Sustainable Bamboo Fiber-Tannin Composite Foam: A Green Substrate for Vertical Greening Systems

Ju He,[a,#] Menghan Li,[b,#] Peiwen Zhao,[c] Fangying Li,[a,]* Kexin Lyu,[c] Jiuping Rao,[b,]* and Weigang Zhao [b,]*

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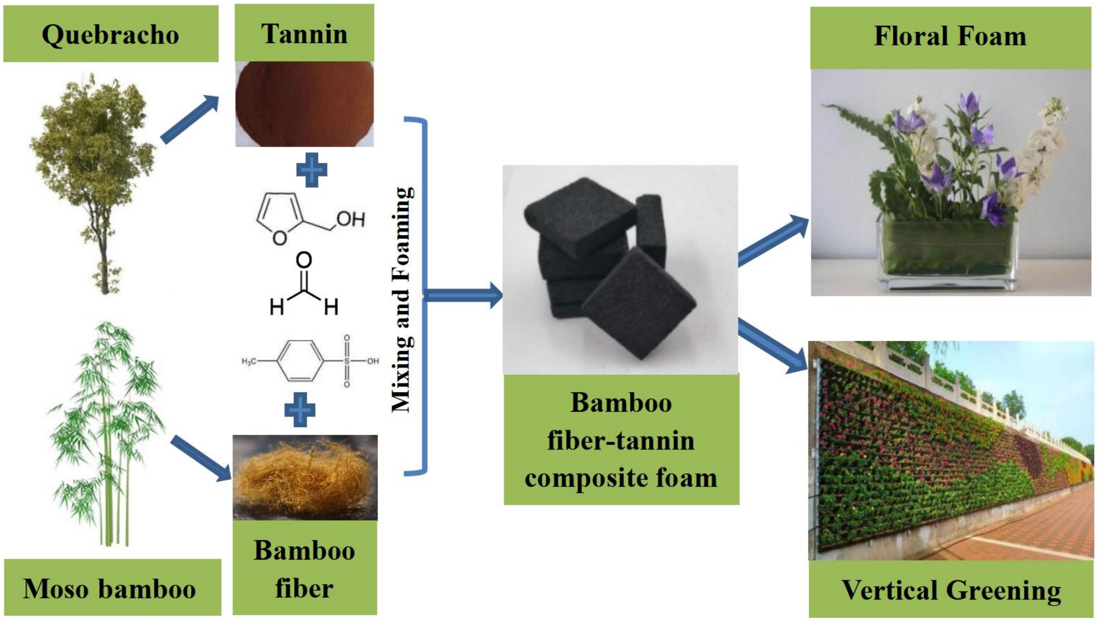
GRAPHICAL ABSTRACT



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Tannin-based biomass foam was prepared through a self-foaming process at room temperature. The material's density, porosity, microstructure, mechanical properties, thermal stability, limiting oxygen index (LOI), brittleness, as well as water absorption and retention properties, were studied. Adding 2% bamboo fibers in varying forms did not affect the uniformity of the foam cells. The density, porosity, thermal stability, and LOI of the foam material remained largely unchanged. The compressive strength of the unmodified tannin foam was 0.043 MPa, while the addition of 2% bamboo fibers increased the compressive strength by 72%. Even when the effect of density was excluded, the specific compressive strength was enhanced by 60%. Additionally, brittleness, measured as the slagging percentage, was significantly reduced from 16.12% to 4.78%. The modified foam could absorb up to 26.5% of its weight in water, with excellent water retention capabilities of 78.1% after 120 h while retaining its structural integrity under intermittent wetting conditions, making it suitable for vertical greening applications. This demonstrates its suitability for vertical greening applications, where moisture exposure is frequent. In conclusion, the bamboo fiber-reinforced tannin-based foam exhibits excellent mechanical properties and superior water absorption and retention performance.

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Keywords: Tannin foam; Bamboo fiber; Vertical greening; Density; Mechanical properties; Water absorption and retention

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INTRODUCTION

With the rapid acceleration of global urbanization and the intensification of climate change, urban ecological problems are becoming increasingly severe (Meng *et al.* 2021). Traditional urban greening methods struggle to meet the spatial constraints and ecological restoration needs of high-density urban environments. Vertical greening, an emerging urban greening technique, has garnered significant attention due to its ability to fully utilize vertical spaces, optimize the microenvironment on building surfaces, alleviate urban heat island effects, and improve air quality (Robinson *et al.* 2020). However, existing vertical greening substrate materials, such as traditional soil and phenolic foam, suffer from issues such as excessive weight, difficult installation and maintenance, and negative environmental impacts during production (Wang *et al.* 2022; Liu *et al.* 2024). Thus, there is an urgent need for lightweight, environmentally friendly, and sustainable alternative materials.

In recent years, the concepts of green building and sustainability have gained widespread traction, prompting a shift in building material research towards biomass-based materials that are abundant, environmentally friendly, and renewable (Addo-Bankas *et al.* 2021). While phenolic foam is a traditional lightweight substrate material with good water retention and aeration properties, its production involves the consumption of large amounts of non-renewable resources and the release of hazardous by-products (such as free phenol and formaldehyde), thus posing potential environmental risks. Additionally, phenolic foam is brittle, prone to chipping, and structurally weak (Zhao *et al.* 2015; Ebaid *et al.* 2023; Simonini *et al.* 2024). Consequently, the development of a novel substrate material that is lightweight, mechanically robust, water-retentive, aerated, and environmentally sustainable has become a critical area of research (Del Saz-Orozco *et al.* 2015; Wu *et al.* 2020; Sarika *et al.* 2021). In practical applications, the foam material may serve as either a standalone substrate for vertical greening or as part of a composite system supported by an underlying framework. For example, the foam could be integrated with a bamboo culm framework to provide additional structural support, especially in large-scale vertical wall arrangements. This flexibility allows the foam to adapt to various greening scenarios, with performance requirements such as lightweight structure, water retention, and mechanical strength playing a critical role in determining its suitability for standalone or supported applications (Wu *et al.* 2020).

Tannins, natural polyphenolic compounds widely found in plants, exhibit excellent antioxidant, antibacterial, and weather-resistant properties, making them an ideal biomass material. Tannins share a similar chemical structure with phenols and can be used as partial substitutes for phenolic compounds in foam production (Shirmohammadli *et al.* 2018; Wu *et al.* 2020; Hao *et al.* 2021). The advantages of tannin-based foams include a simple foaming process, mild foaming conditions, and the ability to cure spontaneously at room temperature. The foam preparation process relies on a combination of ingredients, each serving a distinct purpose. For instance, n-pentane acts as a physical blowing agent, expanding the foam structure through bubble formation during reaction-induced heating. Polysorbate 80, a nonionic surfactant, is used to stabilize the bubbles by reducing surface tension and preventing coalescence, thereby ensuring uniform cell structure. Other components, such as glyoxal and formaldehyde, function as crosslinking agents, while p-toluenesulfonic acid serves as an acidic curing agent to promote the polymerization of tannin and resin precursors. Together, these ingredients enable the controlled formation of a lightweight, porous foam with desirable mechanical and thermal properties (Simonini *et al.* 2024).

However, like phenolic foam, unmodified tannin foams also exhibit significant limitations, particularly in terms of mechanical strength and brittleness, which hinder their practical application. To address these mechanical shortcomings, researchers have attempted to introduce reinforcing agents (Li *et al.* 2013; Zhou *et al.* 2019; Wu *et al.* 2020; Sarika *et al.* 2024). Among the various reinforcing materials, natural plant fibers such as bamboo fibers have gained attention due to their light weight, high strength, excellent moisture absorption, and biodegradability (Zhou *et al.* 2019; Wu *et al.* 2020). In addition, the use of formaldehyde in foam preparation raises concerns due to its classification as a known carcinogen. However, once the foam has been cured, the formaldehyde is chemically bonded within the polymer matrix, significantly reducing its potential release during typical usage conditions unless under extreme conditions.

Bamboo fibers are readily available, easy to obtain, and possess outstanding specific strength and modulus, making them ideal for enhancing composite materials (Hsu and Young 2024). By combining bamboo fibers with tannin-based foam, the mechanical properties of the foam can be significantly improved, enhancing its structural stability and service life. The addition of bamboo fibers not only improves the compressive strength and brittleness of tannin-based foam but also enhances its water absorption and retention capabilities, which are critical for plant cultivation in vertical greening systems (Zhuo *et al.* 2020; Adil *et al.* 2024). Vertical greening systems require substrates that can supply adequate moisture for plant growth, as poor water retention can lead to plant dehydration and death. The porous structure of bamboo fibers increases the foam's water absorption capacity and allows for sustained water retention, thereby reducing the frequency of watering and lowering maintenance costs. Furthermore, the composite of bamboo fiber-reinforced tannin foam exhibits excellent environmental adaptability and thermal stability, maintaining stable physical properties under various climatic conditions. Studies have shown that the inclusion of bamboo fibers creates a uniform support network within the foam, reduces cell wall thickness, and increases porosity, further enhancing the material's thermal properties (Mougel *et al.* 2019; Chakkour *et al.* 2023). These improvements make bamboo fiber-reinforced tannin foam suitable not only for vertical greening applications but also for potential use in energy-saving insulation for buildings.

In summary, substrate material selection is crucial for the growth of plants in vertical greening systems. While traditional soil provides good water and nutrient retention, its weight increases the difficulty and cost of installation and maintenance. Although phenolic foam is lightweight, it suffers from environmental concerns and is prone to hydrolytic degradation in moist environments, limiting its longevity. In contrast, bamboo fiber-reinforced tannin foam offers advantages such as light weight, superior water retention, excellent aeration, and high mechanical strength and durability, effectively addressing the limitations of existing substrates in vertical greening systems. This study aimed to systematically investigate the preparation process and application potential of bamboo fiber-reinforced tannin foam as a lightweight, eco-friendly, and cost-effective substrate for urban vertical greening. The study first analyzes the effects of bamboo fibers in different forms (mesh sizes) on the density, porosity, mechanical properties, thermal stability, and water absorption and retention of tannin-based foams. It further explores the reinforcing effects of bamboo fibers on the foam's mechanical performance and water management capabilities. Finally, the study compares the water absorption and retention properties of bamboo fiber-reinforced tannin foam with traditional phenolic foam, validating its feasibility for vertical greening applications. The findings of this study demonstrate the broad potential for bamboo fiber-reinforced tannin foam in vertical greening systems, providing theoretical support for the development of lightweight, environmentally sustainable, and efficient biomass-based substrates and contributing to the advancement of urban green building and sustainable development.

EXPERIMENTAL

Reagents and Materials

The tannin used in this study was quebracho tannin with a condensed tannin content of 70% ± 2.0% and a moisture content of 4 to 5%, purchased from Xinhua China Co., Ltd. This quebracho tannin was sourced from the heartwood of *Schinopsis balansae*, known for their high condensed tannin content. Bamboo fibers were provided by Yong'an Forestry Group Co., Ltd., Fujian, China. The fibers were sieved using Taylor standard sieves into different length categories (150 to 200-mesh, 115 to 150-mesh, and 100 to 115-mesh), then dried to control their moisture content between 4.0 and 5.5%, and stored in a sealed dry container for later use. Furfural and n-pentane were purchased from Tianjin Guangfu Fine Chemical Research Institute, both of analytical grade. Diethyl ether (analytical grade) and formaldehyde solution (37%) were purchased from Shanghai Macklin Biochemical Co., Ltd. Glyoxal, polysorbate 80 (brand name Tween-80), and p-toluenesulfonic acid were obtained from China National Pharmaceutical Group, all of analytical grade.

Preparation of Bamboo Fiber-Reinforced Tannin Foam Substrate for Vertical Greening

The preparation process of the bamboo fiber-tannin composite foam (BTF) is illustrated in Fig. 1. First, the sieved bamboo fibers and powdered quebracho tannin were dried, then mixed thoroughly and placed into a foaming mold. A specific amount of furfural, 37% formaldehyde aqueous solution, polysorbate 80, and n-pentane were measured into a beaker and stirred until a uniform mixture was obtained. A 65% aqueous solution of p-toluenesulfonic acid was then added to the mixture, and the solution was manually stirred for 10 seconds before being poured into the foaming mold. After an additional 20 seconds of manual stirring, the mold was placed in a fume hood to allow the foam to cure at room temperature through spontaneous foaming. Approximately 2 min later, the foaming process was completed, forming a black foam material. The foam was then removed from the mold, and the surface layer (1 to 2 mm) is trimmed off. Three series of samples were prepared and named as BTF-x, where x represents the mesh size of the bamboo fibers (*e.g.*, BTF-150 to 200 indicates the addition of 2% bamboo fibers of 150 to 200-mesh). As a control, tannin foam without bamboo fibers (BTF-0) was prepared using the same procedure.

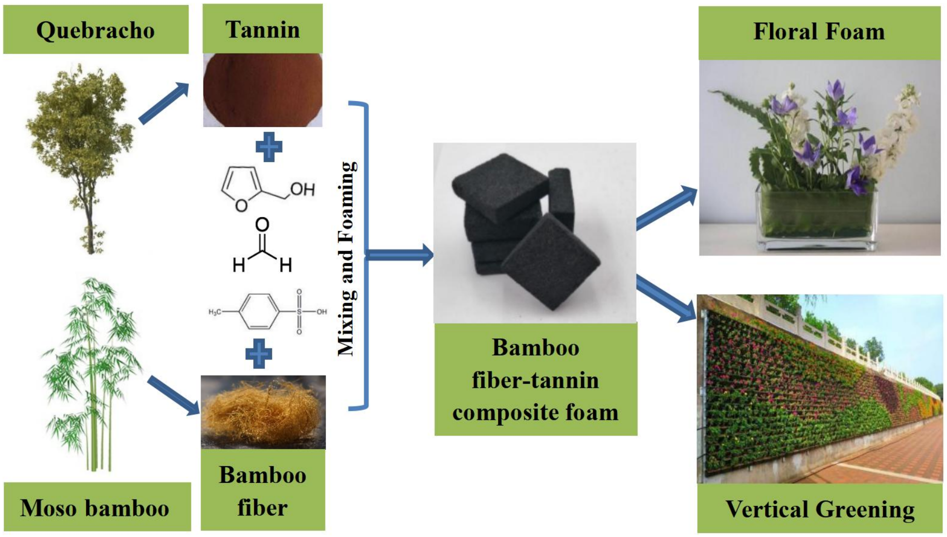

Fig. 1. Schematic diagram of the preparation process for bamboo fiber-tannin composite foam

The apparent density was calculated as the average of six samples, each with dimensions of 30 × 30 × 15 mm, prepared under the same conditions. The true density was determined as the average of five samples, each with dimensions of 30 × 30 × 30 mm, using a true density analyzer (JWGB Densi 100A, Best Instrument Technology Co., Ltd., Beijing). The porosity (Φ) was calculated using the formula $\Phi = (d_s - d) / d_s$, where d_s is the true density of the solid matter, and d is the apparent density of the porous material, allowing the porosity of the foam to be determined (Tondi *et al.* 2009). Fiber morphology was analyzed using a Morfi Compact fiber analyzer (Techpap, France). For each test, 0.03 g of bamboo fiber of varying lengths was weighed, dispersed in a small amount of water, and diluted to 1000 mL. The water temperature was maintained at room temperature throughout the test. Microscopic morphology was observed using a Hitachi S3400 FEG scanning electron microscope (SEM) with an acceleration voltage of 10 kV. The oxygen index of the samples was measured according to the method specified in GB/T 2406.1-2008/ISO 4589-1:1996. The samples had dimensions of 100 × 10 × 10 mm, with 15 samples prepared under the same conditions. The oxygen index values were calculated based on the measurements. Thermal stability was evaluated using a Q50 thermogravimetric analyzer (TGA, TA Instruments, USA) under a constant nitrogen flow and a heating rate of 10 °C/min. Thermal conductivity was measured using an HS-DR-5 transient plane source thermal conductivity analyzer (Shanghai Heson Instrument Technology Co., Ltd., China) under 50% humidity at 22 °C. Foam samples with dimensions of 30 × 30 × 15 mm were used, and the results represent the average of six samples. Compressive properties were tested according to the GB/T 8813-2008 standard. Samples with dimensions of 30 × 30 × 15 mm were tested using a 10 kN pressure sensor and a compression rate of 2 mm/min. During the test, deformation and load were continuously recorded to produce stress-strain curves. The compressive strength was calculated as the average of three samples, each prepared under the same conditions. Brittleness was assessed by the degree of pulverization following the method described in the national standard GB/T 12812-2006 and related literature (Wu *et al.* 2020). Sandpaper (36-grit, 0.5 mm particle size) was fixed on the foam surface, and a 200 g weight was placed on top. The foam was manually abraded 30 times, and the mass difference before and after abrasion was measured to calculate the slagging percentage. Foam sample dimensions were 50 × 50 × 50 mm, and the results represent the average of three samples. Water absorption performance was tested by cutting bamboo fiber-reinforced tannin foam samples into dimensions of 20 × 20 × 20 mm and recording their dry weight (W1). The samples were then fully immersed in water until saturation. At various time intervals, the samples were removed from the water, and excess surface water was gently wiped off to ensure accurate weight measurement. The samples were immediately weighed, and their saturated weight (W2) was recorded. Water absorption was calculated based on the weight difference before and after immersion. Water retention performance was tested by evaluating the foam’s ability to retain moisture over 72 h after saturation. The saturated samples were placed in an environment at room temperature to air dry naturally. The samples were weighed (W3) at regular intervals to record weight changes, allowing the water retention rate to be calculated. The residual pH was measured at room temperature in the solution extracted by wringing foam samples of 20 × 20 × 20 mm. These specimens had been previously hydrated by capillarity in deionised water during 60 min.

RESULTS AND DISCUSSION

Bamboo Fiber Morphology Analysis

The average length and diameter of bamboo fibers from different series were measured using a fiber analyzer. Three groups of bamboo fibers were selected for composite modification of the tannin foam, specifically fibers in the ranges of 150- to 200-mesh, 115- to 150-mesh, and 100- to 115-mesh. The fiber morphology analysis results are shown in Fig. 2.

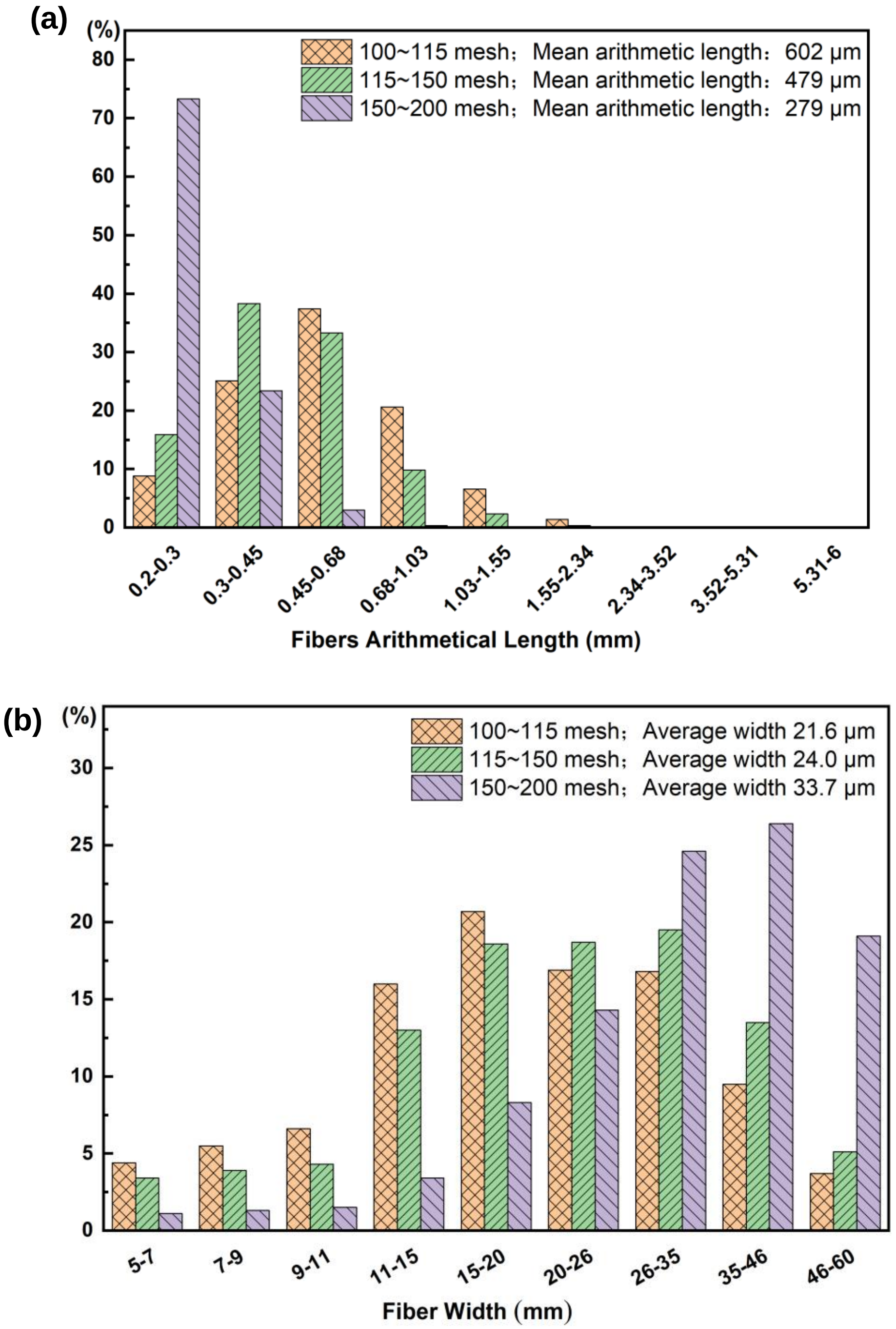

Fig. 2. Dispersion of different bamboo fibers in water: (a) microscopic fiber arithmetical length; (b) Width distribution

The results indicate that for 150- to 200-mesh bamboo fibers, the average length was 602 µm, with most fibers distributed in the 0.2 to 6 mm range. The average width was 21.6 µm, primarily distributed in the 5 to 60 µm range. For 115- to 150-mesh bamboo fibers, the average length was 479 µm, also primarily distributed between 0.2 and 6 mm, with an average width of 24 µm and a distribution range of 5 to 60 µm. In the case of 100 to 115-mesh bamboo fibers, the average length was 279 µm, mostly within the 0.2 to 6 mm range, with an average width of 33.7 µm, distributed between 5 and 60 µm. As expected, there were significant differences in the length and width of bamboo fibers obtained under different sieving conditions. The fiber length and width decreased as the-mesh size increased (Chen *et al.* 2022).

Apparent Density and Porosity

As a lightweight porous foam material, the density of bamboo fiber-tannin composite foam is one of the most critical physical properties influencing and determining its overall performance. According to the preparation mechanism of foam materials, the density of lightweight foams decreases with an increase in the amount of foaming agent and a reduction in the amount of curing agent. Therefore, the foaming agent and curing agent are the key factors in controlling the foam's density (Zhao *et al.* 2010; Wu *et al.* 2020). In this study, the content of the foaming agent and curing agent was kept constant while the effect of adding 2% bamboo fibers of different sizes on the density and porosity of the tannin-based foam was explored, as shown in Fig. 3.

The results indicate that the density of the tannin foam without bamboo fiber was 61.6 kg/m³. After adding 2% bamboo fibers of different sizes, the densities of BTF-100 to 115, BTF-115 to 150, and BTF-150 to 200 were 61.9, 62.5, and 66.3 kg/m³, respectively. The analysis suggests that the addition of bamboo fibers increased the foam's density due to the increase in the initial resin viscosity caused by the fibers (Zhou *et al.* 2019). As the bamboo fiber content was relatively small, the maximum density increase was only 7%, such that the resulting density was close to that of pure tannin-based foam. Further analysis of the foam's porosity revealed that the tannin-based foam had a porosity as high as 95.9%, and the porosity of the bamboo fiber-reinforced tannin foams also remained above 95% (Fig. 3).

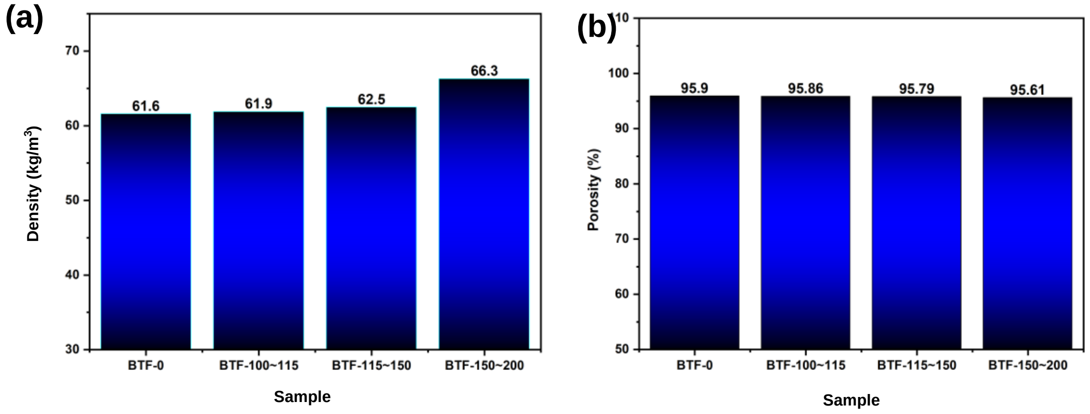

Fig. 3. The impact of different bamboo fibers on (a) density and (b) porosity of tannin-based foam

The high porosity and low density make this foam an ideal lightweight porous material with excellent water absorption, retention, and thermal insulation properties

(Ajabli *et al.* 2023). What's more, increased porosity is advantageous for vertical greening systems, as it promotes better water retention and air permeability within the substrate material. These properties ensure that plant roots have access to adequate moisture while maintaining sufficient aeration, preventing conditions that may lead to waterlogging or root rot. Furthermore, a highly porous structure facilitates nutrient transport and supports the development of robust root systems, both of which are essential for plant health in vertical configurations (Wu *et al.* 2020; Hsu and Young 2024).

Microstructural Analysis

The microstructures of the tannin-based foam and bamboo fiber-tannin composite foam are shown in Fig. 4.

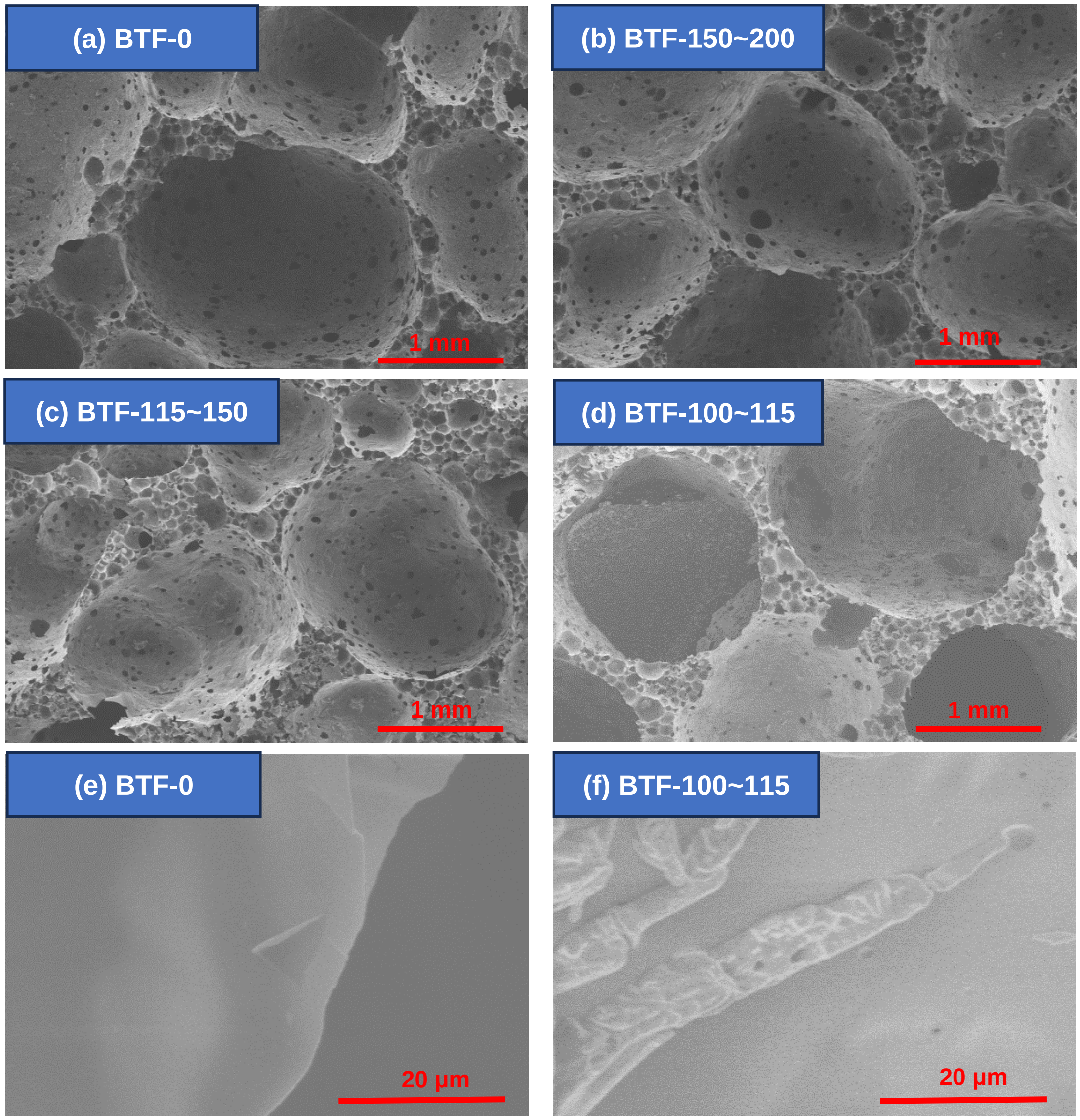

Fig. 4. Microstructure of tannin-based foams and bamboo fiber reinforced tannin-based foams

Both the tannin-based foam (Fig. 4a) and the bamboo fiber-tannin composite foams (Figs. 4b-d) exhibited a porous structure with uniform cell sizes. The pore diameters were approximately 1 mm, and the foam walls were populated with numerous smaller pores. This increased porosity is advantageous for its potential application as a substrate material in vertical greening systems. A closer examination of Fig. 4e, which shows the tannin-based foam without bamboo fibers, reveals a smooth cell surface. In contrast, Fig. 4f, which displays the bamboo fiber-tannin composite foam, clearly shows the presence of bamboo fibers embedded within the structure. The surface of the bamboo fibers is not smooth, which can be attributed to two primary factors: first, the bamboo fibers are affected by the acidic curing agents during the resin reaction (García-Bordejé *et al.* 2017; Sun *et al.* 2022); second, natural defects on the fiber surface, along with the presence of residual pectin, wax, and impurities, contribute to this roughness (Ma *et al.* 2018). No significant cracks were observed at the interface between the bamboo fibers and the foam, indicating a strong interaction between the fibers and the tannin-based foam. This suggests good interfacial bonding between the two components, which enhances the potential for improving the mechanical properties of the tannin foam (Zhou *et al.* 2019).

Thermal Performance

Figure 5 presents the thermogravimetric analysis (TGA) curves of bamboo fiber, tannin-based foam, and bamboo fiber-tannin composite foam. The analysis revealed significant differences between the TGA curves of pure bamboo fiber and tannin-based foam. The thermal degradation of pure bamboo fiber occurred in three distinct stages: in the initial phase (<120 °C), mass loss is primarily attributed to the evaporation of physically adsorbed water on the fiber surface; between 120 and 387 °C. Further mass reduction occurred due to the pyrolysis of cellulose, hemicellulose, lignin, and volatile compounds; and above 387 °C, the bamboo fiber underwent further degradation of surface groups, leading to the formation of a carbonaceous layer (Zhou *et al.* 2013; Machado *et al.* 2020).

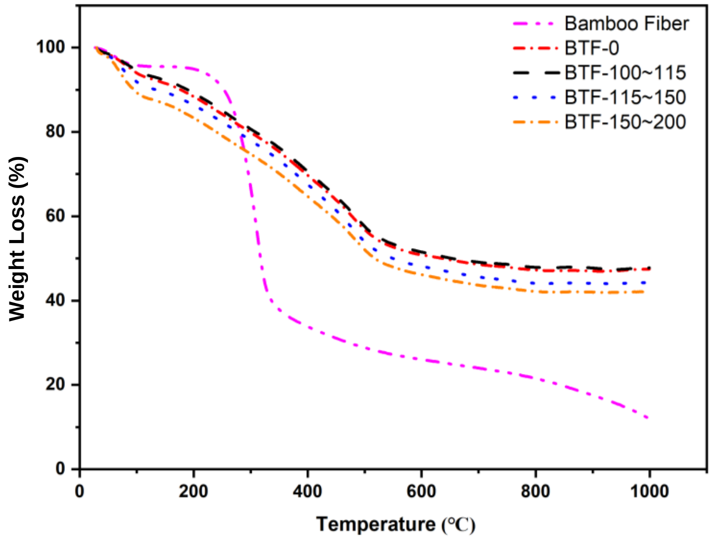

Fig. 5. TGA curves of the bamboo fibers and tannin-based foams

In contrast to the thermal decomposition of pure bamboo fiber, the thermal degradation curves of the tannin-based foam and bamboo fiber-reinforced tannin foam were quite similar. As shown in the figure, both materials exhibited a three-step thermal degradation process. Below 110 °C, the initial mass loss could be attributed to the evaporation of moisture and the pyrolysis of some volatile compounds. In the range of 110 °C to 531 °C, the primary cause of mass loss was due to the decomposition of polymer chains and the degradation of surfactants and curing agents. The decreased weight loss at specific temperatures during thermal degradation performance of the foam can be attributed to the aromatic rings in tannin, which promoted char formation during thermal decomposition. This char layer acted as a protective barrier, slowing down further degradation of the material. Above 531 °C, the main factors contributing to mass loss are the breaking of polymer chains and the formation and release of low-molecular-weight carbon-based compounds (Delgado-Sánchez *et al.* 2018; Wu *et al.* 2020).

In porous polymer foams, the presence of numerous pores within the solid polymer framework means that thermal conductivity and heat transfer are primarily influenced by the gas conductivity within the pores. The thermal conductivity of the foam depends on its density, pore size distribution, and the thermal conductivity of the polymer itself. Of course, other components and additives used in the foam preparation process can also affect the final thermal conductivity of the foam (Mougel *et al.* 2019; Sarika *et al.* 2021). The thermal conductivity study of tannin-based foam and bamboo fiber-reinforced tannin composite foam revealed that the thermal conductivity of BTF-0 was 0.042 W/(m·K), while that of BTF-100 to 115, BTF-115 to 150, and BTF-150 to 200 was 0.043, 0.041, and 0.040 W/(m·K), respectively. As the foam density and pore size were similar, the effect of pore density and average pore size on thermal conductivity could be considered negligible. Thus, the addition of 2% bamboo fibers had little effect on the thermal conductivity of the tannin-based foam, which exhibited excellent thermal insulation properties.

The limiting oxygen index (LOI) is a measure used to assess the flammability of materials, indicating the minimum oxygen concentration required to sustain combustion. LOI is expressed as the oxygen content in an oxygen-nitrogen mixture, and materials with an LOI of 27% or higher are considered flame-retardant (Weng *et al.* 2023). Figure 6 shows that the LOI values for BTF-0, BTF-100 to 115, BTF-115 to 150, and BTF-150 to 200 were 31.2, 32.1, 33.2, and 30.9%, respectively. This indicates that both tannin-based foam and bamboo fiber-reinforced tannin foams exhibited similar LOI values, likely due to their comparable densities and pore sizes. The LOI of neat bamboo fibers was measured as 23.5%, which is significantly lower than the LOI of tannin-based foam (31.2%) and bamboo fiber-reinforced tannin foams (32.1% to 33.2%). The higher LOI values observed in the tannin-containing foams can be attributed to the aromatic structure of tannins, which promotes the formation of a stable char layer during combustion. This comparison highlights the critical role of tannins in enhancing the flame-retardant properties of the composite foam (Delgado-Sánchez *et al.* 2018; Wu *et al.* 2020). These foams meet the requirements of the "Wall Insulation Material Standard" (GB/T 8624G-2012) and can be classified as B1-grade flame-retardant materials. Additionally, during the combustion process of the bamboo fiber-reinforced tannin foams, no flames or hot droplets were observed, confirming their high-temperature resistance. The flame-retardant and thermal insulation properties of the bamboo fiber-reinforced tannin foams were comparable to those of phenolic foams. These findings suggest that the addition of bamboo fibers to the BTFs had a negligible impact on the thermal performance, thermal conductivity, LOI, and thermal stability of the composite foams. Furthermore, the small amount of bamboo fiber added did not affect the flammability of the foams. Therefore, due to the excellent thermal insulation and flame-retardant properties exhibited by the bamboo fiber-reinforced tannin foams, they not only serve as an ideal substrate for vertical greening but also provide effective thermal insulation for buildings, offering broad and safe application prospects.

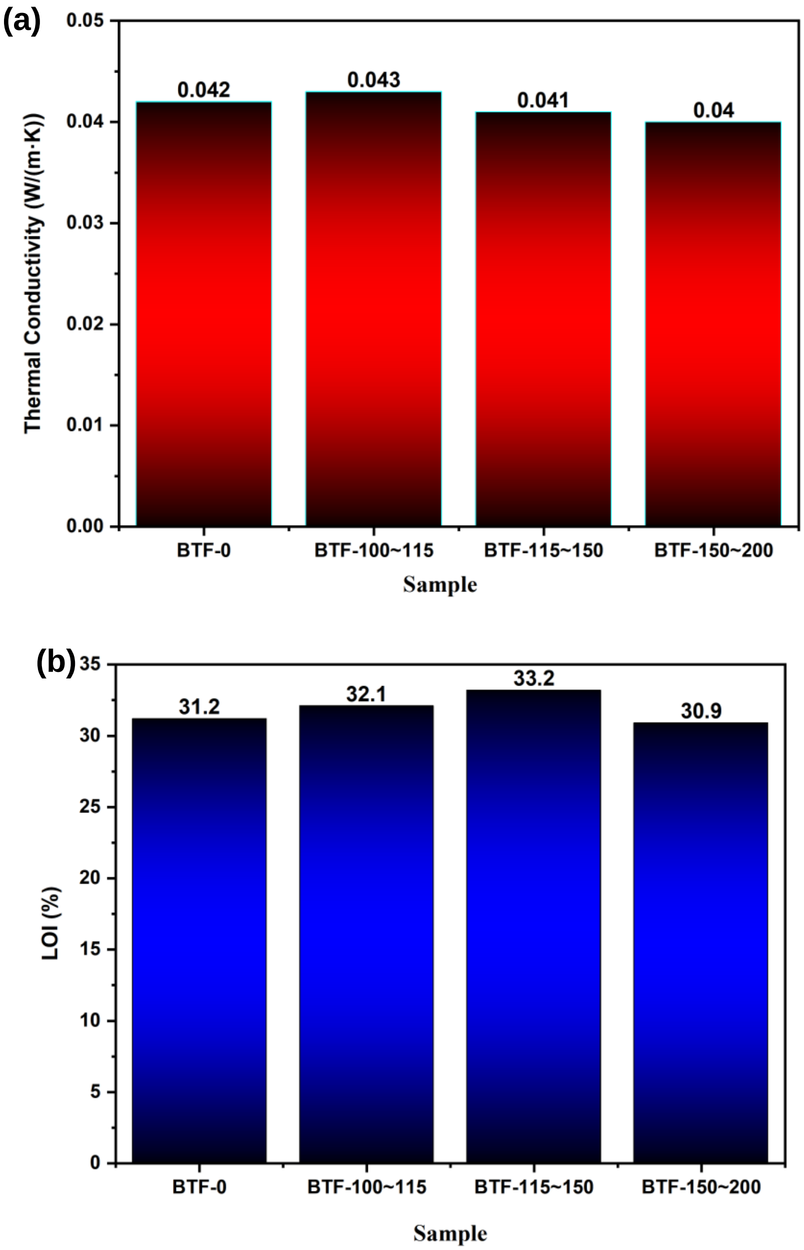

Fig. 6. The impact of different bamboo fibers on the thermal property of LOI and thermal conductivity

Mechanical Performance

Further testing of the foam's compressive strength was conducted to analyze the effect of bamboo fiber addition on the mechanical properties of tannin-based foam by establishing the relationship between fiber morphology, density, compressive strength, and specific compressive strength. While neat bamboo fiber foams were not prepared in this study, previous research has demonstrated that bamboo fibers can independently form lightweight porous structures with favorable mechanical properties. These findings support the role of bamboo fibers in enhancing the compressive strength and reducing the brittleness of the bamboo fiber-tannin composite foams (Hsu and Young 2024). As shown in Fig. 7(a), the density of the bamboo fiber-reinforced tannin foam (BTF) with 2 wt.% bamboo fibers remained relatively constant, ranging from 60 to 70 kg/m³.

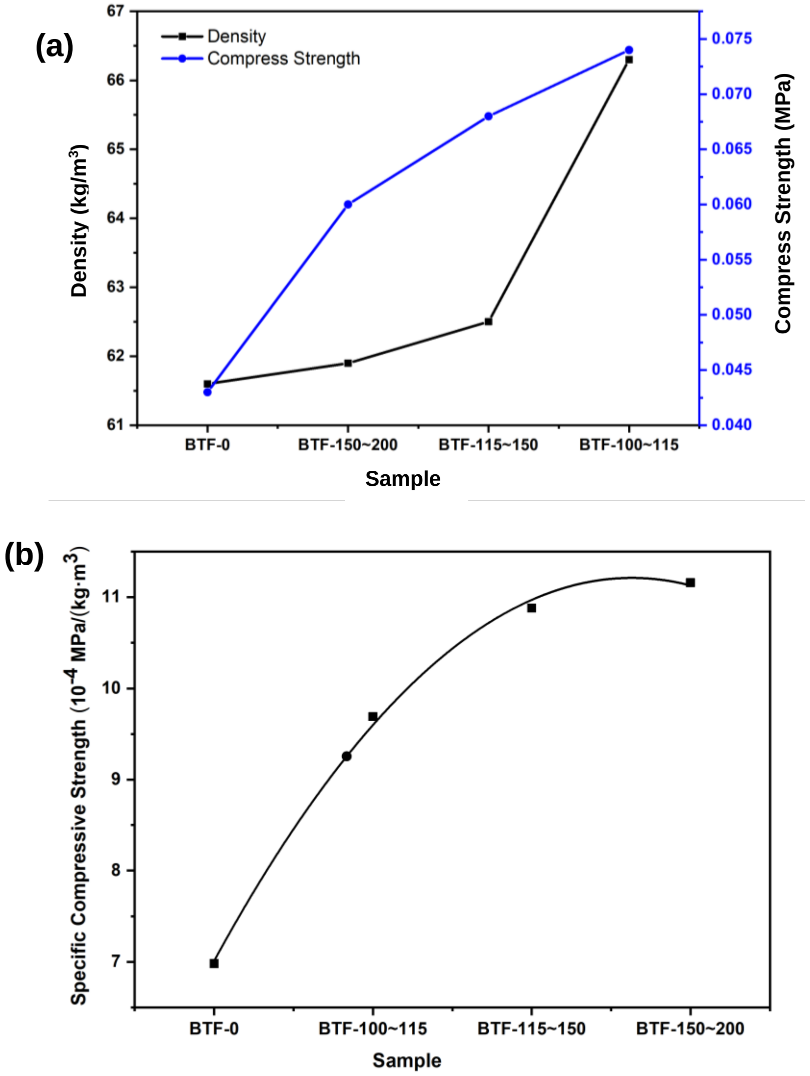

Fig. 7. (a) The influence of different fiber morphology on foam density and mechanical properties; (b) The relationship between bamboo fiber morphology and specific compressive strength

The results showed that the compressive strength of the tannin-based foam (BTF-0) was 0.043 MPa. However, the compressive strengths of BTF-100 to 115, BTF-115 to 150, and BTF-150 to 200 increased by 40%, 58%, and 72%, respectively, compared to BTF-0, demonstrating a significant enhancement effect. These results indicate that bamboo fibers of different lengths resulted in varying degrees of improvement on the mechanical properties of tannin-based foam. To clarify the effect of fiber length on the foam's mechanical properties, specific compressive strength (compressive strength/density) was used to eliminate the influence of foam density on compressive performance. As shown in Fig. 7(b), the specific compressive strengths of BTF-100 to 115, BTF-115 to 150, and BTF-150 to 200 increased from 6.98 to 9.69, 10.88, and 11.16 [10^{-4} MPa/(kg·m³)], respectively. Notably, the specific compressive strength of BTF-150~200 was enhanced by 60%.

The improvement in compressive strength and specific compressive strength indicates that the hydroxyl groups on the bamboo fibers formed strong interactions with the flavonoid structures in the tannin, resulting in a more stable network structure. The interaction between the hydroxyl groups of the bamboo fibers and the tannin-flavonoid structures allowed the bamboo fibers to provide robust support within the foam, greatly enhancing the bonding between the bamboo fibers and the tannin-based foam. Additionally, the morphology and length of the bamboo fibers significantly influenced the foam's performance. Larger fiber contact areas facilitate stronger bonding between the flavonoid structures and the hydroxyl groups on the bamboo fibers, but the length of the bamboo fibers affects the foam's pore size. When the bamboo fiber length was slightly greater than the pore size of the tannin foam, it facilitated the connection of adjacent foam walls, reducing pore size and strengthening the network structure of the foam.

Considering both the density, the thermal performance and compressive strength results, the bamboo fibers in the 115- to 150 mesh size range demonstrated the most pronounced reinforcing effect. Further analysis of the pulverization degree of BTF-115 to 150 revealed that the addition of bamboo fibers reduced the slagging percentage from 16.12% to 4.78%, a decrease of 70%, indicating a significant improvement in the foam's brittleness. Therefore, the addition of 2 wt.% bamboo fibers (115 to 150-mesh) produced tannin-based foams with superior mechanical properties, significantly enhancing the compressive strength and reducing brittleness, making it a more suitable material for use as a vertical greening substrate.

Water Absorption and Retention Performance

To evaluate the potential of bamboo fiber-reinforced tannin foam for use in vertical greening, water absorption and retention tests for sample BTF-115~150 were conducted. By measuring water uptake at different times (0.5, 1, 3, 5, and 10 h), maximal absorption was reached during the first initial min of contact with water (<30 min).

The experimental results showed that the water absorption result for unmodified tannin foam was 26.3%, while the water absorption of bamboo fiber-reinforced tannin foam slightly increased to 26.5%. While the increase was small, it reflects the contribution of bamboo fibers to water retention properties. Further water retention tests demonstrated that the bamboo fiber-reinforced tannin foam could retain over 78.1% of its water content over an extended period of 120 h, which is considerable to traditional phenolic floral foam (Table 1). This improvement in performance can be attributed to the excellent moisture absorption properties of bamboo fibers and their uniform distribution within the foam, which creates a porous structure that effectively promotes water storage and retention. The outstanding water absorption and retention capabilities make bamboo fiber-reinforced tannin foam particularly suitable for vertical greening systems, as it can reduce the frequency of watering while maintaining a consistently moist environment around plant roots for extended periods.

The mechanical performance was measured for dry samples, which is the considerable mechanical strength. It is interesting to evaluate the mechanic property after water absorption. The mechanical performance of TBF-115~150 foam after 10 cycles of water absorption and drying was evaluated. As shown in Fig. 8, the stress-strain curve after cycling revealed a minor decrease in stress levels during the plateau region and at the maximum compressive strength. However, the elastic modulus and the densification point were largely unaffected, indicating that the foam retained its structural integrity and load-bearing capacity even after repeated exposure to water. These findings demonstrate the foam's durability and suitability for applications such as vertical greening, where materials are frequently subjected to moisture cycling.

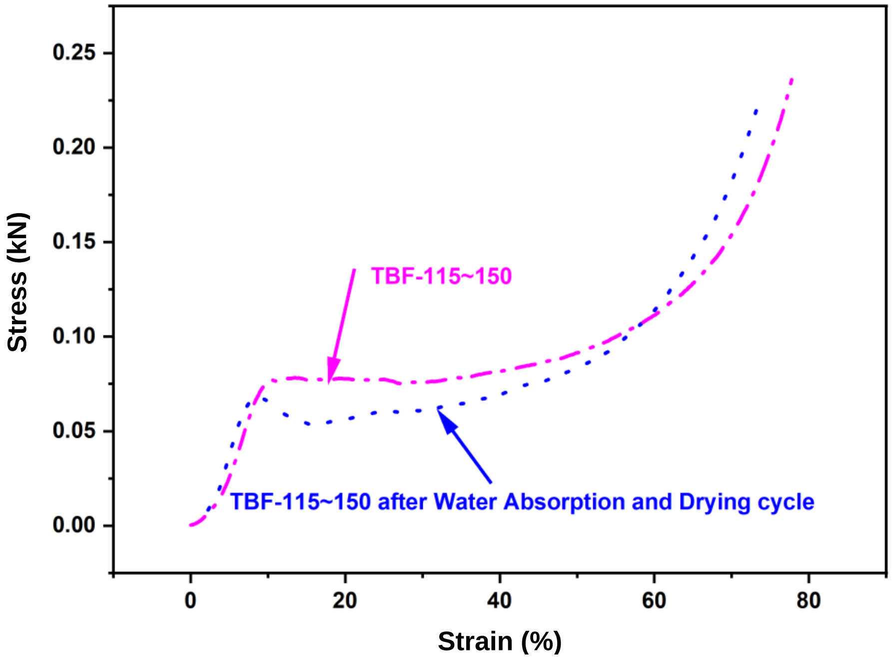

Fig. 8. The strain-stress curves of the sample BTF-115~150 before and after 10 times of water absorption and drying cycle

Table 1. Water Absorption and Retention Performance of Bamboo Fiber-Tannin Composite Foam and Commercial Phenolic Foam

	Water Absorption (%)					Water Retention (%)	pH
	0.5 h	1 h	3 h	5 h	10 h	120 h	/
Tannin foams	23.3	24.7	25.4	25.8	26.3	76.3	4.3
Bamboo Fiber-Tannin Composite Foam	23.5	24.8	25.4	25.9	26.5	78.1	4.4
Commercial Phenolic Foam	31.5	32.3	32.5	32.7	32.9	86.6	5.1

CONCLUSIONS

1. This study successfully developed a bamboo fiber-reinforced tannin-based foam material and systematically investigated the effects of bamboo fiber addition on foam density, porosity, microstructure, thermal stability, limiting oxygen index (LOI), brittleness, and mechanical properties.
2. The addition of 2% bamboo fibers significantly improved the foam's compressive strength by up to 72%, while reducing brittleness, as evidenced by a slagging percentage reduction to 4.78%. Other properties such as density, porosity, thermal conductivity, LOI, and thermal stability were minimally affected by the bamboo fibers.
3. The bamboo fiber-reinforced tannin foam exhibited excellent water absorption (26.5% after 10 h) and water retention capabilities (78.1% after 120 h), making it suitable for

applications requiring moisture support, such as vertical greening.

4. This lightweight and multifunctional material, with its superior mechanical strength, water absorption, retention performance, and thermal stability, has promising application prospects as an alternative to traditional phenolic foams in vertical greening systems.
5. Due to the formaldehyde used, further studies on alternative, low-toxicity crosslinking agents are recommended to enhance the material's environmental and health safety profile.

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