation of polystyrene waste, mainly from packaging, poses a major challenge due to its prolonged lifespan and non-biodegradability.

In this context, using sorghum husk as a raw material for particle board manufacturing represents a promising innovation. Sorghum, widely cultivated in Africa, generates a significant amount of husk, often regarded as valueless waste.

Scientific literature has increasingly explored the use of agricultural by-products within the building industry. Studies have demonstrated the effectiveness of sorghum husks ash as a mineral addition in concrete [5]-[7].

Various studies have focused on different applications and properties of particle boards made from sorghum bagasse. Iswanto *et al.* [8] concentrated on the effect of resin type and pressing parameters on the properties of sorghum bagasse particle boards. They utilized three types of resins, urea-formaldehyde (UF), phenol-formaldehyde (PF), and isocyanate, and varied the pressing temperature from 120˚C to 180˚C depending on the resin type. The results showed that isocyanate resin offered the best performance, with Modulus of Elasticity (MOE) values ranging from 951.25 to 3628.46 MPa and Modulus of Rupture (MOR) values from 5.10 to 25.89 MPa, indicating the critical role of resin choice and pressing conditions in panel quality.

In a subsequent study, Iswanto *et al.* [9] examined the influence of coating materials on sorghum bagasse particle boards (SBP). They used bamboo weaving with and without bark, as well as thin plywood, to manufacture three-layer panels with a target density of 0.7 g/cm^3. The results showed that panels using bamboo weaving without bark as the surface layer had the highest MOR values, suggesting that surface treatment significantly improves SBP properties.

Kusumah *et al.* [10] [11] explored the use of citric acid as an adhesive for manufacturing particle boards from sweet sorghum bagasse. They investigated the effects of pre-drying the particles and the concentration of citric acid on the panels' properties. The findings indicated that MOR and MOE values increased with rising citric acid concentration, peaking at 20% by weight. Additionally, the study demonstrated that optimal pressing conditions were at a temperature of 200˚C for 10 minutes, enhancing the panels' moisture resistance.

While previous studies often favored the use of resins such as urea-formaldehyde, phenol-formaldehyde, and isocyanate, it is essential to direct research towards safer and more environmentally friendly alternatives. In this light, the innovation lies in using recycled polystyrene as a binder for particle boards. Polystyrene, frequently used and generally considered waste, finds a new application here. Its transformation into a binder for particle boards paves the way for the valorization of this material, offering a potentially less harmful solution than conventional resins.

2. Materials and Methods

2.1. Sorghum Husk (SH)

Sorghum husk serves as the primary reinforcing element in the manufacturing of sorghum and polystyrene-based particle boards. The preparation process of this material involves several essential steps. Initially, the sorghum husks undergo mechanical grinding to achieve the appropriate particle size. After grinding, the obtained particles are dried in a controlled-temperature oven to eliminate any residual moisture, thus ensuring optimal quality for board manufacturing. The dried material is then sieved, allowing for the separation and classification of particles into different size ranges. Table 1 illustrates the various granular classes resulting from this sieving process.

Table 1. Granular classes.

Size	Coarse mixture	Fine mixture
Retention on 2.50 mm sieve	35%	5%
Retention on 1.250 mm sieve	30%	10%
Retention on 0.630 mm sieve	20%	20%
Retention on 0.315 mm sieve	10%	30%
Retention on 0.160 mm sieve	5 %	35%

2.2. Expanded Polystyrene (EPS)

The expanded polystyrene (EPS) utilized in this research is sourced from recycled packaging materials. This decision is driven by the observation that EPS often ends up overlooked and discarded in landfills or the natural environment, creating considerable ecological issues. Employing EPS waste as a matrix in composite materials serves to repurpose this resource and helps address the problems associated with its disposal.

2.3. Binder Preparation

To create the binder for the composite materials, expanded polystyrene is dissolved in a chosen organic solvent, with gasoline being the solvent of choice in this research [12]. This procedure involves carefully adding polystyrene to the solvent and stirring continuously to achieve a consistent and uniform bonding agent.

Determining the precise solvent quantity for effectively dissolving the polystyrene is critical, characterized by the ratio *k*, which is calculated as follows:

$$k = \frac{\text{mass of solvent}}{\text{mass of polystyrene}}$$

Fine-tuning of this ratio was accomplished through numerous experimental attempts. A specific quantity of solvent was accurately measured and combined with polystyrene until all the solvent had evaporated. The mass of the polystyrene that dissolved was recorded, leading to the establishment of the optimal *k* ratio at 1.4.

The consistency of the adhesive is directly influenced by the *k* ratio. A *k* value lower than 1.4 leads to insufficient solvent for complete dissolution, producing a thick, viscous binder with undissolved polystyrene particles. In contrast, a *k* value exceeding 1.4 leads to an overabundance of solvent, thus diminishing the binder's viscosity and negatively affecting its capacity to effectively bind the reinforcing elements.

2.4. Composite Mix Design

For the construction of the composites, two binder ratios were specifically chosen based on initial experiments. These ratios, denoted as dosage *d*, are formulated as follows:

$$d = \frac{\text{mass of binder}}{\text{mass of husks}}$$

The chosen dosages, set at 0.8 and 1, have been carefully calibrated to reduce potential structural issues like fragmentation, while ensuring the uniformity of the composites.

For classification purposes in this research, the composites are designated by their binder dosage and the particle size of the rice husk, as detailed in **Table 2**.

Table 2. Codification of composites according to granularity and dosage.

Type of granularity	Code	Dosage
Fine	MF0.8	0.8
	MF1	1
Coarse	MG0.8	0.8
	MG1	1

2.5. Composite Implementation

- **Preparation of Sorghum Husks (SH)**

Initially, the sorghum husks undergo a drying process in a controlled oven environment until they reach a consistent weight, confirming the removal of all moisture. After drying, these husks are categorized into various granular classes to prepare for the different experimental mixes, differentiating between finer and coarser textures.

- **Process of mixing**

The mixing phase is pivotal in the production of the composite, ensuring a homogeneous distribution of the sorghum husks within the polystyrene matrix. Meticulous mixing is essential to guarantee the uniformity of the composite, directly influencing its final properties.

- **Specimen fabrication**

The production of the composite plates is carried out using a cold compaction method. The mixture of sorghum husks and polystyrene-based binder is placed in a specially designed metal mold for the experiment, with internal dimensions of 571 mm × 148 mm × 40 mm. Compaction is accomplished using a mechanical press, which exerts a constant and even pressure of 10 MPa on the mixture. This pressure is maintained for 5 minutes to allow for a good distribution of the composite within the mold [12]. This step is crucial to achieve uniformity within the composite and to preserve the integrity of the sorghum husks while limiting the stress exerted on the mold (**Figure 1**).

Figure 1. Plate produced through compaction.

Post-compaction, the plates are carefully extracted from the mold and transferred to a climate-controlled environment set at 20˚C (±1˚C). They remain there until they reach a stable weight, indicating the elimination of residual solvents. Subsequently, the plates are cut to predetermined dimensions of 11 mm thickness, 76 mm width, and 314 mm length. These prepared specimens are then utilized for three-point bending tests to evaluate their elasticity and breaking stress under static bending [13].

The samples also undergo swelling tests. After a 24-hour immersion period, they are removed and allowed to drain for 10 minutes. The weight and dimensions (length, width, thickness) are measured, with width and thickness evaluated at five distinct points and length at two. These data are used to calculate the moisture content, degree of swelling in each dimension, volumetric swelling, and water absorption [13].

3. Results and Discussions

3.1. Physical Properties of Particle Boards

Table 3 showcases the outcomes from the physical testing of the particle boards. These data reveal marked differences between the samples, highlighting the potential influence of the sorghum particle size and binder quantity on the physical properties of the materials.

Table 3. Physical properties of particle boards.

Composites	Mass loss (%)	Density	Water absorption	Swelling (%)			
				Thickness	Length	Width	Volumetric
CM0.8	7.16 ± 0.59	0.493 ± 0.074	30.16 ± 2.50	9.36	1.57	1.53	12.78
FM0.8	7.69 ± 0.64	0.393 ± 0.059	35.17 ± 2.92	11.93	1.78	2.07	16.28
CM1	6.49 ± 0.54	0.594 ± 0.089	25.58 ± 2.13	8.52	0.85	1.12	10.67
FM1	6.76 ± 0.53	0.477 ± 0.072	27.05 ± 2.25	9.79	1.27	1.48	12.83

3.1.1. Mass Loss of Particle Boards

The analysis of mass loss data for the sorghum husk and polystyrene-based particle boards shows that major mass loss typically occurs within the first 72 hours, with complete stabilization observed at 144 hours (Figure 2). This trend is consistent across all boards, irrespective of granularity or binder dosage.

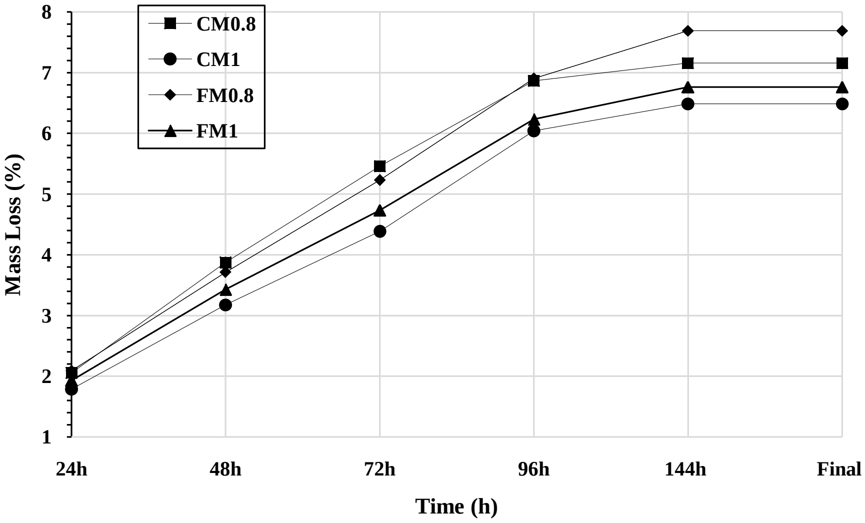

Figure 2. Mass loss of composites.

Regarding the effect of granularity, it is observed that both fine (FM0.8 and FM1) and coarse (CM0.8 and CM1) particle boards exhibit similar rates of mass loss, suggesting that particle size does not have a major impact on component volatilization. This observation may indicate that the characteristics of the polymer matrix and the interactions between the polystyrene and the sorghum husks are more determining factors in mass loss than granularity itself.

In terms of binder dosage, results show a slight tendency towards greater mass loss for particle boards using a dosage of 0.8 compared to those using a dosage of 1 (FM0.8 and CM0.8 versus FM1 and CM1). This observation may seem counterintuitive as a higher solvent dosage in the binder should theoretically lead to greater mass loss. A possible explanation could lie in the distribution and interaction of the binder with the sorghum particles. If the binder is better distributed or interacts more effectively with the particles at a higher dosage, it could reduce solvent volatilization.

It is also worth mentioning that the observed differences between dosages are relatively minor. This suggests that within the used dosage range (0.8 to 1), the amount of binder only moderately affects mass loss due to solvent volatilization. However, it is possible that more significant variations in dosages could produce more pronounced effects on mass loss.

3.1.2. Swelling of Particle Boards

Swelling tests are crucial for assessing the durability of particle boards under moist conditions, a critical factor in the application of these materials in settings where exposure to water is possible. These tests measure the ability of the boards to maintain their structural and dimensional integrity when subjected to immersion.

When comparing the swelling of fine granularity (FM) boards to those of coarse granularity (CM), it is observed that FM boards exhibit a higher swelling rate in all measurements. This could indicate that the increased specific surface area of the finer particles is more susceptible to water retention, which results in more pronounced swelling. However, considering the density results where FM boards have a lower density than CM series, it appears that the density of the board plays a predominant role in the swelling phenomenon. A lower density may translate into increased porosity, allowing water to infiltrate more easily and cause greater swelling.

Regarding binder dosage, boards with a lower binder dosage (0.8) show a higher thickness swelling than those with a higher dosage (1). This could suggest that the additional binder contributes to better cohesion and reduction of inter-particle spaces, thereby limiting water absorption and retention. However, this trend is not as pronounced in measurements of swelling in length and width, suggesting that the orientation or distribution of the particles, as well as the overall cohesion of the board, play a role in the swelling response.

These observations imply that to improve the moisture resistance of particle boards, a balance must be found between particle size and binder dosage. Optimized granularity and adapted binder dosage can help minimize swelling and maximize the durability of the board.

Figure 3 illustrates the swelling in different dimensions and the volumetric swelling of the boards after a 24-hour immersion, providing a clear visualization of how each board reacts to water exposure.

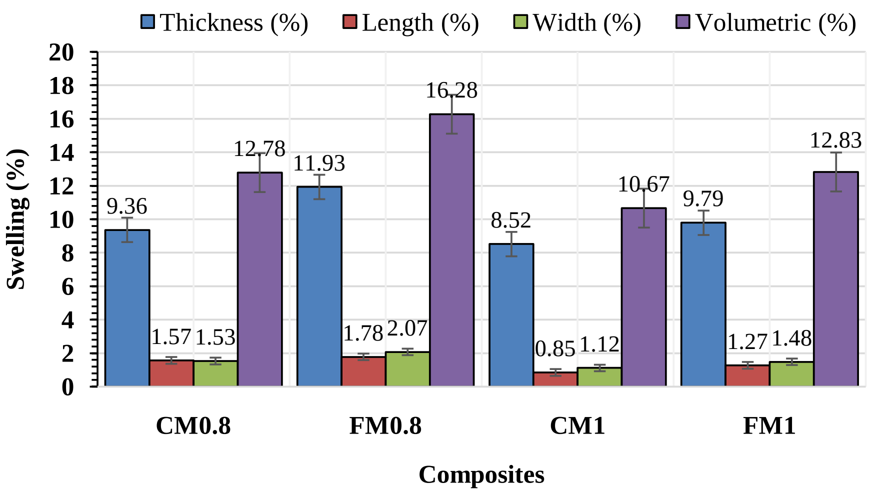

Figure 3. Behavior of particle boards after 24-hour immersion.

3.2. Mechanical Properties of Particle Boards

Figure 4 visually compares the MOR, MOE, and stiffness of the different particle boards, highlighting the influence of granularity and binder dosage.

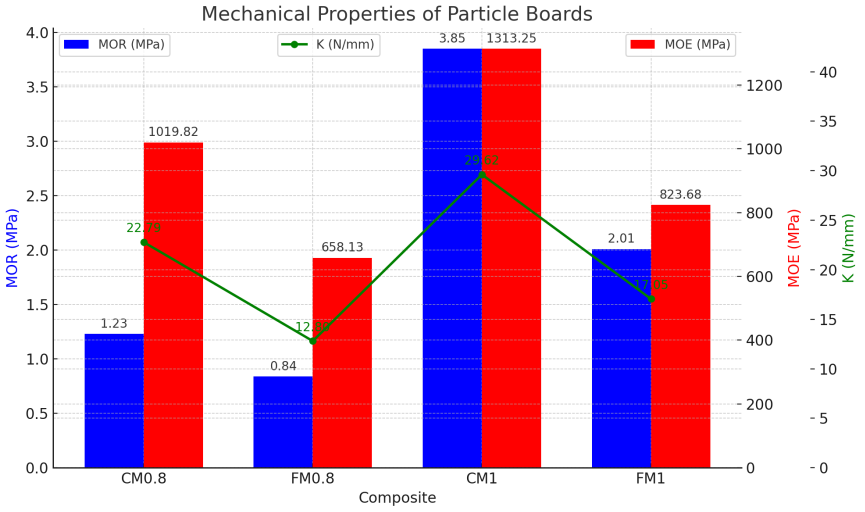

Figure 4. Comparison of mechanical properties of particle boards.

Coarse granularity particle boards (CM0.8 and CM1) consistently demonstrate higher values for these three mechanical parameters compared to fine granularity boards (FM0.8 and FM1). This trend indicates that larger particle size positively contributes to the material's mechanical strength and stiffness. The larger particle size in the CM series may facilitate better mechanical interlocking within the polystyrene matrix, leading to more effective force transmission and distribution throughout the board.

Regarding the effect of binder dosage, boards with a binder dosage of 1 (CM1 and FM1) display higher values of MOR, K, and MOE compared to those with a binder dosage of 0.8 (CM0.8 and FM0.8). This improvement in mechanical properties with a higher binder dosage can be attributed to the increased presence of polystyrene, which strengthens the structure of the board and improves the bonding between particles.

These observations highlight the importance of further research to identify the optimal binder dosage. A binder dosage above 1 could potentially further enhance the mechanical properties of the boards, although it remains to be determined if a saturation point might be reached, beyond which additional increases are not beneficial.

In summary, particle size and binder dosage have a clear impact on the mechanical strength of particle boards. Larger particles and increased binder dosage contribute to better strength and stiffness. In-depth studies on a wider variety of binder dosages could optimize the mechanical properties of sorghum husk and polystyrene-based particle boards, thus enhancing their application in demanding conditions.

In light of these results, design modifications such as veneering or coating could be considered to further enhance the mechanical properties of the boards. Veneering could not only improve aesthetics but also increase resistance to bending and deformation. Similarly, coatings or surface treatments could increase durability and moisture resistance, thus expanding the application potential of these boards in more demanding environments.

In conclusion, the mechanical properties of sorghum husk and polystyrene-based particle boards pave the way for various applications, particularly in interior construction and furniture. To optimize their use, special attention must be paid to the formulation, including particle size and binder dosage, as well as finishing techniques that could enhance their performance. These efforts could make these particle boards more attractive for a wider range of applications, especially in contexts where durability and mechanical strength are paramount.

4. Conclusions

This study focused on the development and evaluation of particle boards based on sorghum husks, integrating polystyrene as a binder. The goal was to develop an innovative composite material by valorizing agricultural waste and contributing to sustainable construction practices.

The findings indicate that the physical and mechanical properties of the particle boards vary significantly depending on the granularity of the sorghum particles and the binder dosage. Boards with larger particles and a higher binder dosage demonstrated improved mechanical strength and increased rigidity. Regarding the response to swelling after immersion, it was observed that boards with fine granularity and lower binder dosage exhibited greater swelling, highlighting the importance of the formulation in the material's response to moisture.

These discoveries pave the way for potential use in the construction industry, particularly for internal uses such as furniture, wall coverings, and flooring, where resistance to bending and dimensional stability are essential. Moreover, the ecological nature of these boards, combining agricultural waste and recycled binder, aligns with sustainable development goals and offers an interesting alternative to conventional construction materials.

This research also underscores the need for further optimization of the board formulations to enhance their properties. Future studies could explore different binder dosages, as well as the incorporation of various types of reinforcements or surface treatments, to strengthen the durability and mechanical resistance of the boards. Additionally, a deeper analysis of the environmental impact and sustainability of these materials would be beneficial to fully assess their viability in large-scale construction applications.

In conclusion, the results of this study contribute to a better understanding of sorghum husk and polystyrene-based particle boards and highlight their potential as innovative construction materials. The focus on utilizing agricultural waste and recycled binders is part of an ecological construction approach, offering promising prospects for the construction industry in its quest for more sustainable and environmentally friendly solutions.

Authors' Contributions

- *Conceptualization and study design*: E. Olodo, V. Doko, E. Chabi
- *Data collection*: C. Yarou, H. Gbian E. Chabi
- *Data analysis and interpretation*: E. Chabi, H. Gbian
- *Manuscript drafting*: E. Chabi
- *Critical manuscript review for intellectual content*: E. Olodo, V. Doko, E. Chabi, H. Gbian
- *Final manuscript approval:* H. Gbian, E. Chabi, V. Doko, C. Yarou, E. Olodo

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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