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Study of Rice Husks and Expanded Polystyrene Composites for Construction Applications

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Abstract

In the current context of environmental challenges, this study focuses on developing innovative and eco-friendly composites using rice husk and recycled expanded polystyrene. This dual-responsibility approach valorizes a by-product like rice husk, often considered waste, and reuses polystyrene, a plastic waste, thereby contributing to CO_2 emission reduction and effective waste management. The manufacturing process involves dissolving recycled polystyrene into a solvent to create a binder, which is then mixed with rice husk and cold-compacted into composite materials. The study examines the impact of two particle sizes (fine and coarse) and different proportions of recycled polystyrene binder. The results show significant variations in the mechanical characteristics of the composites, with Modulus of Rupture (MOR) values varying from 2.41 to 3.47 MPa, Modulus of Elasticity (MOE) ranging from 223.41 to 1497.2 MPa, and Stiffness Coefficient (K) from 5.04 to 33.96 N/mm. These characteristics demonstrate that these composites are appropriate for various construction applications, including interior decoration, panel claddings, and potentially for furniture and door manufacturing when combined with appropriate coatings. This study not only highlights the recycling of agricultural and plastic waste but also provides a localized approach to addressing global climate change challenges through the adoption of sustainable building materials.

Keywords

Rice Husk, Recycled Expanded Polystyrene, Eco-Friendly Composites, Waste Valorization, Sustainable Construction

1. Introduction

Rapid industrialization and exponential global population growth have led to the generation of a considerable amount of waste, including waste from agriculture and plastics. This poses significant environmental challenges that require sustainable and innovative solutions. In this context, waste valorization, particularly of agricultural by-products like rice husk and EPS (expanded polystyrene), represents an opportunity to mitigate these challenges.

Rice husk, a residual material from rice milling processes, had a global production exceeding 520 million tons in 2022 [1]. Although abundant, its management remains problematic due to its environmental impact when discarded or burned. Similarly, polystyrene, predominantly used in packaging, presents challenges in terms of biodegradability, thereby contributing to plastic pollution.

Previous research on utilizing rice husk in construction materials has mainly focused on its incorporation as a mineral additive in concrete, a common practice in Asia where this material is abundant. Other studies have explored its potential as an aggregate, thus replacing traditional mineral aggregates [2]-[4].

Concerning polymer matrices, previous work has shown the feasibility of incorporating rice husk as reinforcement in composites made with polypropylene, polyethylene, and various resins. For example, Atuanya [5] observed that the tensile strength of low-density recycled polyethylene composites increased with a rice husk filler load up to 10%. Nwanonenyi and Obidegwu [6] also studied these composites and reported distinct variations in mechanical properties. Zafar *et al.* [7] achieved maximum tensile strength at 5% weight load of RH. Zhang *et al.* [8] found that increasing the RH load to 70% by weight decreased the tensile properties. Works like those of Dimzoski [9] have revealed that adding rice husk to a polypropylene matrix impacted the tensile and flexural modulus.

Other studies have examined the effect of adding compatibilizers to these composites. For example, Toro [10] used a compatibilizer in a polypropylene and rice husk composite, which improved the tensile modulus and water absorption. Chen *et al.* [11] used copolymers as compatibilizers to improve adhesion between different matrices. Rajendran *et al.* [12] improved the properties of rice husk through UV ozonolysis, leading to increased tensile strength. Simone Rosa [13] also examined the effect of a coupling agent on the mechanical properties of rice husk and polypropylene composites.

In addition to polyethylene and polypropylene matrices, other matrices have been evaluated, including two specific types of rubber: Standard Malaysian Rubber Grade L (SMR L) and epoxidized natural rubber (ENR 50), as utilized in studies by Attharangsan [14].

Several factors influence the mechanical properties of these composites. For example, the particle size of rice husk impacts tensile strength, as observed by Petchwattana [15]. Moreover, the hydrophilic nature of rice husk can increase water absorption in composites, especially at higher filler levels. Methods such as electron beam irradiation and plasma processing have been explored to improve adhesion between rice husk and the polymer matrix.

However, the use of expanded polystyrene in rice husk-based composites is a less explored avenue. Abdulkareem and Adeniyi [16] developed fiber-reinforced plastic composites from rice husk and polystyrene waste, which were dissolved in a non-disclosed solvent. Rice husks were oven-dried at 50˚C and sieved to a size of 150 µm. The composites, containing between 10 and 40% rice husks, demonstrated enhanced mechanical characteristics, achieving a peak Young's modulus of 365 MPa. Water absorption also increased with the proportion of rice husks. In a study by Joshua O. Ighalo *et al.* [17], similar composites were developed, but with rice husk proportions varying from 20% to 50% by weight in the polystyrene matrix. The polystyrene-based resin was obtained by dissolving polystyrene waste in an unmentioned organic solvent before mixing it with rice husk particles. The composite was then prepared using the solvent casting method. The properties studied included moisture absorption, thermal conductivity, and microstructural characteristics. The results showed that moisture absorption increased with the proportion of rice husk, reaching a saturation point of 5.79% by weight for the composite with 20% rice husk after 5 hours, and 39.17% for that with 50% after 5 days. The maximum thermal conductivity observed was 1.7 W/m˚C for the formulation with 40% rice husk. Nak-Woon Choi *et al.* [18] studied the development of composites based on rice husks and recycled expanded polystyrene (EPS). The binder used for these composites is a styrene solution in which EPS is dissolved, incorporating Trimethylolpropane trimethacrylate (TMPTMA) and benzoyl peroxide (BPO) as the cross-linking agent and initiator, respectively. The composite also included a limestone filler (charge) of a size smaller than 2.5 µm. The methodology involved preparing composites with different binder contents (25%, 30%, 35%) and different filler/binder ratios (0, 0.5, 1, 1.5). Rice husks, dried at 80˚C for 48 hours, are mixed with the binder and hot-molded at 120˚C and 25 MPa for 15 minutes to form the composites. Tests reveal that the apparent density of the composites ranges between 0.80 and 1.60 $kg \cdot m^{-3}$ and increases with binder content and filler/binder ratio. Water absorption decreases to about 2.0% or less when the binder content is 30.0% or more and the filler/binder ratio is 1.0 or more. Similarly, thickness expansion is about 1.0% or less under the same conditions, and a reliable correlation between thickness expansion and water absorption has been established. Regarding flexural strength, it reaches its maximum (37 MPa) with a binder content of 30.0% and a filler/binder ratio of 1.0. Flexural strength after 24 hours of water immersion is generally lower, but the difference is minimal when the binder content is 30.0% or more and the filler/binder ratio is 1.0 or more.

Given the limited research on utilizing expanded polystyrene as a matrix in conjunction with rice husk, the objective of this research is to develop a composite material combining these components. The impact of different factors, including rice husk particle size and the amount of adhesive used, on the physico-mechanical characteristics of the composite will be assessed. This research aims to provide an ecological and economical alternative to traditional construction materials while contributing to waste reduction.

2. Materials and Methods

2.1. Rice Husk

The rice husk underwent a mechanical grinding process and was categorized into four distinct particle size fractions. Two granular formulations were prepared from these four fractions: one fine-grained formulation and one coarse-grained formulation. The specific proportions of each formulation are detailed in Table 1. The intrinsic physical properties of the rice husks are presented in Table 2.

Table 1. Granular mixtures of rice husks were used in this study.

Size	Coarse mixture	Fine mixture
Retained on 1.250 mm sieve	40%	10%
Retained on 0.630 mm sieve	30%	20%
Retained on 0.315 mm sieve	20%	30%
Retained on 0.160 mm sieve	10%	40%

Table 2. Physical characteristics of the rice husks.

Granular mixture	Bulk density ($kg \cdot m^{-3}$)	True density ($kg \cdot m^{-3}$)	Water absorption rate (%)
Coarse mixture	158.63 ± 1.10	632.41 ± 0.72	64.69 ± 0.56
Fine mixture	203.55 ± 0.92	751.09 ± 0.41	82.38 ± 0.55

2.2. Expanded Polystyrene

Sourced from recovered packaging materials, the expanded polystyrene used in this study often ends up overlooked and abandoned in the environment, presenting a significant waste management challenge. Its density ranges between 15 and 25 $kg \cdot m^{-3}$.

2.3. Binder Preparation

The binder preparation involves the solubilization of polystyrene in a chosen organic solvent, specifically using gasoline for this research [19]. The process entails the integration of polystyrene with the solvent and stirring the mixture until a uniform bonding agent is achieved. The balance between the solvent and the polystyrene is determined by the coefficient k, described as follows:

$$k = \frac{\text{mass of solvent}}{\text{mass of polystyrene}} \tag{1}$$

Optimization of this coefficient was achieved through experimental trials. In this method, a specific amount of solvent was measured and combined with polystyrene, allowing for the solvent's complete evaporation, while monitoring the weight of the polystyrene that dissolved. The ideal coefficient k, as identified from these experiments, is 1.4.

Variations in the bonding agent's viscosity are significantly influenced by the coefficient k. A k value lower than 1.4 leads to a suboptimal amount of solvent for full dissolution of the polystyrene, resulting in a thick, paste-like binder with higher viscosity and remnants of undissolved polystyrene. On the other hand, a k value higher than 1.4 results in too much solvent, yielding a binder with reduced viscosity that is less effective in maintaining the cohesion of rice husk particles.

2.4. Composite Formulation

Two binder ratios were rigorously selected for the study, based on preliminary experimental cycles. The ratios, defined by their binder content $d = \frac{\text{mass of binder}}{\text{mass of rice husk}}$, are set at 0.8 and 1. These values were optimized to reduce structural anomalies like disintegration and to enhance the uniformity of the composite.

Continuing in this study, the composites will be referenced based on their binder dosage and the particle size of the rice husk, as indicated in Table 3.

Table 3. Composite coding according to granularity and dosage.

Size	Code	Dosage
Fine	MF1	0.8
	MF2	1
Coarse	MG1	0.8
	MG2	1

2.5. Composite Implementation

Rice Husk preparation: rice husks are first oven-dried to a consistent weight. The various granular categories are subsequently segregated and quantified to create fine and coarse mixtures.

Mixing: this step is crucial for achieving a consistent blend of rice husks within the polymer framework. Effective mixing leads to a uniform composite.

Specimen fabrication: for the composite plates, a method of cold pressing is employed. The blend, consisting of prepared rice husks and the polystyrene-based bonding agent, is placed into a specially designed metal mold for this experiment. The compaction is performed with a hydraulic press to ensure even pressure throughout the blend.

The pressure is increased progressively, without reaching a level that could cause the polymer matrix to leak or compromise the composite's structural integrity. This pressure level is maintained until stability is achieved, signaling that the mixture has attained the desired uniformity.

After the pressing stage, the plates are removed from the mold for air-drying at the laboratory's controlled room temperature, set at 20˚C ± 1˚C. During this period, the plates are monitored every 8 hours for weight stability, signaling their readiness and the absence of residual solvents. These plates, cut to specific measurements of 11 mm thick, 76 mm wide, and 314 mm long, are then subjected to various tests.

Firstly, they are subjected to a three-directional swelling test. For this, they are submerged in water, also maintained at a controlled temperature of 20˚C ± 1˚C, for 24 hours. Post-immersion, the samples are removed, allowed to dry for 10 minutes, and then weighed. Their dimensions (length, width, and thickness) are precisely recorded at specified points – width and thickness at five different points, and length at two points, all uniformly spaced. These measurements facilitate the calculation of moisture content, swelling in three dimensions, volumetric swelling, water absorption, and density [20] (**Figure 1**).

Additionally, on these same plates, 3-point bending tests are conducted to determine the elastic modulus and the static flexural breaking stress [20].

Figure 1. Machined plates.

3. Results and Discussion

3.1. Evaluation of the Composite's Physical Characteristics

The findings from the physical assessments of the composite materials are summarized in **Table 4**. The data show noticeable differences between the composites, indicating that the particle size of rice husk and the quantity of binder used might play a crucial role in defining the material attributes of the composite structures.

3.1.1. Mass Loss of the Composites

The analysis of composite mass loss after compaction and air storage reveals significant variations based on composite parameters, specifically granularity and binder dosage. Composites with finer rice husk particles (MF1 and MF2) exhibit more pronounced weight reduction (13.17% for MF1 and 12.48% for MF2) in contrast to those with coarser particles (MG1 and MG2), which show reductions

Table 4. Physical properties of composites.

Composites	Mass loss (%)	Density ($kg \cdot m^{-3}$)	Swelling (%)			
			Thickness	Length	Width	Volumetric
MG1	8.43	0.693	10.01	1.97	3.00	15.17
MF1	13.17	0.700	3.33	0.64	2.70	6.36
MG2	7.34	0.710	15.53	1.90	3.84	22.27
MF2	12.48	0.720	0.72	2.10	1.60	2.07

of 8.43% for MG1 and 7.34% for MG2. This could be due to several reasons. Firstly, the greater ratio of fine particles in MF1 and MF2 might lead to an increased overall exposed surface area, thus facilitating the release of volatile substances and moisture. Secondly, the distribution of particle sizes in these blends could result in a structure that is more permeable, enhancing the release of volatile elements. Additionally, it's conceivable that chemical interactions between the finer rice husks and polystyrene are more dynamic, resulting in faster weight reduction.

Figure 2 displays the comparative weight reduction across various composite formulations. These observations are essential for comprehending the post-manufacturing behavior of composites and for enhancing the development of their material properties for upcoming uses.

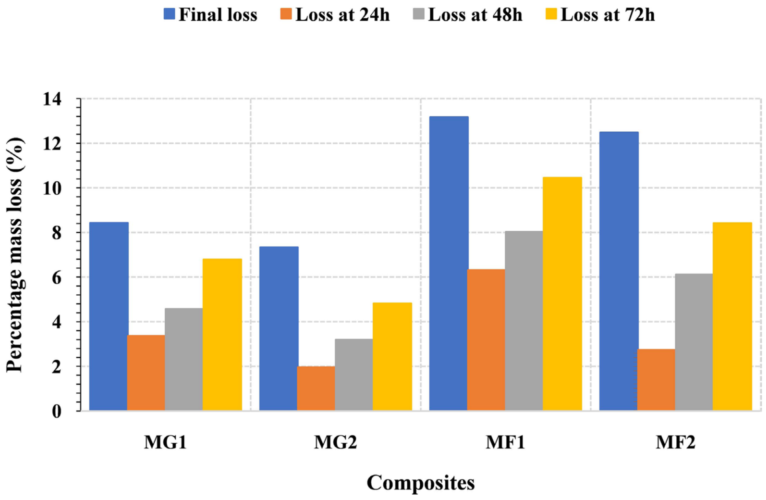

Figure 2. Mass loss of Rice Husk-Polystyrene Composites over time.

3.1.2. Composite Density Measurements

Density measurements of the composites range from 0.693 $kg \cdot m^{-3}$ for MG1 to 0.720 $kg \cdot m^{-3}$ for MF2. These values are depicted in Figure 3 as a histogram.

The density slightly increases when transitioning from a coarse to a fine mixture for the same binder dosage. The density tends to increase when transitioning from coarser to finer mixtures at the same binder dosage. This change could

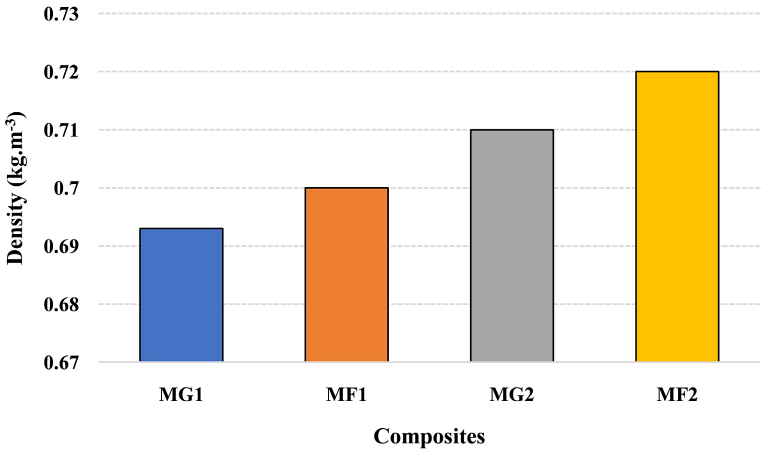

Figure 3. Density distribution of various rice husk and polystyrene-based composites.

be attributed to a more efficient envelopment of the finer rice husk particles by the polymer matrix, leading to the composite's densification.

Moreover, an increase in binder dosage from 0.8 to 1 also seems to slightly elevate the density, possibly due to the added weight and improved cohesion provided by the increased presence of the polymer matrix.

Compared with the results of Nak-Woon Choi *et al.* [18], where the density of composites varies from 0.80 g/cm^3 to 1.60 g/cm^3, it is notable that the densities in this study are comparatively lower. This difference could be explained by the absence of limestone fillers in the current formulation and perhaps by differences in manufacturing procedures.

3.1.3. Swelling of the Composites

Submerging the composites in water evaluates their responsiveness to moisture absorption, impacting their long-term durability in damp conditions. The collected data reveals noticeable variances among different composites, in terms of swelling in thickness, length, width, and even volumetrically.

Thickness Swelling: The MG composites, characterized by coarse granularity, display substantial swelling, with MG2 showing the most significant swelling at 15.53%. Conversely, the MF composites, with fine granularity, show more modest growth, with MF2 displaying only a minimal swelling of 0.72%. This observation might be attributed to the inherently more absorptive nature of the coarser structured composites, which are more susceptible to water uptake.

Length and Width Swelling: The dimensional expansion in length and width tends to be minimal for all composites, generally not exceeding 3%. The alignment of rice husk particles within the composite matrix could potentially influence these dimensions of swelling.

Volumetric Swelling: This measurement reflects the cumulative expansion across all three dimensions. MG2 shows the highest volumetric increase, followed by MG1, whereas MF1 and MF2 display considerably lesser swelling.

General Observation: The MG composites appear to have a higher water uptake, presumably due to their more absorptive makeup, which facilitates easier water ingress and noticeable expansion. Conversely, the MF composites appear more resistant to water penetration, suggesting a more compact polymer matrix or enhanced integration with the finer particles, thereby reducing absorption.

However, a contradiction arises when observing that the MF composites, despite their fine granularity, record a higher mass loss in the open air. This could be reasoned by the increased exposed surface area of the finer particles, accelerating the release of volatile substances. It's essential to note that mass loss and swelling are two distinct phenomena, although influenced by the structure of the composites. Mass loss is mainly due to the evaporation of volatile compounds and moisture, whereas swelling is influenced by the composites' ability to absorb and retain water within their structure. Chemical interactions between the rice husks and the binder might also play a role in these observations.

In summary, although all composites show some level of post-immersion swelling, the observed variations indicate that the granularity of the rice husk plays a key role in determining the water resistance of the composites. These results provide valuable insights for the future optimization of composites for specific applications. A more in-depth study of the composites' microstructure could offer deeper insights into the influence of granularity on porosity and, by extension, on swelling.

Figure 4 graphically illustrates these findings, offering an easily comprehensible visual summary.

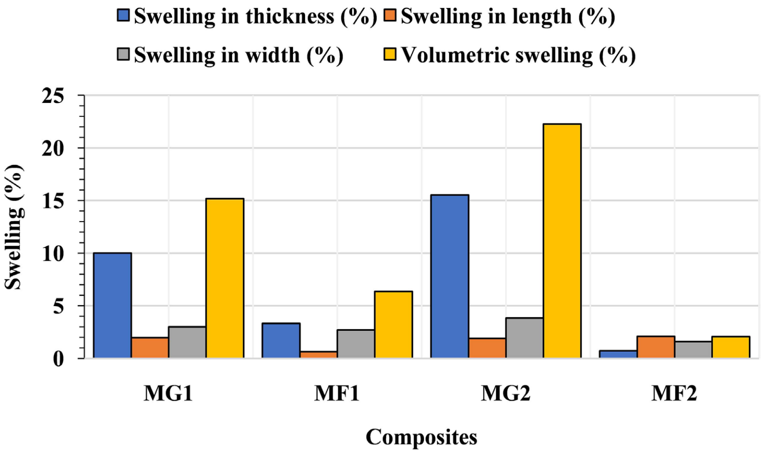

Figure 4. Swelling behavior of Rice Husk-Polystyrene Composites following a 24-hour immersion period.

3.2. Mechanical Properties of the Composites

Table 5 summarizes the outcomes of mechanical testing on the composites. The measured parameters include the Modulus of Rupture in Bending (MOR), the Coefficient of Rigidity in Bending (K), and the Modulus of Elasticity in Bending (MOE).

Table 5. Mechanical characterization of the composites.

Composite	MOR (MPa)	K (N/mm)	E (MPa)
MG1	2.41 ± 0.06	21.73 ± 0.38	942.01 ± 12.31
MF1	3.06 ± 0.08	5.04 ± 0.12	223.41 ± 8.67
MG2	2.61 ± 0.06	33.96 ± 0.45	1497.92 ± 30.58
MF2	3.47 ± 0.11	13.63 ± 0.23	529.14 ± 10.58

The Modulus of Rupture in Bending gives an indication of the material's maximum strength before breaking when subjected to a bending force.

The MOE (Modulus of Elasticity in Bending) represents the stiffness of the material and its ability to deform elastically under load. A high MOE indicates a stiffer material.

The Coefficient of Rigidity in Bending is also a measure of stiffness.

Typically, a high MOR is often linked to a high MOE because good bonding in the composite leads to both good strength and good stiffness. However, factors like particle distribution, porosity, etc., can influence this relationship [19].

To offer an in-depth visual analysis, **Figure 5** illustrates the mechanical properties of the composites, highlighting differences in MOR and MOE among the various composites.

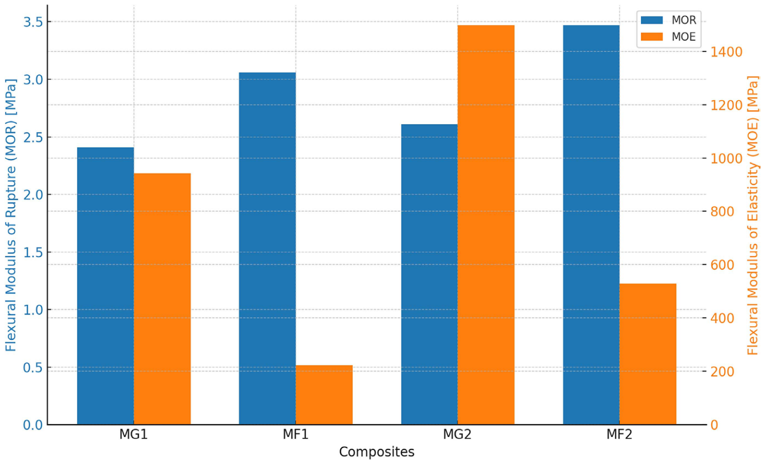

Figure 5. Mechanical property analysis of the composites.

The MF samples exhibit higher MOR than the MG samples, which might be due to more effective distribution and integration of the finer particles within the matrix. The swelling results of the composites corroborate this interpretation. MF composites, having better bonding with the binder, show less swelling compared to MG composites. Better bonding could explain the increased strength (higher MOR) of MF composites.

Conversely, the Modulus of Elasticity in Bending (MOE) is higher for MG composites, indicating greater stiffness. This increase in stiffness could be the result of larger particle sizes in the mix, providing greater mechanical resistance to bending.

As for the Coefficient of Rigidity in Bending (K), it shows an increase for MG composites, corroborating the higher observed MOE for these composites.

4. Conclusions

The incessant search for sustainable solutions for the construction industry has led to this innovative exploration of composites based on rice husk and expanded polystyrene. A pairing is rarely studied in scientific literature. By utilizing two ubiquitous waste materials, this research endeavors to repurpose these substances into resources for environmentally friendly construction applications.

The diversity of rice husk particle sizes and binder dosages has resulted in a range of composites with distinct properties. Composites with fine particle sizes tend to show a greater loss of mass, likely due to an increased overall surface area and a potentially more absorptive composition. However, despite a higher loss of mass, these composites exhibit less swelling when immersed in water, suggesting better adhesion with the binder. Regarding mechanical properties, fine particle composites stood out for their higher flexural strength, while coarse particle composites demonstrated greater rigidity, as evidenced by their flexural modulus of elasticity and flexural stiffness coefficient.

Concerning mechanical properties, these composites hold promise for various applications in construction, especially for interior decoration, ceilings, and other structural elements. Surface treatments, such as the application of PVC films, high-pressure laminates, or fiberglass layers, can further enhance their mechanical properties and durability. These improvements pave the way for more specialized applications, such as joinery and woodwork in building construction.

For future research, it would be interesting to explore ways to improve the melted polystyrene used as a binder, in order to enhance the physical properties such as swelling and the mechanical parameters of the composites. It would also be relevant to consider the long-term durability of the composites under various environmental conditions, such as humidity, UV exposure, and temperature variations. Exploring alternative solvents and adopting different manufacturing methods, such as hot pressing, could also be considered to further optimize the properties of the composites.

In conclusion, this study contributes additional insights into the field of bio-based composites, underscoring the viability of using expanded polystyrene as an effective binding agent.

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Author Contributions

- *Conceptualization and study design*: E. Olodo, V. Doko, E. Chabi.

- *Data collection*: E. Chabi, P. D. Amadji.
- *Data analysis and interpretation*: E. Olodo, V. Doko, E. Chabi, P. D. Amadji, S. P. Hounkpè.
- *Manuscript drafting*: E. Chabi.
- *Critical manuscript review for intellectual content:* E. Olodo, V. Doko, E. Chabi, P. D. Amadji, S. P. Hounkpè.
- *Final manuscript approval:* V. Doko, E. Chabi, P. D. Amadji, S. P. Hounkpè, E. Olodo.

Data and Code Availability

No additional datasets or code repositories are associated with this research.

Ethical Approval

Ethical approval was not required for this research as it did not involve human or animal subjects.

Conflicts of Interest

The authors declare that there are no conflicts of interest that could inappropriately influence, or be perceived to influence, the work reported in this manuscript.

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