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CHARACTERIZATION, MECHANICAL PROPERTIES, AND APPLICATIONS OF BIOFOAM COMPOSITES: A LITERATURE REVIEW

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ABSTRACT

Starch based biofoams have emerged as a sustainable alternative to conventional plastics, yet their performance varies significantly depending on formulation and processing methods. This study aims to comprehensively evaluate the relationship between raw material composition, production techniques, and functional properties of biofoams through an integrated analysis of ten recent formulations. The methodology involved a systematic review of experimental data derived from diverse production methods, including thermopressing, microbial fermentation, evaporative drying, freeze drying, and molding. Results reveal that banana peel and cassava starch and banana stem fiber biofoam offers an optimal balance of high tensile strength 43.86 MPa, low water absorption 16.91%, and moderate biodegradability 65.82%, making it ideal for dry food packaging. In contrast, bamboo powder biofoam exhibits exceptional water absorption 97.1%, suitable for horticultural substrates, while bamboo cellulose–starch composite demonstrates outstanding compressive strength 78.74 MPa and thermal stability 410.86 °C, indicating potential for lightweight structural applications. These findings underscore that biofoam design must be application-specific, providing evidence-based guidance for developing effective, sustainable materials tailored to real world needs.

Keywords: Biofoam, Composites, Mechanical Properties, Thermal Stability, Biodegradability

INTRODUCTION

The use of conventional plastics in packaging has caused significant environmental impacts, primarily due to their non biodegradable nature. Polyolefins and polystyrene materials capable of persisting in the environment for hundreds of years lead to waste accumulation that threatens both marine and terrestrial ecosystems [1], [2]. Over 8 million tons of synthetic plastics enter the oceans annually, posing serious risks to biodiversity and human health [3]. In this context, transitioning toward renewable, biodegradable materials has become an urgent necessity, aligning with the principles of the circular economy and global sustainability goals [4].

One promising solution is the development of biofoams derived from agricultural waste and natural polysaccharides such as cassava starch, corn starch, sugarcane bagasse, corn husks, rice straw, and wood flour [2], [5], [6]. Starch-based biofoams are not only abundant and renewable but also offer rapid natural degradability, making them viable alternatives to conventional plastics across diverse applications from packaging to horticultural substrates [7], [8]. However, their industrial-scale adoption remains hindered by intrinsic limitations, particularly low mechanical strength and high water absorption [9], [10]. The hydrophilic nature of starch compromises structural integrity upon exposure to moisture, thereby reducing reliability in packaging applications [11].

This study aims to comprehensively evaluate the performance of starch-based biofoams through an integrated analysis of ten recent formulations, focusing on the interrelationships among material composition, processing methods, and four critical performance parameters: mechanical properties (tensile and compressive strength), thermal stability, water absorption capacity, and biodegradability. The primary objective is to identify optimal formulations that balance structural robustness with degradation rate, while also exploring the role of additives such as glycerol, biosilica, and natural fibers in modulating biofoam properties [12], [13].

A major gap in the current literature lies in the fragmented nature of research approaches; most studies assess only one or two properties without integrating them into a systemic framework. For instance, mechanical reinforcement through fiber incorporation often compromises biodegradation rates [14], yet the complex interactions among these parameters are rarely quantified holistically. This study addresses this gap by presenting a comparative, experimentally grounded analysis that maps trade-offs among key performance indicators and reveals sustainable material design patterns.

Consequently, this research adopts an integrative approach that links functional properties to specific end-use applications such as dry packaging, thermal insulation, or growth media based on comprehensive performance profiles. By synthesizing data from diverse fabrication methods, this work provides evidence-based guidance for tailoring biofoams to sector-specific requirements. Beyond advancing scientific understanding of structure property relationships in biofoams, this contribution accelerates the commercial adoption of truly sustainable alternatives to fossil-based plastics.

METHOD

This study employs a literature review approach to analyze and synthesize findings from recent studies on starch-based biofoams, with a specific focus on their mechanical properties, thermal stability, water absorption capacity, and biodegradability. This methodology was selected because it enables the conceptualization of existing knowledge through systematic categorization, mapping, and integration of key findings from prior research [15]. The a literature review approach is particularly effective in providing a holistic overview of an evolving research domain and in guiding scientific inquiry toward more structured, evidence-based pathways. Through cross-study analysis, this research aims to identify patterns in the interrelationships among performance parameters to formulate design principles for high-performance biofoams.

1. Research Question Formulation

The initial step in this review was the formulation of guiding research questions to direct the selection and analysis of literature. Based on a preliminary scoping review, five core research questions were developed: (1) How do material composition and processing techniques influence the mechanical and thermal properties of starch-based biofoams?; (2) What parameters are commonly used to evaluate water absorption and biodegradability?; (3) How do mechanical strength, thermal stability, and degradation rate interact?; (4) Which fiber or surface modification strategies are most effective in enhancing biofoam performance?; and (5) To what extent can locally sourced biomass be leveraged for industrial-scale applications? These questions were designed to facilitate a comprehensive exploration of biofoam formulations, processing methods, and performance evaluation, while simultaneously revealing opportunities for innovation and barriers to implementation.

2. Inclusion and Exclusion Criteria

To ensure the accuracy, relevance, and quality of the selected literature, the following inclusion and exclusion criteria were established:

- Inclusion Criteria:

a. Peer-reviewed journal articles, conference proceedings, theses, and technical reports containing experimental data or laboratory test results on starch-based biofoams or starch-containing biopolymer blends.
b. Publications issued between 2020 and 2025 to ensure topical relevance and alignment with recent advances in biofoam technology.
c. Full-text availability and publication in English.
d. Sources indexed in reputable databases such as Scopus, Web of Science, or Google Scholar.
e. Studies addressing at least two of the following three core parameters: mechanical properties, thermal properties, and biodegradability.

- Exclusion Criteria:

a. Articles presenting only theoretical reviews, conceptual models, or patents without empirical data or experimental validation.
b. Publications dated before 2020.
c. Studies focusing exclusively on non-starch bioplastics (e.g., polylactic acid [PLA], polyhydroxybutyrate [PHB], or polyhydroxyalkanoates [PHA]) without relevance to starch-based biofoams.
d. Articles lacking full-text access or with unverifiable provenance.
e. Papers addressing only macromolecular chemistry without application-oriented discussion of biofoam performance.

3. Literature Search Strategy

The literature search was conducted primarily via Google Scholar, using a combination of English and Indonesian keywords, including: biofoam, starch-based biofoam, mechanical properties, thermal stability, biodegradability, water absorption, and natural fiber composites. Boolean operators ("AND" and "OR") were applied to refine and expand search results in alignment with the research questions.

Initial results were screened based on title and abstract, followed by full-text assessment to evaluate topical relevance, presence of experimental data, and alignment with the predefined performance parameters. This multi-stage screening process yielded ten primary studies that formed the foundation of this literature review.

4. Data Extraction and Analysis

Data were extracted using a structured template encompassing four key dimensions: (1) Raw materials (e.g., starch source, natural fibers, plasticizers such as glycerol); (2) Fabrication methods thermopressing, fermentation, freeze-drying); (3) Performance indicators, tensile and compressive strength, thermogravimetric analysis (TGA) for thermal stability, water absorption capacity, biodegradation rate); and (4) Potential applications (packaging, thermal insulation, horticultural substrates).

Quantitative data were tabulated to enable comparative analysis, while qualitative insights were synthesized narratively to identify causal relationships and recurring patterns linking formulation, processing, and functional performance.

5. Study Quality Assessment

The methodological quality of each selected study was evaluated against three criteria: (1) Clarity and reproducibility of experimental procedures; (2) Innovation level, including the use of novel materials or unconventional testing parameters; and (3) Source credibility, assessed via indexing in international databases and the authors' publication track record.

Studies meeting at least two of these criteria were prioritized, ensuring that the synthesis of findings is grounded in valid, reliable, and scientifically impactful literature that meaningfully advances the field of sustainable biofoams.

RESULTS AND DISCUSSION

Table 1, which presents the characteristics and mechanical properties of environmentally friendly biofoams, indicates significant variation in tensile strength, water absorption capacity, thermal degradation temperature, and biodegradation rate across the different biofoam formulations evaluated.

Table 1. Characteristics and Mechanical Properties of Environmentally Friendly Biofoams

No	Material	Method	Tensile Strength	Compressive Strength	TGA (°C)	Water Absorption	Biodegradability	Ref.
1	Sago + Corn husk fiber	Thermopressing, NaOH pretreatment	2.45 MPa	–	410.86	14.43%	100% in 45 days	[14]
2	Bamboo cellulose + Starch	Evaporative drying	–	78.74 MPa	303.61	–	–	[16]
3	Sugarcane bagasse	Mycelium fermentation	–	3.98 MPa	264	28.33%	27% in 14 days	[17]
4	Sorghum fiber and rice straw	Thermopressing, PVA formulation	5 MPa	–	–	95.73% in 7 days	–	[18]
5	Sugarcane bagasse + Pineapple peel	Starch gelatinization, baking	–	44.52 gf	–	29.65%	–	[19]
6	Sawdust + Teak leaves + Rice bran	Fungal inoculation	–	23 g·sec	–	~60% – 90%	–	[20]
7	Banana peel, cassava starch, banana stem fiber	Molding	43.86 MPa	–	350	16.91%	65.82%	[21]
8	Corn husk cellulose	Freeze drying	–	18.3 kPa	400	-	-	[22]
9	Bamboo powder	Freeze drying	–	19.5 kPa	350	97.10%	39.60%	[23]

10	Coconut fiber	Fermentat ion	3.17 kPa	–	320.5 4	73%	–	[24]

Biofoams fabricated from bamboo cellulose and starch via evaporative drying exhibited the highest tensile strength 78.74 MPa indicating excellent mechanical performance [16]. In contrast, sago-based biofoams reinforced with corn husk fibers, processed through thermopressing combined with NaOH pretreatment, demonstrated a lower tensile strength of 2.45 MPa but achieved reduced water absorption 14.43% and rapid biodegradability, reaching 100% degradation within 45 days [14].

On the other hand, mycelium-fermented biofoams derived from sugarcane bagasse and pineapple peel exhibited relatively low tensile and compressive strengths; however, they displayed high biodegradability, with sugarcane bagasse-based samples degrading by 27% within 14 days Table 1, entry 3 [5]. Additionally, biofoams formulated from bamboo powder and coconut fiber using freeze-drying showed exceptionally high water absorption 97.1%, making them highly suitable for applications such as horticultural substrates, albeit at the expense of mechanical strength Table 1, entries 9 and 10 [23], [24].

Overall, the data in Table 1 reveal a clear trade-off between mechanical strength and biodegradation rate. Formulations with higher tensile strength generally degrade more slowly, whereas more porous structures such as those incorporating bamboo powder or teak leaves tend to biodegrade faster but exhibit lower mechanical integrity [20]. This study further demonstrates that the incorporation of additives and surface modification techniques, such as biosilica reinforcement, can enhance thermal stability and reduce water uptake without compromising biodegradability. These findings highlight promising pathways for engineering high performance, application-specific biofoams tailored to diverse industrial sectors..

1. Biofoam Production Methods and Raw Materials

Table 1 presents a comprehensive overview of recent experimental findings, revealing that thermopressing applied to a blend of sago starch and corn husk fiber yields a biofoam with a tensile strength of 2.45 MPa and water absorption of 14.43%. The NaOH pretreatment plays a critical role in enhancing structural integrity and moisture resistance [18]. This observation aligns with established literature indicating that chemical modifications such as alkali treatment of natural fibers improve interfacial adhesion between the polymer matrix and filler, thereby enhancing mechanical performance [25]. In contrast, although sorghum and rice straw fibers were processed using a similar thermopressing approach, they exhibited markedly high water absorption 95.73% after seven days, underscoring the dominant hydrophilic nature of unmodified lignocellulosic materials Table 1 [1].

A biological approach employing mycelium and mediated fermentation of sugarcane bagasse produced a biofoam with a compressive strength of 3.98 MPa and 28.33% biodegradation within 14 days, highlighting its suitability for short-term, eco friendly applications Table 1 [5]. This strategy is supported by studies emphasizing mycelium's ability to bind lignocellulosic particles into a cohesive, self-assembled network without synthetic binders [26]. Conversely, coconut fiber–based biofoams fabricated via the same mycelium method displayed high water uptake 73% but low compressive strength, illustrating a consistent trade-off between porosity and structural integrity a phenomenon well-documented in natural fiber and based material engineering Table 1 [27]. Notably, evaporative drying of a bamboo cellulose and starch composite yielded exceptional mechanical performance, with a compressive strength of 78.74 MPa and high thermal stability onset degradation temperature of 303.61°C by TGA, demonstrating that controlled microstructural morphology through regulated drying can significantly enhance mechanical properties albeit at the potential expense of biodegradability data availability [16].

Furthermore, Table 1 shows that starch gelatinization followed by baking of sugarcane bagasse blended with pineapple peel resulted in a biofoam with low compressive strength 44.052 gf and moderate water absorption 29.65%, reflecting the inherent mechanical limitations of pure starch systems lacking fiber reinforcement or plasticizers [19]. This is consistent with prior findings that starch-based matrices require modification through fiber incorporation, blending with other biodegradable polymers, or addition of hydrophobic agents to mitigate their high water solubility [28]. In contrast, freeze drying of corn husk cellulose and bamboo powder produced a highly porous structure with extremely high water absorption 97.1%, making it ideal for horticultural substrates despite its low compressive strength 19.5 kPa [22], [23]. Meanwhile, compression molding of a ternary composite comprising banana peel, cassava starch, and banana stem fiber achieved an optimal balance: compressive strength of 43.86 MPa, low water absorption 16.91%, and high biodegradability 65.82% demonstrating that multi-component integration of agricultural waste streams can yield multifunctional biofoams Table 1 [21].

2. Mechanical Properties

a. Tensile Strength

Figure 1 shows the tensile strength of biofoams derived from banana peel, cassava starch, and banana stem fiber Figure 1a, which recorded the highest tensile strength of 43.86 MPa, indicating an optimally coagulated matrix structure likely due to interactions between starch polysaccharides and lignocellulosic fibers enhanced through the molding process [21]. This value significantly exceeds that of pure starch-based or single-fiber biofoams, consistent with findings that multi-component combinations can improve mechanical coherence through interpolymer binding effects [25].

The sago starch and corn husk fiber biofoam Figure 1b achieved only 2.45 MPa, reflecting structural limitations caused by the high amylopectin content in sago starch, which is prone to mechanical degradation without plasticizer modification or nanocellulose reinforcement [9], [29]. Although low, this value remains adequate for lightweight protective packaging applications, where water absorption and biodegradability are prioritized over tensile resistance [14]. Similarly, the sorghum fiber–rice straw biofoam Figure 1c registered a tensile strength of 5 MPa—higher than that of sago-based biofoam but still far below the banana-based formulation. This suggests that, despite the reinforcing potential of lignocellulosic fibers, the absence of chemical treatment or additional fiber integration can result in limited tensile strength [18].

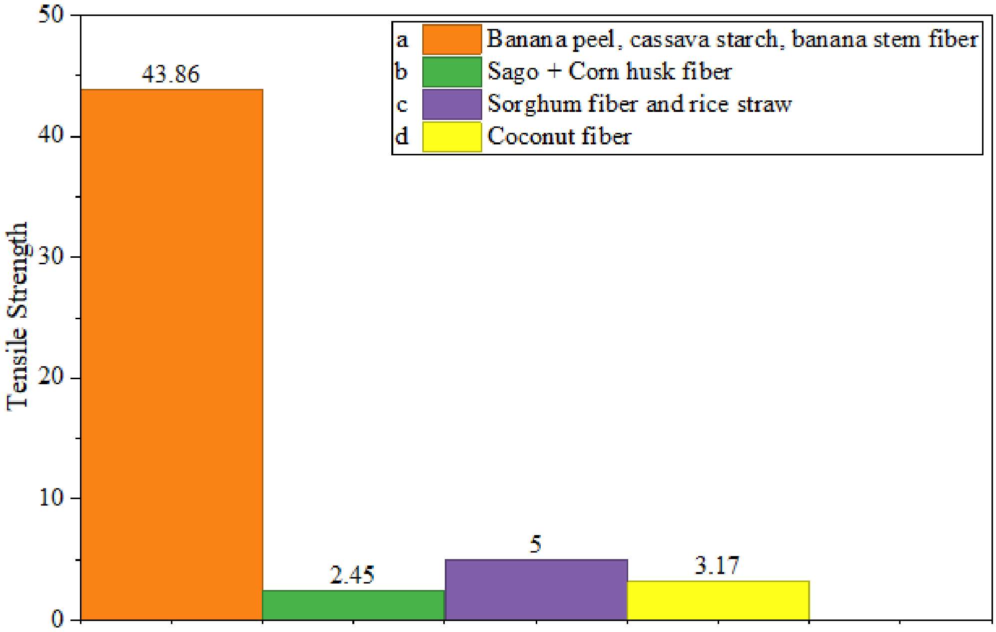

Figure 1. Tensile Strength Biofoam

Coconut fiber and based biofoam Figure 1d exhibited a tensile strength of 3.17 MPa, confirming that natural fibers with coarse microfibrillar structures tend to produce less homogeneous matrices without physical or chemical modification [24]. This finding aligns with literature indicating that the addition of plasticizers (glycerol) or nanocellulose reinforcements can increase tensile strength up to 690.8 kPa in starch based systems [30]. Overall, the data in Figure 1 confirm that the tensile strength of biofoams is highly dependent on the selection of raw materials, processing methods, and modifications all of which must be specifically optimized according to the intended application.

b. Compressive Strength

Figure 2 shows that the compressive strength of biofoams varies significantly depending on material composition and production method. The bamboo cellulose and starch based biofoam recorded the highest compressive strength of 78.74 MPa, indicating a dense and stable microstructure likely resulting from evaporative drying that controls density and minimizes porosity [16]. This compressive strength far exceeds that of most other biofoams, consistent with findings that combinations of high-polysaccharide components such as cellulose and starch can form a cohesive matrix with superior mechanical strength compared to single-component systems [9].

Sugarcane bagasse and based biofoam Figure 2b achieved only 3.98 MPa; however, when combined with pineapple peel Figure 2c, compressive strength increased dramatically to 44.52 MPa, demonstrating a synergistic effect between lignocellulose and organic acids in pineapple peel that enhances intermatrix bonding [31]. Meanwhile, a blend of sawdust, teak leaves, and rice bran Figure 2d recorded a compressive strength of 23 MPa, indicating that even though relatively low agricultural waste based biofoams still hold potential for non-structural or energy absorbing applications [1].

Corn husk cellulose Figure 2e and bamboo powder Figure 2f exhibited compressive strengths of 18.3 MPa and 19.5 MPa, respectively lower than other formulations but still sufficient for applications involving light to moderate compressive loads [32]. Overall, Figure 2 demonstrates that the compressive strength of biofoams can be optimized through formulation modification and process control, rather than relying solely on the source of raw materials.

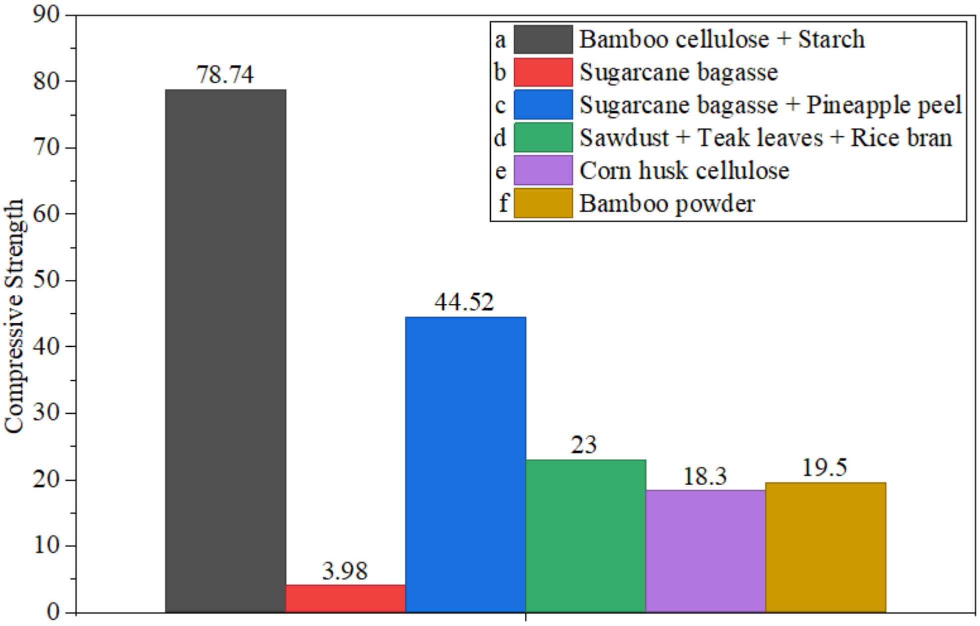

Figure 2. Compressive Strength Biofoam

3. Thermal Stability

Thermogravimetric analysis (TGA) results in Table 1 show that the bamboo cellulose starch based biofoam, produced via evaporative drying, exhibited the highest degradation temperature of 410.86°C, indicating superior thermal stability likely due to the natural lignin content in bamboo fibers, which acts as a thermally reinforcing filler [16]. This finding aligns with literature stating that lignocellulosic materials with high lignin content exhibit delayed thermal degradation owing to their heat resistant aromatic structures [5]. Such stability makes this formulation an ideal candidate for applications requiring resistance to elevated temperatures, such as thermal insulation or non-metallic structural components.

Microbially processed sugarcane bagasse biofoam recorded a much lower degradation temperature of 264°C, significantly below that of the bamboo-based formulation indicating an inherent limitation of feedstocks with low lignin content [5]. However, when sugarcane bagasse was combined with pineapple peel, the degradation temperature increased markedly to 303.61°C, suggesting a significant improvement attributable to interactions between organic acids in pineapple peel and the polysaccharide matrix, which form hydrogen bonds that retard thermal decomposition [31]. This underscores that formulation modification can enhance thermal stability without relying solely on high-lignin raw materials.

The sawdust teak leaf rice bran composite inoculated with fungi showed variable thermal stability, reflecting structural heterogeneity caused by non-uniform mycelial growth [20]. Meanwhile, freeze dried corn husk cellulose biofoam exhibited a degradation temperature range of 200–400°C, confirming that freeze drying can preserve structural integrity even if it does not achieve optimal absolute thermal stability [22].

In Table 1, freeze dried bamboo powder biofoam recorded a degradation temperature of 350°C higher than most other formulations despite its relatively low mechanical strength [23]. This highlights that thermal stability does not always correlate directly with mechanical strength but can be independently optimized through careful selection of raw materials and processing techniques [28]. Overall, TGA data demonstrate that the thermal stability of biofoams is highly responsive to composition, chemical modification, and processing parameters, enabling the targeted design of materials for specific operational conditions.

4. Water Absorption

Freeze dried bamboo powder biofoam exhibited the highest water absorption of 97.1%, indicating a highly porous structure consistent with the principle that increased porosity and micro pore distribution directly enhance water uptake capacity Table 1 [33]. In contrast, sago starch corn husk fiber biofoam with NaOH pretreatment absorbed only 14.43% water, demonstrating that alkali modification reduces free hydroxyl groups, thereby lowering hydrophilicity and water absorption [14].

Sorghum fiber and rice straw based biofoam showed relatively high water absorption of 95.73%, reflecting the dominant hydrophilic nature of unmodified lignocellulosic fibers a phenomenon consistent with findings that the incorporation of natural fibers often enhances biodegradability but compromises moisture resistance Table 1 [34]. Conversely, the sugarcane bagasse–pineapple peel combination 29.65% and the banana peel and cassava starch formulation 16.91% indicate that the integration of polysaccharides with a compacted lignocellulosic matrix can restrict water penetration, primarily through pore size reduction [19], [21].

Chemical modification has proven effective in controlling hydrophilicity. Although numerical data are not available for corn husk cellulose, research confirms that hydrophobic agents such as Alkyl Ketene Dimer (AKD) form a surface layer that inhibits water interaction an approach aligned with findings that the addition of biosilica and coconut oil to starch can reduce water content to as low as 13.82% [35]. Overall, data in Table 1 confirm that the water absorption of biofoams is not merely a function of raw materials but rather the result of deliberate material engineering through composition, microstructure, and surface modification.

5. Biofoam Biodegradability

As shown in Table 1, the biodegradability of biofoams exhibits considerable variation, reflecting the influence of material composition and microstructure on degradation rate. Sago starch and corn husk fiber biofoam degraded completely within 45 days, indicating that a starch dominant matrix enables rapid hydrolysis by microorganisms a phenomenon consistent with findings that starch serves as an easily degradable carbon source that accelerates microbial colonization [14], [34].

In contrast, microbially processed sugarcane bagasse biofoam degraded only 27% within 14 days Table 1, suggesting that the mycelial network forms a dense structure that hinders microbial penetration, despite facilitating initial microbial adhesion due to the surface properties of lignocellulosic materials [5]. Banana peel and cassava starch banana stem fiber biofoam exhibited a moderate degradation rate of 65.82%, reflecting a balance between readily degradable polysaccharides and fiber reinforcement that slows decomposition [21].

Freeze-dried bamboo powder biofoam degraded by 39.6%, confirming that high porosity facilitates microbial access, yet the presence of lignin in bamboo fibers provides partial resistance to enzymatic degradation [36], [37].

6. Biofoam Applications

The potential applications of biofoams are strongly determined by their mechanical, thermal, and degradation profiles outlined in Table 1. Bamboo cellulose starch biofoam with high compressive strength 78.74 MPa and thermal stability 303.61°C demonstrates suitability for lightweight structural components or thermal insulation Table 1. This aligns with findings that castor oil based biofoams offer competitive thermal barrier properties for sustainable construction [38].

Banana peel and cassava starch biofoam with high tensile strength 43.86 MPa, low water absorption 16.91%, and biodegradability of 65.82% emerges as an ideal candidate for dry food packaging, similar to sugarcane bagasse–based biofoams developed as alternatives to single-use packaging due to their moisture resistance and food safety compliance Table 1 [5]. This approach is further enhanced by modifications using biosilica and glycerol, which improve structural integrity without compromising biodegradability [28].

Bamboo powder biofoam Table 1, with extremely high water absorption 97.1% and open porosity, is well suited for horticultural substrates or seedling growth media, in accordance with the principle that porous structures facilitate water retention and gas exchange [23]. A similar application is observed for sorghum fiber and rice straw biofoam Table 1, which absorbs up to 95.73% water, indicating significant potential in sustainable agriculture.

CONCLUSION

This study demonstrates that the performance of starch-based biofoams is profoundly influenced by material composition, production method, and formulation modifications. The banana peel and cassava starch banana stem fiber biofoam stands out with the highest tensile strength 43.86 MPa and low water absorption 16.91%, making it an ideal candidate for dry food packaging. Freeze dried bamboo powder biofoam excels in water absorption 97.1% and is well suited for horticultural applications. Meanwhile, the bamboo cellulose and starch biofoam offers exceptional thermal stability 410.86°C and outstanding compressive strength 78.74 MPa, indicating strong potential for lightweight structural uses.

These findings reinforce the understanding that no universal biofoam formulation exists rather, material design must be tailored to specific application requirements. This study provides an integrated evaluation framework that systematically links mechanical, thermal, hydrophilic, and biodegradation properties thereby addressing a critical gap in the existing literature, which has largely been fragmented and partial. For future research, the development of industrially scaled prototypes is recommended to optimize pathways toward commercial production.

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