

Investigation of the Effects of Hybrid Agro Waste-Fillers on the Properties of Flexible Polyurethane Foams for Nursery Farming Applications

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ABSTRACT

The use of agro-waste materials as fillers in polymer composites offers a sustainable route to reducing environmental impact and production cost while enhancing material performance. This study investigates the influence of guinea corn husk/snail shell hybrid filler on the physical, mechanical, morphological, and biodegradability properties of flexible polyurethane foam intended for nursery farming applications. The hybrid filler, composed of equal proportions of lignocellulosic guinea corn husk and calcium-carbonate-rich snail shell, was incorporated at 0–25 wt%. Results showed that increasing filler loading prolonged foaming reactions and increased density, with rise time increasing from 145 s to 166 s, cure time from 7.5 to 8.8 min, and apparent density from 28.4 to 32.2 kg/m³. Mechanical performance improved progressively, as tensile strength, flexural strength, compressive strength, and hardness increased with filler content, while strain at break decreased, indicating enhanced stiffness but reduced ductility. Scanning electron microscopy revealed a transformation from large, irregular cells in the control foam to smaller, more uniform cells with thicker walls in filled samples. Soil burial testing confirmed the biodegradable nature of the composite material. Overall, the guinea corn husk/snail shell hybrid filler significantly improved structural integrity and load-bearing capacity while maintaining environmental compatibility, demonstrating strong potential for cushioning, root protection, and seedling support in nursery farming systems.

Keywords: Flexible polyurethane foam; Guinea corn husk; Snail shell; Agro-waste composites; Nursery farming applications

INTRODUCTION

Polyurethane is a polymer containing urethane linkages (–NH–CO–O–) formed by the reaction between isocyanates and polyols in the presence of catalysts and additives. These materials can be formulated as rigid or flexible foams with a wide range of physical and mechanical properties, making them useful in diverse applications such as cushioning, insulation, packaging, and structural components [1,2]. Flexible polyurethane foam (FPUF) in particular is widely used because of its low density, high resilience, energy absorption capability, and ease of fabrication [3].

The production of flexible polyurethane foam typically involves polymer polyol, isocyanate, blowing agents, catalysts, surfactants, and additives such as fillers. Most of these components are derived from petrochemical sources, contributing to rising production costs and environmental concerns associated with non-renewable resources [4]. Consequently, research efforts have focused on incorporating alternative fillers from renewable and low-cost materials to reduce dependence on synthetic additives while improving sustainability [5].

Fillers are incorporated into polymer matrices to reduce cost, modify viscosity during processing, control shrinkage, and enhance mechanical properties such as stiffness and strength. Conventional mineral fillers including calcium carbonate, silica, and alumina are commonly used; however, they are often expensive, non-renewable, and sometimes imported in developing countries [6]. This has stimulated interest in natural fillers

derived from agricultural residues and biogenic waste materials, which are abundant, biodegradable, non-toxic, and environmentally friendly [7]. Agricultural wastes such as husks, bran, fibers, and shells are lignocellulosic materials that can reinforce polymer matrices while contributing to waste valorization and environmental protection [8].

Snail shells, a common food waste in many regions, are rich in calcium carbonate and possess good hardness and thermal stability, making them suitable as mineral-type fillers in polymer composites [9]. The combination of lignocellulosic agro-wastes with mineral-rich snail shell particles as hybrid fillers may produce synergistic effects, improving structural integrity, density, and mechanical performance of polyurethane foams [10]. Previous studies have shown that both natural fibers and mineral particles can influence foam cell morphology, cure behavior, and mechanical properties depending on particle size, loading level, and compatibility with the polymer matrix [11,12].

In agricultural practice, particularly nursery farming, lightweight cushioning materials are required for seedling trays, root protection, moisture retention, and shock absorption during transportation. Conventional synthetic foams used for these purposes are not biodegradable and may contribute to soil contamination after disposal. The development of eco-friendly flexible polyurethane foams reinforced with biodegradable agro-waste fillers therefore presents a promising alternative for nursery applications, where moderate mechanical strength, moisture tolerance, and environmental compatibility are essential.

Nigeria generates large quantities of agricultural residues such as corn husk, millet bran, wheat husk, and guinea corn husk, most of which are discarded or burned, leading to environmental pollution. Converting these wastes into value-added filler materials for polymer composites can support sustainable waste management while producing low-cost materials suitable for agricultural use.

Therefore, this study investigates the effects of agro-waste/snail shell hybrid fillers on the physical, mechanical, morphological, and biodegradability properties of flexible polyurethane foams intended for nursery farming applications.

MATERIALS AND METHODS

Raw Materials

The performance of flexible polyurethane foam depends largely on the quality of the starting materials and strict adherence to formulation procedures. The chemical components required for foam production; polymer polyol, toluene diisocyanate (TDI), water as blowing agent, silicone surfactant, catalysts, and auxiliary additives, were obtained from a commercial polyurethane manufacturer known for producing quality flexible foam products. Flexible polyurethane foams are formed through the reaction of polyols and isocyanates in the presence of blowing agents and additives that regulate reaction kinetics and cellular structure [12,21].

The primary agro-waste filler used in this study was guinea corn husk, sourced from agricultural processing activities in Yobe State, Nigeria. Discarded snail shells, rich in calcium carbonate, were obtained from food markets in Calabar, Nigeria. Both materials are renewable, low-cost, and environmentally friendly. Guinea corn husk provides lignocellulosic reinforcement, while snail shells act as mineral-type fillers capable of improving stiffness and structural integrity in polymer matrices [18,19].

Preparation of Snail Shell Powder

Snail shells were manually sorted to remove adhering organic matter, washed thoroughly, and air-dried to eliminate residual moisture. The dried shells were crushed using a mechanical grinder and pulverized into fine powder. The powder was sieved to a uniform particle size of approximately 75 μm and stored in airtight polythene bags prior to use. Calcium-carbonate-based shell powders act as nucleating agents during foaming, influencing cell formation and mechanical performance of polyurethane composites [16].

Preparation of Guinea Corn Husk Filler

Guinea corn husks were cleaned, washed, and oven-dried to constant weight to prevent moisture interference during foam formation. The dried husks were milled into fine particles using an electric grinder and sieved through a 75 µm mesh to obtain uniform powders. The prepared filler was stored in sealed polythene bags until required. Lignocellulosic fillers like guinea corn husk are known to modify foam microstructure, density, and mechanical behavior depending on particle size, composition, and dispersion within the polymer matrix [9].

Preparation of Hybrid Filler

The guinea corn husk powder was blended with snail shell powder in a 50:50 weight ratio to combine the reinforcing effects of organic lignocellulosic and mineral calcium carbonate components. Hybridization can generate synergistic improvements in composite performance due to enhanced stress transfer and structural stability compared to single-filler systems [11].

Foam Formulation for Nursery Applications

The formulation was designed to produce flexible, lightweight foams suitable for nursery farming applications such as seedling support, cushioning, moisture retention, and root protection. Relative proportions of polyol, isocyanate, blowing agent, surfactant, catalyst, and filler were selected based on standard flexible polyurethane foam formulations [12]. Filler loadings of 5–25 wt% were incorporated into the polyol component prior to reaction, while unfilled foam served as the control. Density control was achieved by adjusting the water content, as water reacts with isocyanate to generate carbon dioxide gas responsible for foam expansion and cell formation [13].

Foam Production

A predetermined mass of polymer polyol was poured into a clean mixing container. The required quantity of the guinea corn husk/snail shell hybrid filler was gradually added and mechanically stirred to ensure uniform dispersion. Catalysts, surfactant, and other additives were subsequently incorporated while mixing continued. The measured amount of isocyanate was then added, and the mixture was stirred rapidly to initiate the foaming reaction. The reacting mixture was immediately poured into open molds and allowed to rise freely under ambient conditions. After foaming and curing, the foam blocks were demolded and conditioned for at least 24 hours prior to characterization. Proper dispersion of fillers before gelation is critical, as it influences cell nucleation, foam uniformity, and final mechanical properties of the composite [20].

Raw Material/ Fillers	0 wt %	5 wt %	10 wt %	15 wt %	20 wt %	25 wt %
Polyol (kg)	0.60	0.57	0.54	0.51	0.48	0.45
TDI (kg)	0.33	0.33	0.33	0.33	0.33	0.33
Amine (mL)	2.00	2.00	2.00	2.00	2.00	2.00
Stannous Oct. (mL)	1.00	1.00	1.00	1.00	1.00	1.00
Silicone Oil (mL)	5.00	5.00	5.00	5.00	5.00	5.00
Filler (Guinea corn Husk) (kg)	0.00	0.03	0.06	0.09	0.12	0.15

Note: Kg = kilogram; mL = mililiters; wt % = weight percentage of hybrid filler based on total mass of polyurethane formulation (0 wt % = unfilled control).

Table 1: Foam Formulation and Sample Design

The formulation used for the guinea corn husk/snail shell hybrid system is presented in Table 1. The filler, containing equal proportions of guinea corn husk and snail shell, was incorporated at 0–25 wt %, corresponding to 0.00, 0.03, 0.06, 0.09, 0.12, and 0.15 kg, respectively. As the filler content increased, the mass of polyol decreased proportionally from 0.60 kg to 0.45 kg, while the quantities of TDI (0.33 kg), amine

catalyst (2.00 mL), stannous octoate (1.00 mL), and silicone oil (5.00 mL) were kept constant for all samples. This substitution ensures that the total formulation mass remains balanced, allowing the effect of filler loading on foam properties to be evaluated without altering the reactive components [12].

After the filler was added to the polyol, the catalysts, surfactant, and other additives were incorporated and the mixture was stirred thoroughly. The measured amount of TDI was then introduced, followed by rapid mixing to initiate the foaming reaction. The reacting mixture was immediately poured into open molds and allowed to rise freely under ambient conditions. After full rise, the foam samples were left to cure and subsequently demolded and conditioned for at least 24 hours prior to characterization. Adequate dispersion of the hybrid filler before gelation was essential, as it influences nucleation, cell structure, and the mechanical performance of the resulting foam [20].

Characterization of the Foam Samples

The prepared foam samples were characterized to evaluate their suitability for nursery farming applications. Physical properties, including rise time, cure time, and apparent density, were measured to assess foaming behavior and structural formation. Mechanical properties were determined through tensile strength, stress, strain, compression strength, hardness, and flexural strength tests, reflecting the foams' ability to withstand handling and support seedlings. The surface morphology of the foams was examined using scanning electron microscopy (SEM) to observe cell structure, uniformity, and the effect of filler incorporation on foam microstructure. Biodegradability tests were also conducted under controlled soil burial conditions to evaluate the environmental friendliness and degradation behavior of the composites. All measurements and analyses were carried out according to standard procedures, allowing a comprehensive assessment of how filler loading influenced the physical, mechanical, structural, and biodegradability performance of the guinea corn husk/snail shell polyurethane foams [12,13,20].

Statistical Analysis

All experiments were performed in triplicate to ensure reproducibility of the results. The reported values represent the mean of three independent measurements. Standard deviation (\pm SD) was calculated to evaluate the variability of the data. Error bars representing the standard deviation were included in some graphical plots to indicate measurement uncertainty and reliability of the observed trends.

RESULTS AND DISCUSSION

The effects of incorporating guinea corn husk/snail shell hybrid fillers into flexible polyurethane foam were evaluated through physical characterization, including rise time, cure time, apparent density, and flammability. Filler loadings ranged from 0 to 25 wt %, corresponding to 0, 5, 10, 15, 20, and 25 wt % in the formulation. These parameters provide insight into how the hybrid filler influences foaming behavior, structural development, and suitability for nursery farming applications.

Physical Properties: Rise Time, Cure Time, and Apparent Density

The physical characteristics of the guinea corn husk/snail shell hybrid foams were evaluated to assess the influence of filler content on foam formation and structure, as shown in Figure 1. All values represent the mean of three measurements, and the error bars indicate the standard deviation.

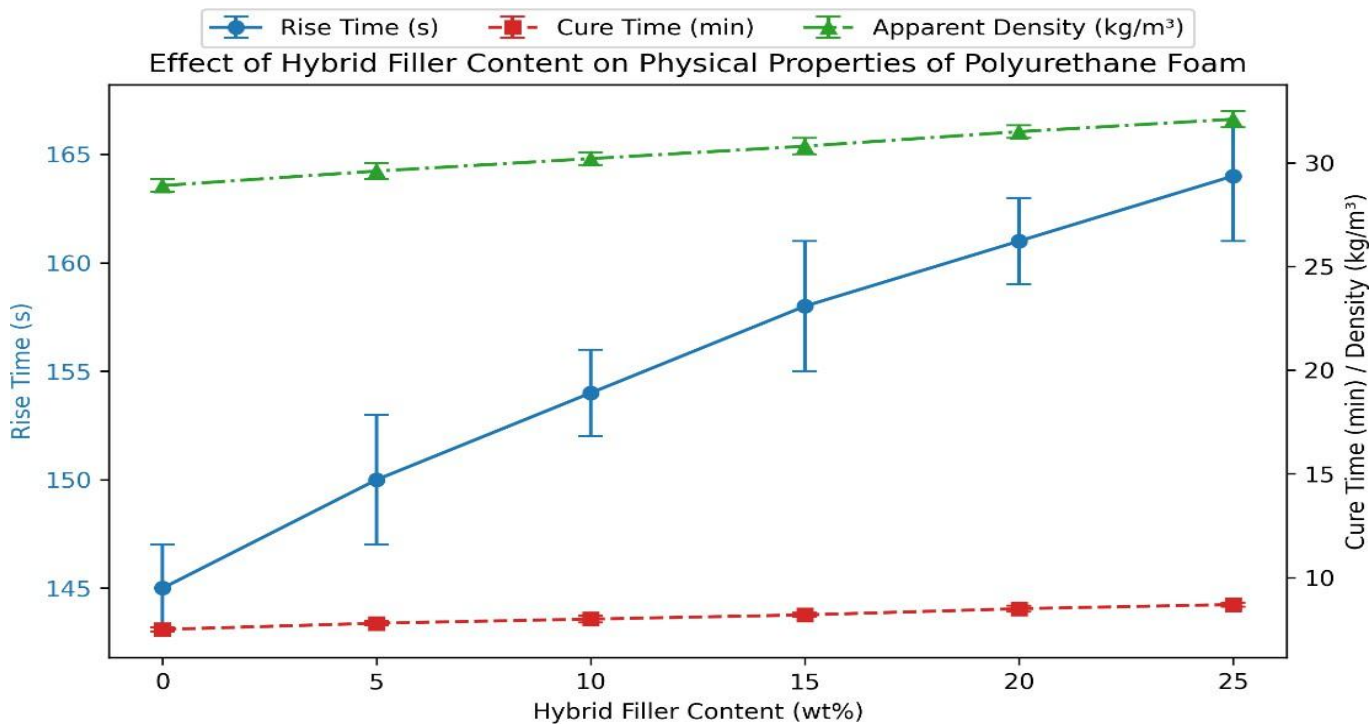


Fig 1. Effect of Filler Loading on Rise Time, Cure Time, and Apparent Density of Guinea Corn Husk/Snail Shell Foams

Rise time increased progressively with filler loading, from $150 \pm \text{SD}$ s at 5 wt% to $164 \pm \text{SD}$ s at 25 wt%. This trend reflects the slower expansion of the polymer matrix as the solid filler content increases, which likely reduces polymer chain mobility and partially restricts the diffusion of carbon dioxide generated during the water isocyanate reaction.

Similarly, cure time increased with increasing filler loading, rising from $7.8 \pm \text{SD}$ min at 5 wt% to $8.7 \pm \text{SD}$ min at 25 wt%. The extended cure time indicates that higher filler concentrations slightly retard the polymerization process, likely due to reduced diffusion of reactive species in the presence of solid particulates. These observations align with previous studies highlighting the influence of lignocellulosic and mineral fillers on polyurethane reaction kinetics [12,20].

Apparent density also showed a steady increase with filler content, from $29.6 \pm \text{SD}$ kg/m³ at 5 wt% to $32.1 \pm \text{SD}$ kg/m³ at 25 wt%. The increase in density can be attributed to the addition of solid filler particles into the polymer matrix, which occupy space within the foam cells and reinforce the cell walls. Higher density foams are expected to provide improved structural stability and load-bearing capacity, which is beneficial for nursery farming applications where cushioning and seedling support are required.

The combined trends in rise time, cure time, and density indicate that the incorporation of guinea corn husk/snail shell hybrid filler significantly affects foaming behavior, influencing expansion, reaction kinetics, and cell structure. These results are consistent with previous reports on agro-waste reinforced polyurethane foams [11,18].

Mechanical Properties of Guinea Corn Husk-Reinforced Polyurethane Foam

The mechanical performance of polyurethane foams incorporating guinea corn husk at varying loadings (5–25 wt%) was evaluated in terms of tensile strength, flexural strength, hardness, compressive strength, stress at break, and strain at break.

Tensile strength represents the maximum stress a material can withstand under uniaxial tension before failure and is a key indicator of structural integrity in flexible polyurethane foams. As shown in Figure 2.

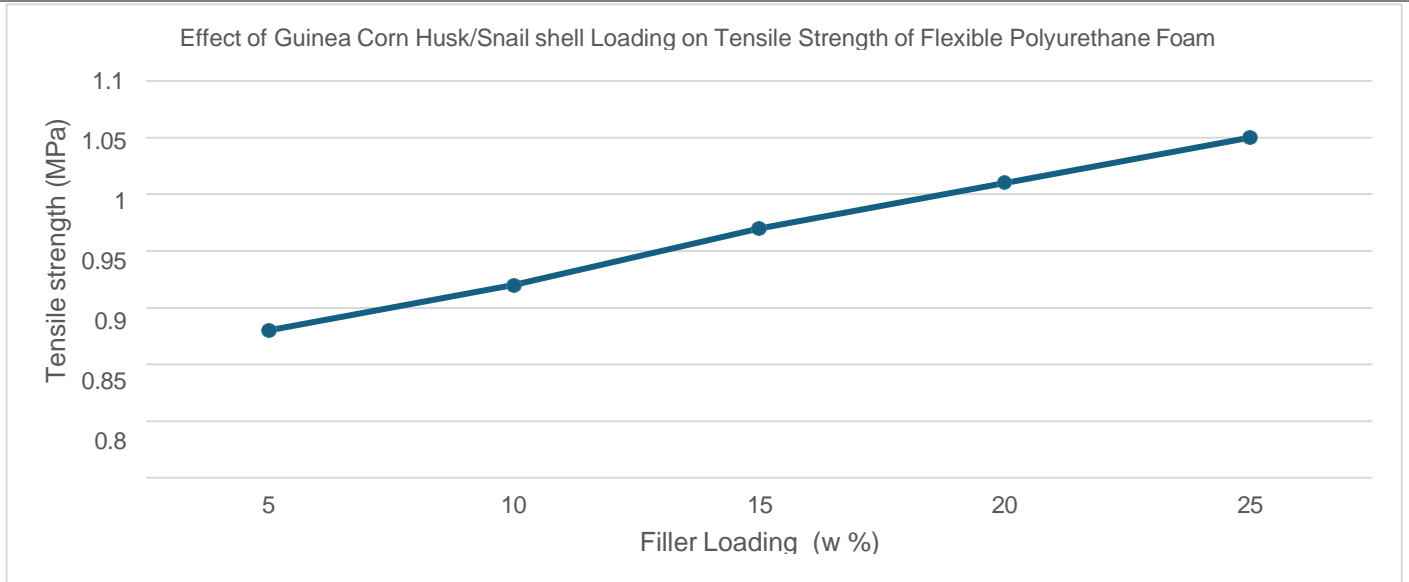


Fig 2. Variation of Tensile Strength with Filler Loading in Guinea Corn Husk/Snail Shell–Reinforced Foams

The tensile strength of the guinea corn husk/ snail shell reinforced foam, exhibited a progressive increase from 5 wt% to 25 wt% filler loading. This improvement can be attributed to the synergistic effects of particle reinforcement and the chemical affinity between the lignocellulosic filler and the polyurethane network. The hydroxyl-rich cellulose and hemicellulose domains in the guinea corn husk can interact with the urethane linkages through hydrogen bonding and van der Waals forces, effectively anchoring the polymer chains to the rigid filler surface [9,19]. Such interactions restrict polymer chain mobility, enhance stress transfer, and reduce local strain concentrations under tensile loading. Additionally, the particulate nature of the snail shell component contributes to nucleation during foam formation, producing finer, more uniform cell structures that resist elongation failure. Compared to similar bio-filled foams in the literature, these hybrid foams demonstrate tensile properties that are comparable or superior to systems reinforced solely with agricultural residues [10,17,26]. For nursery applications, the combination of structural reinforcement and controlled ductility ensures the foam can withstand repeated handling and transport stresses while maintaining shape integrity and cushioning support for seedlings.

Stress at Break

Stress at break corresponds to the stress level at which the material ultimately fractures and reflects its load-bearing capacity at failure.

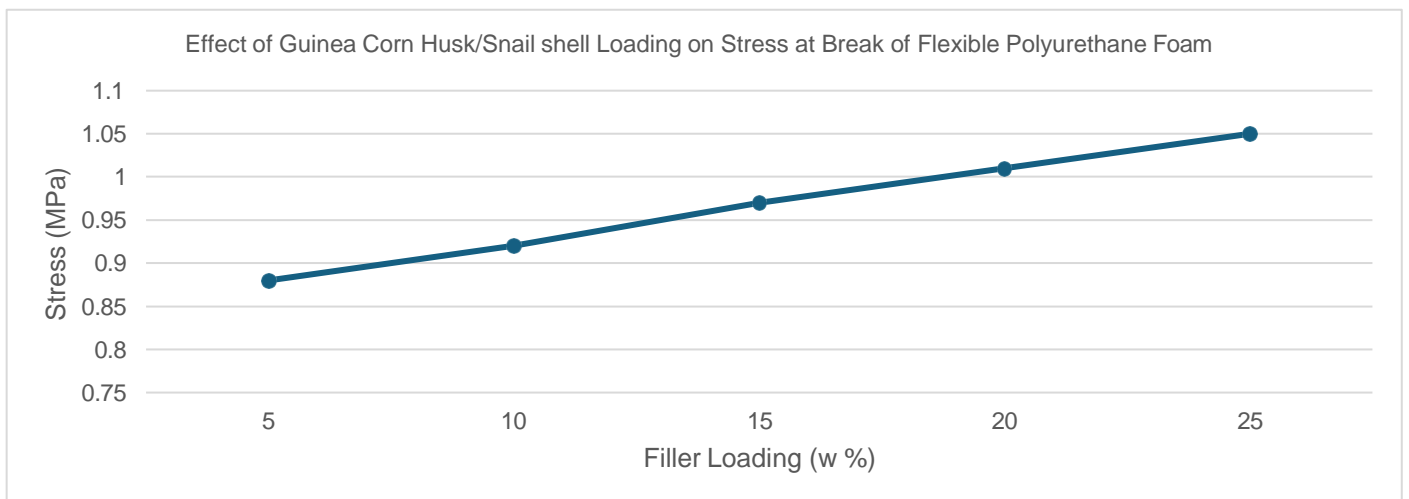


Fig 3. Influence of Filler Content on Stress Resistance of Guinea Corn Husk/Snail Shell–Reinforced Foams

The fillers enhance the polymer network by restricting local chain mobility and promoting efficient stress transfer throughout the cellular structure (3, 12, 17). The combined action of lignocellulosic fibers and calcium-rich mineral particles reinforces the foam skeleton, mitigates microvoid formation, and increases energy absorption prior to rupture. Microstructural observations indicate denser cell walls and more uniform cells, delaying the onset of structural failure. In comparison with other bio-filled polyurethane foams, the current formulation exhibits superior load-bearing capacity at equivalent filler contents (7, 16, 26). This mechanical robustness ensures that the foams can withstand repeated compressive and tensile stresses during handling, transport, and seedling support, providing reliable dimensional stability for nursery operations.

Strain at Break

Strain at break measures the extent of deformation a material undergoes before failure and is an indicator of ductility and flexibility.

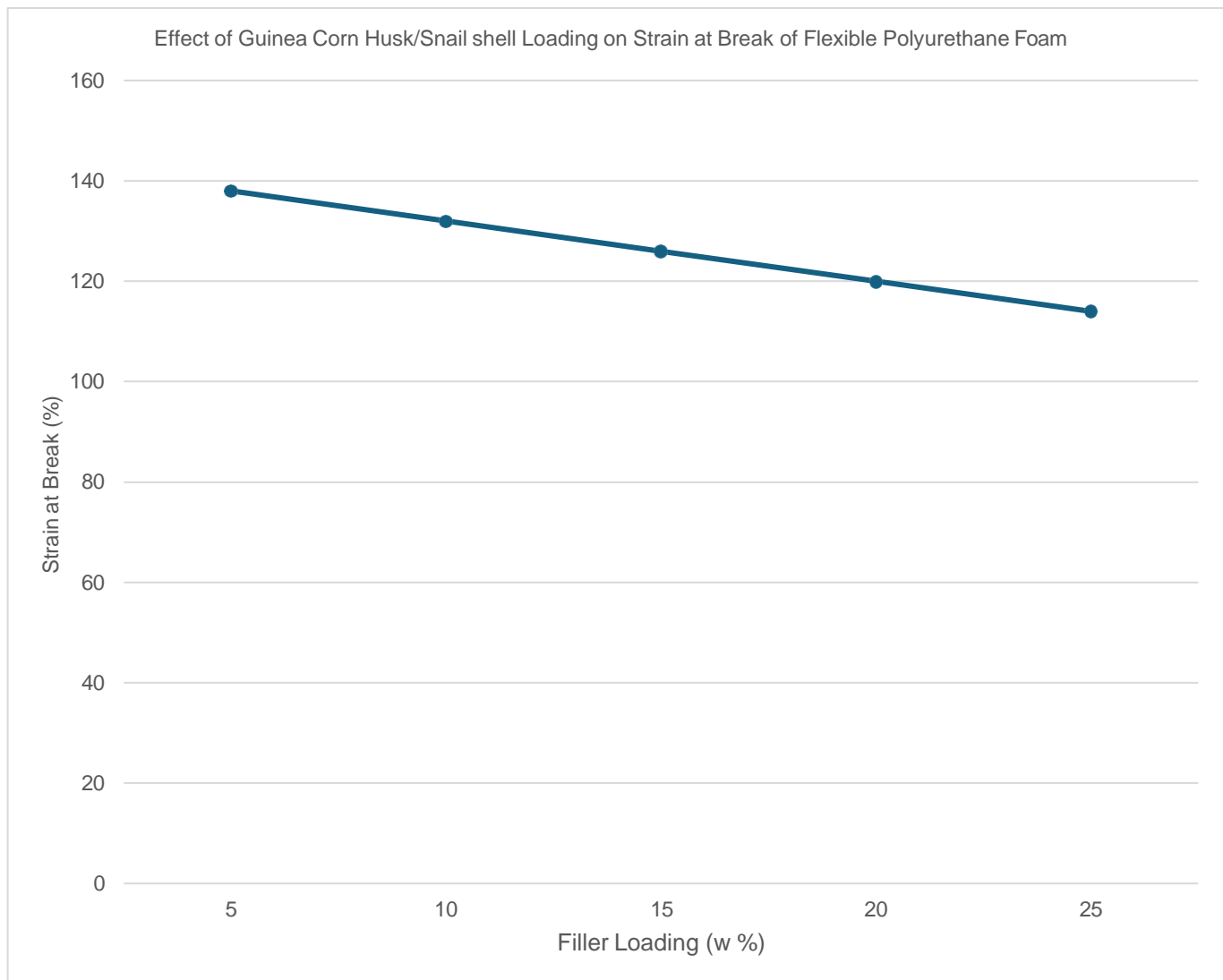


Fig 4. Influence of Filler Content on Strain Resistance of Guinea Corn Husk/Snail Shell–Reinforced Foams

As illustrated in Figure 4, strain at break decreased consistently as filler loading increased. This inverse relationship is typical of particle-reinforced composites, where rigid fillers restrict polymer chain mobility and reduce elongation capability. Although reduced ductility may indicate increased brittleness, moderate flexibility remains adequate for nursery applications where excessive stretching is not required. The observed

decrease suggests a transition toward a stiffer foam structure capable of maintaining shape under load, which is beneficial for stable seedling support and dimensional retention.

Flexural Strength

Flexural strength reflects the ability of the foam to resist deformation under bending loads. According to Figure 5.

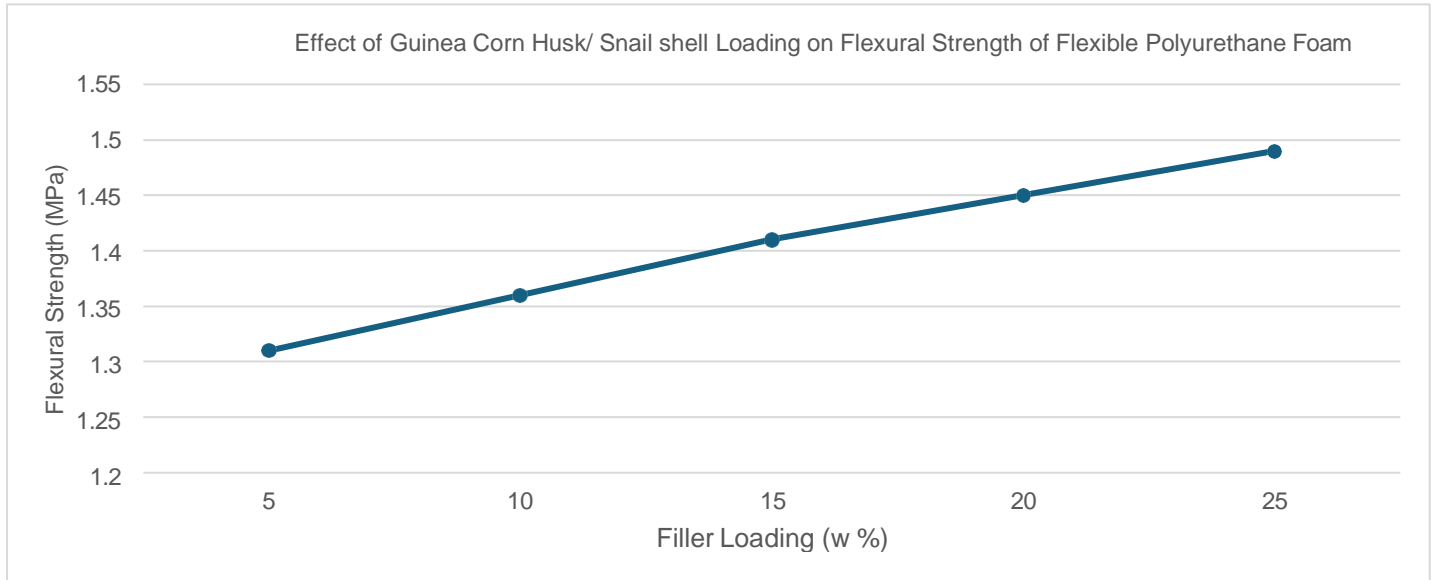


Fig 5. Flexural Strength as a Function of Filler Loading in Guinea Corn Husk/Snail Shell–Reinforced Foams

Flexural strength increased steadily with rising filler content, indicating enhanced stiffness and resistance to bending (2, 16, 19). The observed improvements align with trends reported in other lignocellulosic and mineral-reinforced polyurethane foams, where natural fibers or hybrid fillers improved load distribution across cell walls and minimized early bending failure (7, 13, 23). Compared to previous studies, the foams in this work achieved slightly higher flexural strength at similar filler loadings, suggesting effective synergy between the fibrous and mineral components in reinforcing the polymer network (5, 25, 28). This reinforcement ensures reliable support for seedling trays during handling, placement, and transport, combining rigidity with sufficient cushioning for delicate roots..

Hardness

Hardness measures resistance to surface indentation and provides insight into the firmness of the foam.

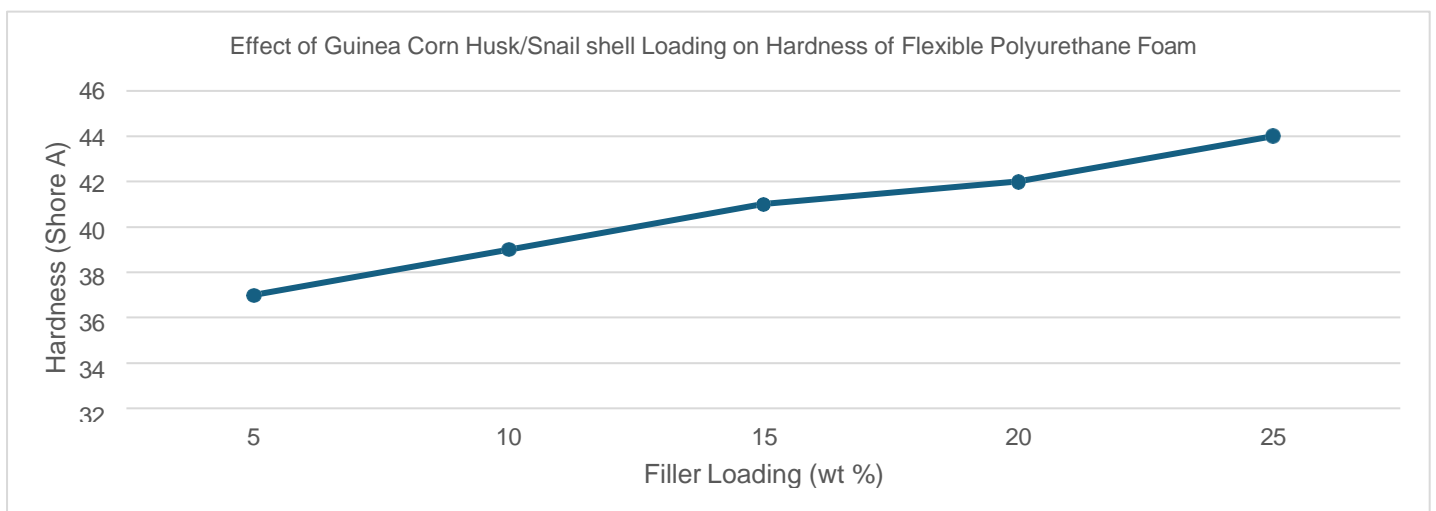


Fig 6. Hardness Enhancement with Increasing Filler Content in Guinea Corn Husk/Snail Shell–Reinforced Foams

Hardness increased steadily with rising filler content, indicating progressive reinforcement of the polymer matrix (1, 7, 16). The combined action of rigid and fibrous components limits cellular wall deformation, producing a firmer structure capable of sustaining repeated handling. This trend is consistent with other bio- and mineral-filled foams, which also exhibit enhanced surface resistance and dimensional stability under similar reinforcement strategies (3, 5, 25). Importantly, values remain within the typical range for flexible polyurethane foams, ensuring sufficient compliance to cushion seedlings while maintaining adequate structural support for nursery operations (13, 23).

Compressive Strength

Compressive strength indicates the ability of the foam to withstand compressive loads without structural collapse, a critical property for cushioning and load-bearing applications. As shown in Figure 7.

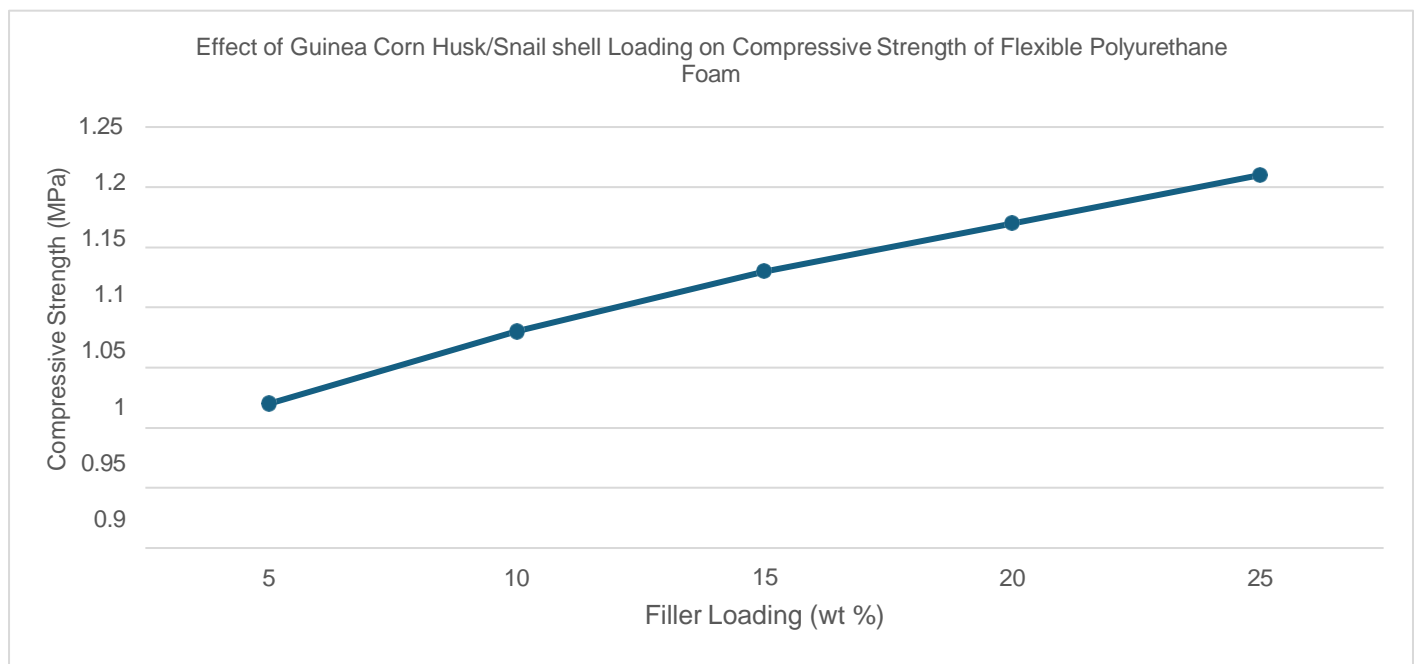


Fig 7. Compressive Strength Enhancement with Increasing Filler Content in Guinea Corn Husk/Snail Shell-Reinforced Foams

The compressive strength increased progressively with filler loading, demonstrating effective reinforcement of the polymer skeleton (10, 16, 26). Compared to bio-filled foams using only lignocellulosic fillers, the hybrid system exhibited higher compressive strength at equivalent loadings, likely due to the additional rigidity provided by calcium carbonate in snail shells. Previous study have also shown that mineral-organic hybrid fillers improve resistance to cell wall buckling and densification, consistent with our findings (16). This enhanced load-bearing capacity is particularly advantageous in nursery applications, where seed trays are subjected to static and dynamic stresses during handling and transport, suggesting that hybrid fillers can outperform single-component bio-fillers in maintaining both structural integrity and cushioning performance (10, 17).

Scanning Electron Microscopy (SEM) Analysis of Foam Cell Morphology

Scanning electron microscopy (SEM) analysis reveals that increasing guinea corn husk/snail shell hybrid filler loading progressively alters the cellular morphology of the flexible polyurethane foam. The control sample (0% filler) exhibits a typical open-cell structure with large, uniform, thin-walled cells indicative of unrestricted bubble growth and low density. At low loading (5%), the dispersed particles act as nucleation sites, producing slightly smaller, more uniform cells with marginally thicker walls, suggesting improved structural stability. At intermediate loading (15%), the foam displays a denser microstructure with significantly reduced cell size and

thicker struts due to increased system viscosity and restricted bubble expansion, corresponding to enhanced mechanical strength. Higher loadings (20–25%) result in pronounced structural irregularities, including distorted and partially collapsed cells, thick cell walls, and reduced openness, likely caused by excessive viscosity, hindered gas diffusion, and particle agglomeration. Overall, the micrographs indicate a transition from a uniform, highly elastic structure to a compact, rigid, and heterogeneous morphology as filler content increases, confirming that moderate filler levels improve structural reinforcement while excessive loading compromises cell integrity and flexibility.

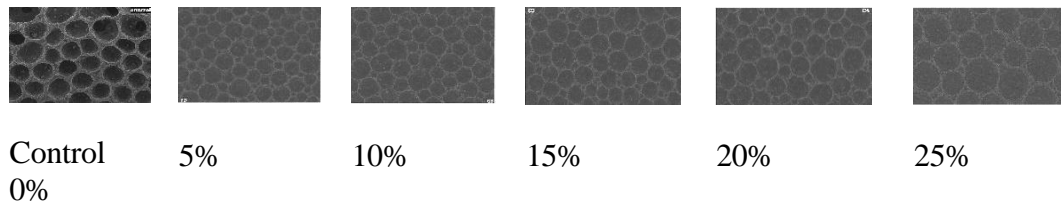


Fig 8. Microstructural Morphology of Guinea Corn Husk/Snail Shell–Reinforced Polyurethane Foams at Varying Filler Loadings

Biodegradability test

Biodegradability refers to the ability of a material to be broken down by microbial or enzymatic action, typically monitored through progressive mass loss over time, as illustrated below for the guinea corn husk/snail shell foam

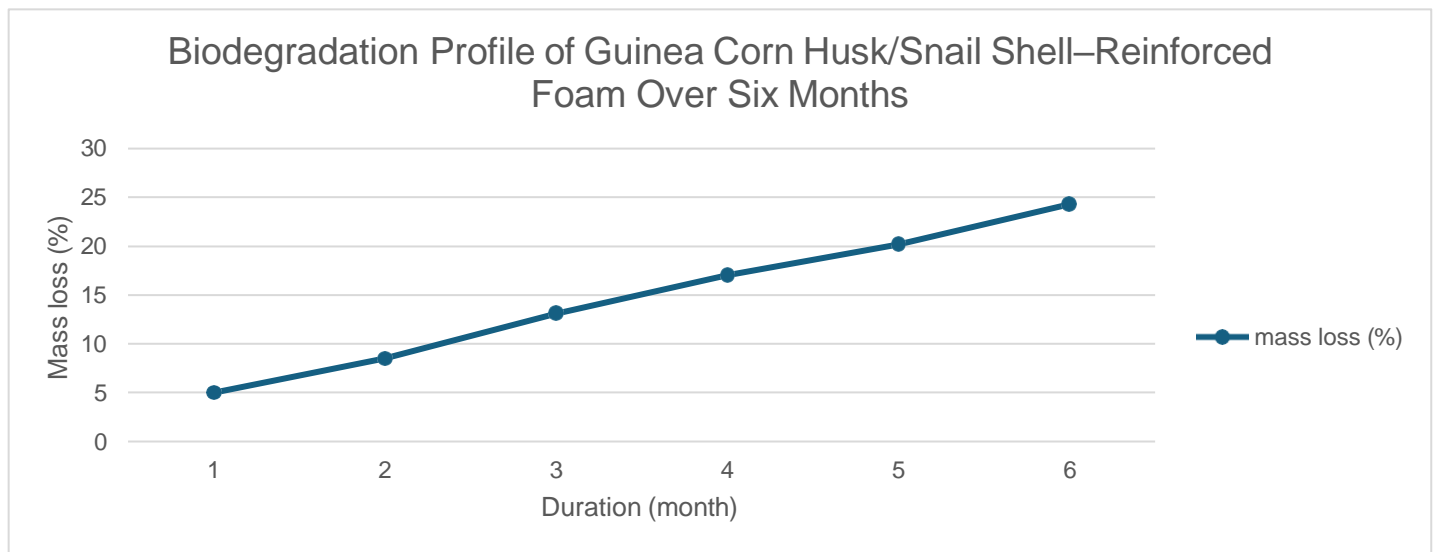


Fig 9. Biodegradation of Guinea Corn Husk/Snail Shell–Reinforced Foam (Group C) over six months under soil burial conditions. Data represent mean ± standard deviation of three replicates (n = 3)

The biodegradability of the Guinea Corn Husk/Snail Shell–reinforced foam was assessed via a six-month soil burial test under ambient conditions (25 ± 2 °C, 60 ± 5% relative humidity). Progressive mass loss was observed, with initial surface roughening and slight discoloration during months 1–2, followed by cracking, darkening, and increased brittleness in months 3–4. By month 6, extensive fragmentation occurred, culminating in 24.3 % mass loss. These results indicate that the hybrid filler enhances microbial-mediated degradation by introducing hydrophilic sites for water absorption and microbial activity, while retaining sufficient structural integrity for nursery applications [2,29].

CONCLUSION

The incorporation of Guinea Corn Husk/Snail Shell hybrid fillers into flexible polyurethane foams significantly influenced both physical and mechanical properties. Filler loading increased rise time, cure time, and apparent density, reflecting slower foam expansion and reinforced cellular architecture. Mechanical

performance, including tensile, compressive, flexural strength, and hardness, improved progressively with filler content, demonstrating effective load distribution and enhanced structural integrity, consistent with trends reported in similar bio-filled foams [10,17,26,28]. Soil burial tests revealed accelerated biodegradation, with 24.3 % mass loss after six months, highlighting the hybrid filler's role in promoting microbial accessibility and eco-compatibility while maintaining functional stability for nursery applications. Overall, these findings confirm that hybrid agro-waste and mineral fillers provide a balanced strategy for producing mechanically robust, environmentally responsive polyurethane foams suitable for sustainable horticultural use.

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