

Article

Exploring the Application Method of Bamboo Powder in Promoting the Development of Sustainable Outdoor Furniture

Yafei Fan ¹, Ziqian Zhu ¹, Jiacheng Luan ² and Yi Liu ^{3,4,*} 

¹ School of Art and Design, Beijing Forestry University, Beijing 100083, China; fanyafei530@163.com (Y.F.); julie20050714@163.com (Z.Z.)

² Academy of Arts & Design, Tsinghua University, Beijing 100084, China; 19801311130@163.com

³ Key Laboratory of Wood Material Science and Application, Beijing Forestry University, Beijing 100083, China

⁴ Beijing Key Laboratory of Wood Science and Engineering, Beijing Forestry University, Beijing 100083, China

* Correspondence: liuyichina@bjfu.edu.cn

Abstract: With the depletion of fossil fuels, more and more green products are appearing in daily necessities. Bamboo is a common sustainable biomaterial with the characteristics of fast growth, easy bending, low cost, and easy processing, and it is widely used in furniture design. However, the poor aging resistance and UV resistance of natural bamboo materials limit their application in outdoor furniture. In order to improve the service life of outdoor bamboo furniture, this study prepared bamboo boards from bamboo powder and utilized them in the design of outdoor furniture. The research was conducted in two stages. In the first stage, functional modification was carried out on the surface of bamboo fibers (BF). Epoxy resin and UV absorber ZnO were introduced into the bamboo powder matrix, and a three-dimensional network structure of bamboo powder-based polymer material was formed by adjusting the material ratio and reaction conditions. With the increase of ZnO content, the absorption of moisture by the bamboo powder-based polymer materials decreased. The compressive strength of 1.5%ZnO-Board reached 36.8 MPa, exceeding the compressive strength of C30 concrete. In the second stage, 1.5% ZnO-Board was selected for solidification and demolding, and used as the seat surface for outdoor chairs. Through the car crushing experiment, the chair panel did not undergo significant deformation during the car crushing process. The anti-aging experiment showed that the structure and morphology of the panel would not be damaged by long-term UV irradiation. The panel did not show any weight changes in the anti-water-absorption experiment. By using low-contrast color combinations, the seats can be organically integrated into the environmental background, effectively enhancing the coordination and unity of the overall aesthetic harmony of the space. Compared with the commonly used plastic outdoor seats, the outdoor seats prepared in this study showed a 144% increase in carbon reduction effect. This study highlights the potential of modified bamboo powder for the design of outdoor furniture, which is of great significance to reducing outdoor plastic products and promoting sustainable life.

Keywords: sustainable biomaterials; bamboo powder modification; high strength; UV resistance; furniture design



Citation: Fan, Y.; Zhu, Z.; Luan, J.; Liu, Y. Exploring the Application Method of Bamboo Powder in Promoting the Development of Sustainable Outdoor Furniture. *Sustainability* **2024**, *16*, 11282. <https://doi.org/10.3390/su162411282>

Academic Editors: Farshid Pahlevani and Smitrupa Biswal

Received: 11 November 2024

Revised: 17 December 2024

Accepted: 19 December 2024

Published: 23 December 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Since the Industrial Revolution, human productivity has significantly increased, but this progress has also led to environmental degradation and resource depletion [1]. Some harmful chemical wastes from industrial processes are difficult to degrade within a short period, leading to groundwater contamination, which, through the food chain, ultimately poses serious health risks to humans [2,3]. In response to these challenges, the concept of sustainable design has emerged, with many designers increasingly adopting sustainable materials in their products to reduce the use of non-degradable substances such as plastics [4–6]. Furniture, being an essential part of daily life, is naturally a key area for

the implementation of sustainable design principles. Currently, the design of furniture with sustainability in mind primarily focuses on technical aspects such as materials and manufacturing processes. Among the materials used, wood is widely favored for its natural, environmentally friendly, and biodegradable properties, aligning with the goals of the green economy [7–10]. However, due to global efforts to conserve forests, many countries have started to reduce timber harvesting. Among all wood-based materials, bamboo, with its high yield and rapid growth cycle, is increasingly being utilized in furniture production. Compared to traditional wood, bamboo offers superior wear resistance, a higher strength-to-weight ratio, lower water absorption, and reduced thickness expansion, with a tensile strength approximately 1.5 times greater than that of common wood [11,12]. Despite these advantages, bamboo furniture is typically used indoors, while bamboo and wooden furniture exposed to outdoor conditions over extended periods can suffer from environmental damage. This exposure leads to chemical reactions in the material, causing significant deterioration in performance, including cracking, deformation, color fading, and surface peeling. Ultraviolet radiation is a primary factor in the photoaging process of wooden furniture, presenting one of the most pressing issues in the outdoor furniture industry.

To address the challenges of poor UV resistance and low durability in bamboo, bamboo plastic composite materials (BPCMs) have emerged as a promising research direction in the bamboo composite materials market. BPCMs are a new class of multifunctional composites, primarily composed of pretreated modified fibers such as bamboo sawdust, bamboo chips, or bamboo residues. These materials utilize the principle of polymer chemical interface fusion, where the fibers are mixed with molten thermoplastic resin in a specific ratio. With the assistance of additives, the mixture undergoes high-temperature processing to form the final product. In this composite, bamboo fiber acts as the reinforcing material, while the resin serves as the matrix. The reinforcing fibers bear the external forces, while the resin wraps around the fiber, which not only puts overall force on the fiber, but also protects the fiber matrix, which envelops the fibers, providing structural support and protecting them from mechanical damage and chemical corrosion. One of the key advantages of bamboo plastic composites is their recyclability, which contributes to reducing environmental pollution and enhancing the aesthetic value of living spaces. Borchani et al. treated natural bamboo fibers (BF) with varying concentrations of alkali and found that the treatment increased both the cellulose content and crystallinity, suggesting that alkali treatment enhances the mechanical strength of bamboo fibers [13]. Jin et al. modified bamboo fibers (BF) using different coupling agents and found that treatment with coupling agents improved the crystallinity of the composite material, with the silane coupling agent exhibiting the most significant effect [14]. Xie and Ma et al. treated BF with a silane coupling agent and observed that the Si-O-C bond on one side of the silane coupling agent reacted with the hydrogen bonds in cellulose, while the organic functional group on the other side interacted with the resin, forming a coupling bond between the BF and the epoxy resin (EP) interface. This interaction enhanced the overall performance of the composite [15,16]. Niu et al. utilized bamboo powder and polybutylene succinate (PBS) as the primary raw materials and determined the optimal formulation for bamboo powder/PBS composites, achieving a flexural strength of 24.87 MPa and a compressive strength of 29.74 MPa [17]. This material can be utilized in various applications such as outdoor furniture, wall panels, flooring, and road barriers, offering an environmentally friendly solution for the use of bamboo residues. In outdoor applications of bamboo-based composite materials, the photodegradation of bamboo significantly affects its mechanical properties and appearance. As a result, the study of bamboo's resistance to light-induced aging has become a key research focus in the field of outdoor furniture. Gruell et al. investigated the relationship between different outdoor aging conditions and the aging effects on coated bamboo [18]. However, the strength of the paint film in this approach is relatively low. With changes in outdoor temperature and humidity, the substrate beneath the coating can absorb or release moisture, leading to internal stress within the surface coating. The incorporation of UV absorbers can enhance the long-term resistance to photodegradation. Inorganic

UV absorbers are typically composed of nanoparticles such as zinc oxide (ZnO), titanium dioxide (TiO₂), iron oxide (Fe₂O₃), and aluminum oxide (Al₂O₃). These nanoparticles exhibit a “blue shift” phenomenon when absorbing UV light, effectively blocking UV radiation. Inorganic UV shielding agents significantly improve the discoloration resistance of coatings. Liufu et al. compared the UV shielding performance of nano-ZnO and nano-TiO₂ and found that both nanoparticles not only enhanced UV shielding but also improved the thermal stability of the material [19]. However, due to nano-ZnO’s stronger absorption of long-wave and medium-wave UV radiation compared to nano-TiO₂, its UV shielding performance was superior [20]. In the context of bamboo furniture design and application, research is closely tied to the distribution of bamboo. The Asia-Pacific region, being the world’s largest bamboo-producing area, has seen more extensive research and application of bamboo and bamboo furniture compared to other regions. Countries such as China, Japan, South Korea, and those in Southeast Asia commonly use bamboo as a raw material for furniture manufacturing. In contrast, in Europe, where bamboo is relatively scarce, research on bamboo is limited. In the Americas, research primarily focuses on the structural properties of bamboo [21–24]. However, traditional craftsmanship remains the dominant design approach for bamboo furniture, but its application in modern home environments is still limited. In recent years, as low-carbon, minimalist, and sustainable concepts have gained traction, the potential applications of bamboo furniture have expanded significantly. Some furniture designers have moved beyond traditional design paradigms, leading to the creation of innovative, practical, and multifunctional bamboo-based furniture. In particular, the physical or chemical modification of bamboo prior to its use in furniture manufacturing has become a major trend in the furniture market. Research has demonstrated that outdoor anti-discoloration recombinant bamboo holds considerable development potential [25,26].

Based on the above summary, natural bamboo exhibits poor waterproofing and UV resistance, making it unsuitable for direct use in outdoor furniture design. Therefore, this study focuses on the recycling of bamboo powder as the primary research material. Initially, the surface of bamboo fibers (BF) was functionally modified and blended with epoxy resin and UV absorber zinc oxide (ZnO). By adjusting the material ratio and reaction conditions, a three-dimensional network structure of bamboo powder-based polymer material was developed to address the inherent limitations of natural bamboo. After determining the optimal ratio for the BPCMs, outdoor furniture production was carried out under the guidance of ergonomic principles. The compatibility between bamboo-based outdoor furniture and the public environment was evaluated through color analysis. This study demonstrates typical interdisciplinary characteristics and provides both data and methodological support for the integration of biomass material development with sustainable design.

2. Materials and Methods

2.1. Materials

Bamboo powder (particle size 30 µm, purchased from Zhufu Bamboo Material Co., Ltd., Zhangzhou, China). Sodium hypochlorite (NaClO₂, purchased from Beijing Bailingwei Technology Co., Ltd., Beijing, China). Nano zinc oxide (ZnO, particle size 30 nm, purchased from Beijing Kaiguo Technology Co., Ltd., Beijing, China). Gamma-(2,3-epoxypropoxy) propyltrimethoxysilane (KH560, purchased from Tianjin Baima Technology Co., Ltd., Tianjin, China). Epoxy resin (EP, Shanghai McLean Biochemical Technology Co., Ltd., Shanghai, China).

2.2. Preparation and Design Application of Bamboo Powder-Based Composite Materials

Preparation of Bamboo Powder-Based Composite Materials

Figure 1 shows the preparation process of bamboo powder-based composite materials. The bamboo powder was filtered through a 100 mesh sieve to remove coarser impurities. Then the bamboo powder was immersed in NaClO₂ solution with a 4% volume fraction, the pH was adjusted to 4.6 with glacial acetic acid, and stirred for 2 h in an 85 °C water

bath. Finally, the sample was rinsed with distilled water and anhydrous ethanol three times to eliminate any residual chemicals [27].

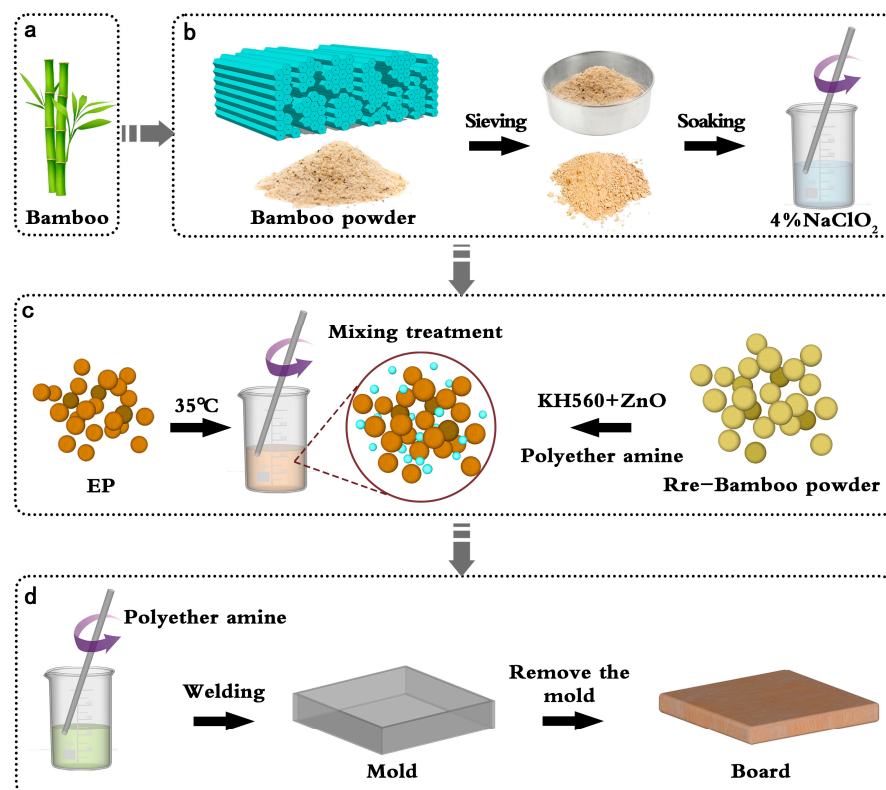


Figure 1. Preparation process ((a) Bamboo powder raw material; (b) Pretreatment of bamboo powder; (c) Blending treatment of zinc oxide, pretreated bamboo powder, and epoxy resin; (d) Curing and demolding process of bamboo powder-based polymers) of bamboo powder-based composite materials.

Next, 20 g EP was weighted and stirred in a beaker at 35°C , then 12 g pretreated bamboo powder was added multiple times. Afterwards, 0.5 g KH560 and 0.5% mass fraction of ZnO were added, and finally 6.6 g of polyether amine was added as a curing agent. After stirring evenly, the mixture was placed into a mold and repeatedly shaken in a shaking machine to eliminate bubbles. The mold was left at room temperature for 24 h before being demolded. According to the above method, we also made three more samples and changed the content of ZnO as the comparative experiment. The content of ZnO was 0%, 1%, and 1.5% of the total mass, respectively.

2.3. Characterization

The microstructure and morphology of the sample were observed using a scanning electron microscope (Hitachi, S-4800, Tokyo, Japan). The sample was bonded to the sample stage with conductive tape and gold spraying treatment for morphology observation. The scanning voltage was 5.0 kV. The infrared spectrum of the microstructure morphology of the sample was tested using a Fourier transform infrared spectrometer (Gangdong, FTIR-650, Shanghai, China) with a spectral resolution of 0.4 cm^{-1} and a scanning range of $400\text{--}4000\text{ cm}^{-1}$. The transmittance of the sample was measured by UV-visible spectrophotometer (Shimadzu, UV-1900i, Kyoto, Japan). The scanning range was 200–800 nm. The sample was subjected to thermogravimetric analysis using a TGA analyzer (TGA209F3, Selb, Germany) with a temperature range of $30\text{--}800^\circ\text{C}$; the testing rate was $10^\circ\text{C}/\text{min}$. The hydrophobicity of the sample was measured by water contact angle experiment (Zhongchen, JC2000D6, Shanghai, China). Compressive strength was tested using a universal testing machine (Instron, 6800, Norwood, MA, USA). The water absorption rate was calculated

by soaking the sample in water for 36 h and comparing the mass changes before and after soaking.

3. Results and Discussion

3.1. Physical and Chemical Characterisation of Bamboo Powder-Based Composite Materials

The microstructure of bamboo powder was examined using SEM, as shown in Figure 2, where some representative pores are highlighted by red circles. The SEM images reveal that the surfaces of the four samples are relatively smooth, with the presence of pores at the microscopic level, which are likely caused by bubbles generated during the stirring process. However, with an increase in the ZnO content, the number of pores gradually decreases, possibly due to ZnO filling the pores. Additionally, the surface activity of the modified bamboo powder is enhanced, leading to increased interface interactions with different materials, which helps to minimize bubble formation. The modified ZnO particles do not exhibit agglomeration in the composite material, likely due to the improved dispersibility of ZnO facilitated by the coupling agent KH560. As the distribution of ZnO becomes more uniform, the surface smoothness of the composite material increases, resulting in a denser and more uniform structure. This uniformly dispersed morphology contributes to improved overall material performance, particularly in terms of long-term durability in outdoor environments. Furthermore, this treatment enhances the structural strength and stability of the composite material.

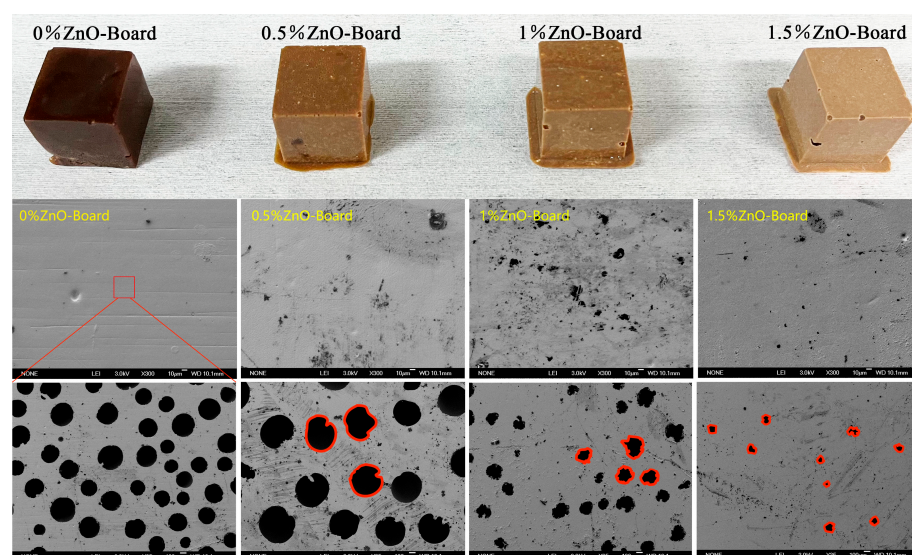


Figure 2. The microstructure of ZnO-Board.

Chemical structure analysis was performed using Fourier transform infrared spectroscopy (FTIR) and thermogravimetric analysis (TGA) to investigate the molecular structural changes that occur during the modification process of ZnO-Board, with a focus on the binding modes and effects of EP, ZnO, and bamboo powder. Figure 3a shows that several samples exhibit absorption peaks at 2920 cm^{-1} , 2850 cm^{-1} , and 1507 cm^{-1} , corresponding to the stretching and bending vibrations of the C-H bonds in $-\text{CH}_3$ and $-\text{CH}_2$ groups of KH560, indicating the successful binding of KH560 to the components. The C=N stretching vibration peak at 1020 cm^{-1} , observed in the ZnO-Board, and the N-H bending vibration peaks of N=O and amide bonds at 1500 cm^{-1} and 1605 cm^{-1} are attributed to the crosslinking reaction between KH560 and cellulose in bamboo powder, forming ester bonds. This reaction contributes to the improvement of the composite material's mechanical strength. The strong peak at 1080 cm^{-1} is identified as the Si-O-Si absorption peak, which appears even without the addition of ZnO, suggesting that KH560 mainly reacted with the hydroxyl groups on the surface of bamboo powder, hydrolyzing and condensing to form Si-O-Si structures. However, with an increase in ZnO content, the intensity of the 1080 cm^{-1}

peak decreases, indicating that the physical dispersion of ZnO in combination with other materials may reduce the bonding strength between the components. The peak between $3300\text{--}3500\text{ cm}^{-1}$ corresponds to the stretching vibration of OH groups, primarily from the surface hydroxyl groups and internal moisture of bamboo powder. As the ZnO content increases, the characteristic OH peak gradually weakens, which may be due to the hydrophobic nature of ZnO, which effectively reduces moisture absorption in the composite material. Furthermore, EP can react with the hydroxyl groups on the surfaces of ZnO and bamboo powder, forming chemical bonds that reduce the material's moisture absorption.

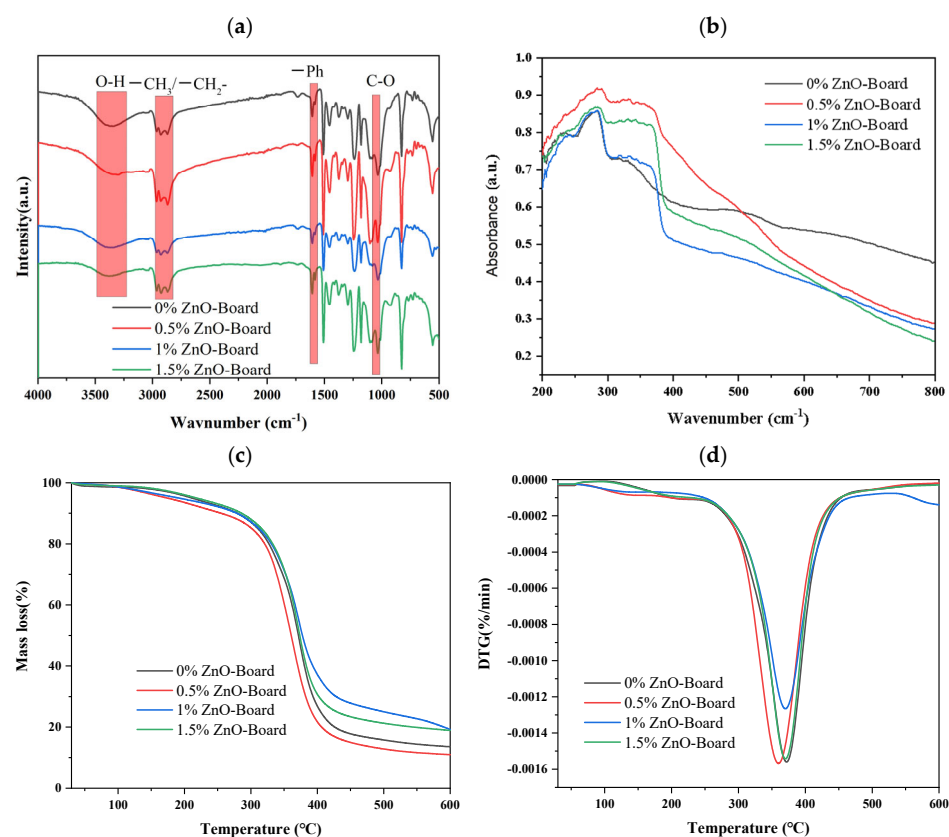


Figure 3. (a) FTIR image of ZnO-Board, (b) UV Visible Absorption Spectroscopy of ZnO-Board, (c) Thermogravimetric curve of ZnO-Board, (d) Thermal degradation rate of ZnO-Board.

UV radiation is a component of solar radiation and can be categorized into three regions based on wavelength: UVA (320–400 nm), UVB (275–320 nm), and UVC (200–275 nm). Since most UVC radiation is absorbed by the ozone layer, outdoor furniture is primarily exposed to UV radiation in the UVA and UVB ranges. Consequently, the UV shielding ability of the material can be evaluated by its average absorbance between 275 and 400 nm. Figure 3b shows that the 0% ZnO-Board exhibits strong absorbance in both the ultraviolet and visible light regions, which is attributed to the high lignin content in bamboo powder. Lignin molecules contain a benzene ring structure, and under UV irradiation, their internal electrons resonate, absorbing UV radiation and undergoing electron transitions. As a result, lignin demonstrates effective UV absorption properties. Additionally, EP, as an efficient UV additive, absorbs UV light most effectively in the 240–330 nm range, particularly in the 300–330 nm region where nearly all of the UV radiation is absorbed. Upon the addition of modified ZnO, the composite material's UV absorption in both the UVA and UVB regions is significantly enhanced. This improvement can be attributed to ZnO's bandgap of approximately 3.37 eV and its exciton binding energy of 60 meV, which provide strong absorption in the UV region [28,29]. Compared to materials without added ZnO, the sample containing ZnO exhibits a narrower absorption peak in the visible light range (350–400 nm). This is because, as the ZnO content increases, the color of the sample lightens, and its

absorbance decreases, leading to a narrower absorption peak. These results indicate that the ZnO-modified sample has excellent UV absorption capabilities.

The thermogravimetric (TG) analysis (Figure 3c) reveals that the four samples exhibit similar thermal degradation patterns, with minimal mass loss observed below 100 °C, primarily due to water evaporation. A rapid mass loss occurs between 100–300 °C, which is mainly attributed to the decomposition of hemicellulose, lignin, and cellulose in the bamboo powder. Lignin, being a complex aromatic polymer, undergoes pyrolysis throughout most of the degradation process [30]. Above 300 °C, the rate of thermal degradation increases significantly, with the maximum degradation peak occurring around 350 °C, corresponding to the thermal decomposition of organic compounds such as EP. At 600 °C, the residual mass of the 0.5% ZnO-Board is the lowest, even lower than the sample without added ZnO, suggesting that the addition of ZnO at this lower concentration does not significantly enhance thermal stability. In contrast, the residual mass of the 1% ZnO-Board is 19.22%, and that of the 1.5% ZnO-Board is 18.91%, both of which are 41.53% and 39.25% higher, respectively, than the 13.58% residual mass of the sample without ZnO. Additionally, the degradation rates of the 1% and 1.5% ZnO-Board samples are lower than those of the other samples (Figure 3d), with the 1% ZnO-Board demonstrating the slowest thermal weight loss rate and exhibiting superior thermal stability.

Figure 4 shows the water contact angle detection test of the sample. Natural bamboo powder exhibits a high water-absorption capacity, making it unsuitable for humid environments. In contrast, the water contact angle of the modified samples exceeds 90°, which can be attributed to the excellent hydrophobic properties of the cured EP, enhancing the water resistance of the bamboo powder composite materials.

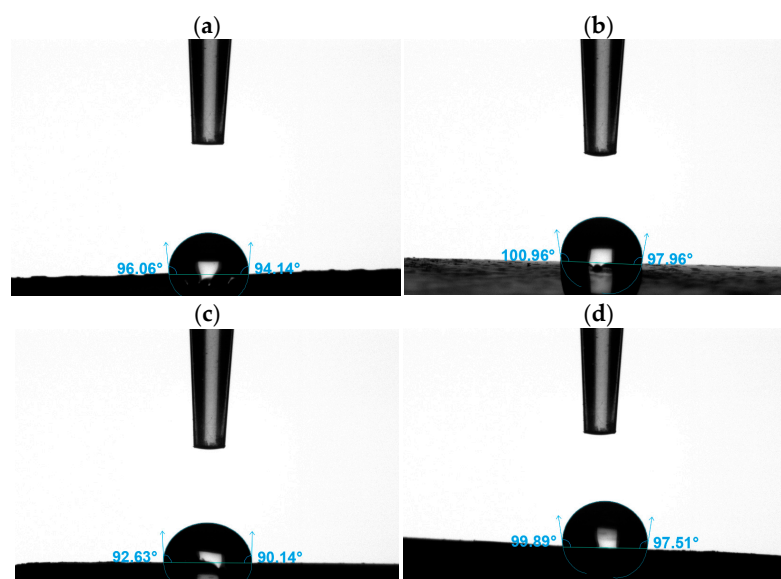


Figure 4. Water contact angle (a) 0% ZnO-Board, (b) 0.5% ZnO-Board, (c) 1% ZnO-Board, (d) 1.5% ZnO-Board.

After the addition of ZnO, the water contact angle of all bamboo powder composite materials increased, except for a slight decrease observed in the 1% ZnO-Board. This suggests that ZnO, as a hydrophobic material, contributes positively to improving the waterproof properties of the composite materials [31]. Hydrophobicity is a crucial factor in the performance of outdoor furniture, as it directly influences its durability and service life.

The samples were soaked in water for 36 h, and the weight gain was measured after this period. Figure 5 illustrates the water absorption curves of the samples. It can be observed that all samples exhibit an increase in weight within the first 6 h. Among them, the 0.5% ZnO-Board shows the highest weight gain, continuing to exhibit slight weight increase beyond 6 h. In contrast, the 1.5% ZnO-Board shows only a minor increase in

weight during the first 6 h, after which the weight gain for all samples stabilizes. After soaking for 36 h, the weight gain of all samples does not exceed 0.3 g. According to Table 1, the calculated weight gain rates of the four samples after 36 h of soaking are 0.4%, 2.4%, 0.3%, and 0.4%, respectively.

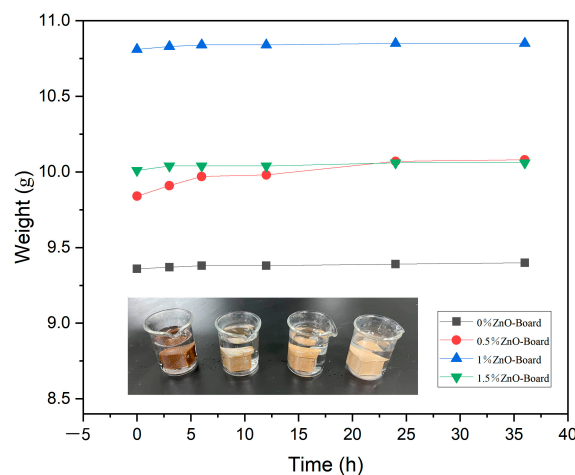


Figure 5. Water absorption curve of ZnO-Board.

Table 1. Water absorption weight of ZnO-Board over time.

Sample	0 h	3 h	6 h	12 h	24 h	36 h
0% ZnO-Board	9.36 g	9.37 g	9.38 g	9.38 g	9.39 g	9.40 g
0.5% ZnO-Board	9.84 g	9.91 g	9.98 g	9.98 g	10.07 g	10.08 g
1% ZnO-Board	10.81 g	10.83 g	10.84 g	10.84 g	10.85 g	10.85 g
1.5% ZnO-Board	10.01 g	10.04 g	10.04 g	10.04 g	10.06 g	10.06 g

All samples show good waterproof effect, among which the weight gain rate of 1% ZnO-Board is the smallest.

Figure 6 presents the compressive strength testing results for four types of ZnO-Board. The mechanical strength of the board without added ZnO is 34.8 MPa, which is 30 MPa higher than the compressive strength of C30 concrete. When 0.5% ZnO is added, the compressive strength decreases to 31.6 MPa, likely due to uneven dispersion of the lower ZnO content, leading to phase separation between the components. However, as the ZnO content increases, the compressive strength of the ZnO-Board improves.

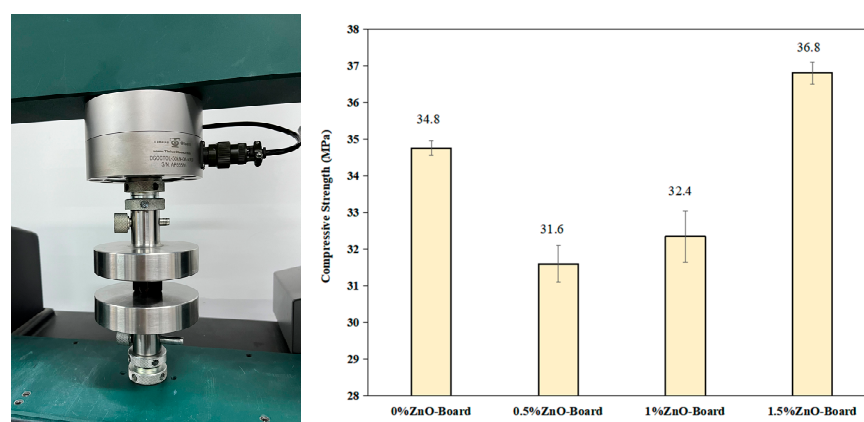


Figure 6. Compressive strength testing of ZnO-Board.

When 1.5% ZnO is added, the compressive strength of the board increases to 36.8 MPa. This improvement is attributed to the uniform distribution of ZnO and the abundant hydroxyl groups on its surface, which can form hydrogen bonds with the bamboo powder. These interactions significantly contribute to enhancing the overall mechanical properties of the material.

After compressive testing, all samples maintained their square shape, but the appearance of the 0.5% ZnO-Board shows significant damage and a reduction in height (Figure 7a). Microscopical analysis of the surface conditions revealed cracks on both the 0% ZnO-Board (Figure 7b) and 0.5% ZnO-Board (Figure 7c). These cracks were primarily concentrated around the pores, with larger gaps between the pores being more prominent in the 0.5% ZnO-Board. This observation suggests that the presence of pores, particularly larger ones, negatively impacts the compressive performance of the material.

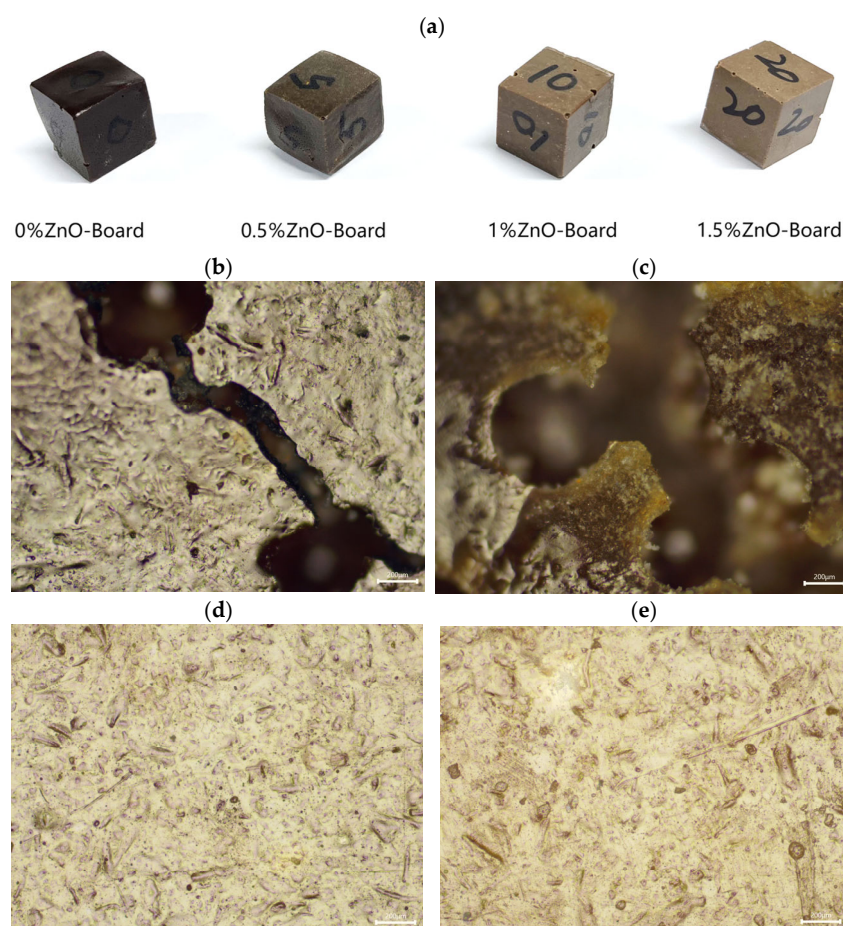


Figure 7. (a) ZnO-Board morphology after compression test. Surface condition after compression test of (b) 0% ZnO-Board, (c) 0.5% ZnO-Board, (d) 1% ZnO-Board, (e) 1.5% ZnO-Board.

The surfaces of the 1% ZnO-Board (Figure 7d) and 1.5% ZnO-Board (Figure 7e) are smooth, with no visible pores. This can be attributed to the beneficial effect of increasing ZnO content, which aids in defoaming.

3.2. Application of Bamboo Powder-Based Composite Materials in Outdoor Chair Design

Based on the analysis of the material properties, the 1.5% ZnO-Board exhibits a balanced combination of excellent thermal stability, UV shielding, and waterproofing. Furthermore, previous researchers have also studied the properties of ZnO-doped EP, which serves as a reference for our analysis of the impact of bamboo powder on the overall performance of the composites. For example, Hao Zhang et al. [32] investigated the influence of ZnO nanoparticles on the EP system and the UV aging resistance of the

modified EP composites. The composites exhibited the strongest UV resistance when the ZnO content was 0.3 wt%, with a maximum tensile strength reaching 82.79 MPa. This demonstrated that a relatively low ZnO content can satisfy UV resistance requirements, and the enhancement in mechanical properties is primarily attributed to the toughening effect of the nanoparticles on the EP. Raluca Somoghi et al. [33] demonstrated that EP composites enhanced with different types of zinc oxide nanofillers exhibited excellent mechanical properties, adhesion, and corrosion resistance. Through a comparison of relevant data from this study, it was discovered that the incorporation of bamboo powder into the blend system of EP and ZnO did not significantly impact the overall UV resistance of the system. However, an increase in ZnO content from 0.3 wt% to 1.5 wt% was necessary. Despite a decrease in the mechanical properties of the entire system, the mechanical properties of the 1.5% ZnO-Board still reached 36.8 MPa. Given that the compressive strength requirement for wooden chairs typically ranges between 10–60 MPa, the 1.5% ZnO-Board can be considered as a primary material for outdoor chair design.

The chair's overall height is 450 mm, with a leg-base diameter of 363 mm and a seat-surface side length of 400 mm. The seat surface measures $400 \times 400 \times 50$ mm, and the design follows a minimalist approach, adhering to the “less is more” principle in modern design (Figure 8). The chair features smooth, simple lines, avoiding complex decorations, and the structural design has been optimized to reduce weight. Additionally, ergonomic considerations are fully incorporated into the chair design to enhance user comfort. The seat width is designed to be ≥ 380 mm, with a seat height ranging from 400 to 440 mm, ensuring the best user experience.



Figure 8. Outdoor chair finished product image.

3.2.1. Design Analysis

User Demand Research

The design of the outdoor seat has been strongly influenced by user demand surveys, with valuable suggestions provided by the users. These inputs have significantly impacted the design direction during the improvement process, addressing concerns such as seat comfort, weather resistance, and aesthetics. Based on the analysis of all effective feedback from the user experience survey, we categorized the user needs into two levels: functional needs and environmental adaptability needs. The survey results were then transformed into a user needs list (Table 2), which guided the final design direction.

Table 2. User demand for outdoor furniture.

User Requirements Category	Specific User Needs	Key Recommendations	Design Expected Features
Functional requirements	Overall comfort of the seat surface	Traditional outdoor seats have poor control over comfort, and users hope that it will not cause fatigue during long-term use.	The seat dimensions and height are designed according to ergonomic principles, ensuring comfort during long-term use and an optimal sitting experience.
	Provide a safe seat structure	Users worry that the seat may turn over or slide when used on uneven ground.	The seat features a stable four-legged or multi-legged support structure with an anti-slip footpad design, ensuring stability on uneven ground.
	Ease of movement and disassembly	In outdoor activities, users need seats that are portable and easy to move, allowing for adaptability across different scenarios while minimizing space occupancy.	The design incorporates lightweight features to enhance mobility and facilitate ease of movement.
Environmental adaptability requirements	Weather resistance (waterproof, UV resistant, corrosion-resistant)	Outdoor seats are exposed to high temperatures, humidity, and direct sunlight for a long time, and weather resistance is a key indicator.	The weather resistance index of the seat panel after functional modification has significantly improved in practical use scenarios.
	Durability and ease of maintenance	It has a longer service life and is easy to perform simple maintenance upon.	Enhance the service life of traditional bamboo, which will not be damaged/be easy to repair.
	Aesthetics and environmental harmony	Users generally prefer simple, aesthetically pleasing designs, with seat shapes that fulfill the majority of outdoor use requirements.	The seat is more simple and beautiful in shape and color, integrating and unifying with the environment.
	Smooth and clean surface of the seat	Outdoor environments often lead to dirt accumulation on seats, so it is essential for users to clean them easily during use.	The seat surface is resistant to the adhesion of mud, dust, and stains, making it easy to clean.

Seat Design

The 1.5% ZnO-Board was selected as the seat surface material. Firstly, the chair surface was processed using a mold. Then, the 304 stainless steel was selected to process the chair legs, which were mainly installed in a cross-splicing form. Finally, we used expansion screws to connect the chair surface and legs together. The final shape of the outdoor chair is shown in Figure 8.

3.2.2. Seat Performance Analysis

In the design of functional bamboo powder-based composite seats, three core performance indicators—load-bearing mechanical performance, UV resistance, and water resistance—are critical. These factors not only determine the seat's durability in outdoor environments but also directly impact its safety, appearance, stability, and environmental sustainability. Based on previous experimental results and performance testing, the following sections will provide a detailed analysis of these three aspects: load-bearing mechanical performance, UV resistance, and water resistance.

Load Bearing Mechanical Performance Testing

In order to evaluate the load-bearing mechanical performance of outdoor chairs made from bamboo powder composite materials, this study assess their load-bearing capacity, structural stability, and mechanical integrity under conditions simulating outdoor use.

Firstly, to test the chair panel, a rolling test was conducted using a three-wheeled vehicle and a medium-sized truck. The vehicle was slowly driven onto the chair panel made from modified bamboo powder, with its wheels completely covering the panel, and held in place for 15 s before being moved away. The experimental results show that the chair panel did not undergo significant deformation during the vehicle's passage, and the surface remained flat, free from cracks or other structural damage. After multiple repeated tests, the panel maintained its shape and structural integrity, demonstrating excellent compressive performance.

Sunscreen Performance Test

In order to evaluate the sun protection performance of the designed outdoor chair under long-term exposure to sunlight, an experiment was conducted by simulating outdoor ultraviolet radiation. The chair was continuously irradiated with 365 nm ultraviolet light for 7 days. The purpose of the test was to analyze the aging of the chair's surface materials under ultraviolet radiation and assess their UV resistance, in order to determine their durability and sun protection effectiveness for outdoor use. Figure 9a shows the chair surface before aging. By comparing the UV-visible spectra before and after the aging experiment (Figure 9b), it was observed that the chair surface retained good UV absorption ability after aging, with a notable increase in UV absorbance in the 300–400 nm range. This can be attributed to the penetration of UVA radiation into the material, which further strengthens the UV curing of the EP. This process results in denser chemical chain segments, darkening the color of the chair's surface and causing a red shift in the UV spectrum. As a result, the absorbance in the visible light range also increased.

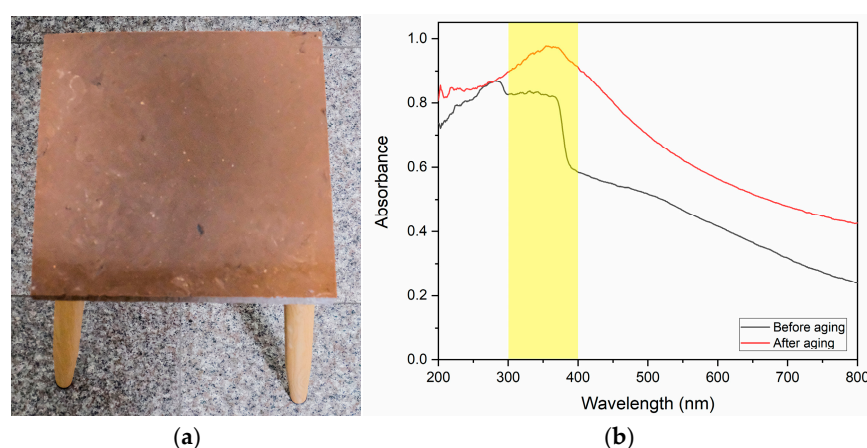


Figure 9. (a) Surface of chair after UV aging, (b) comparison of UV visible spectra before and after aging experiment.

Water Resistance Testing

In order to simulate extreme weather conditions, such as rain or high humidity outdoors, and evaluate the water resistance of the outdoor chair in humid and rainy environments, the chair's surface was removed and fully immersed in room temperature water for 24 h. The chair legs, made of metal, were excluded from the testing. Changes in mass before and after immersion were recorded, and the appearance, gloss, color, and material structural integrity of the surface were compared, with particular attention given to any swelling, cracking, discoloration, or other forms of damage. Based on the data analysis, after soaking for 24 h, no significant changes in the mass of the chair surface were observed (Table 3). The material exhibits a low water-absorption rate, indicating that the three-dimensional network structure of the chair surface effectively reduces water infiltration. During the experiment, no common structural damages such as surface cracking, bubbling, fading, swelling, or deformation were observed after immersion. The material maintained its appearance and structural stability, indicating that the chair's outdoor waterproof performance meets the basic requirements and ensures a long service life.

Table 3. Changes in quality of chair panels over time after immersion in water.

[illegible][illegible]

Carbon Reduction Effect

Currently, outdoor seating is predominantly made from plastic materials. To assess the environmental benefits of bamboo powder-based outdoor seats, a comparison of the carbon footprint across their entire life cycle—ranging from raw material production, manufacturing, and utilization, to sales, use, and disposal—was conducted. The carbon reduction data for each stage is presented in Table 4.

Table 4. Carbon Reduction Data.

Life Cycle Stage	Bamboo Powder Composite Seat (kg/CO ₂ -eq)	Plastic Chair (kg/CO ₂ -eq)	Carbon Reduction Growth Rate (%)
Production of material	2.023	7.5	73%
Product processing and utilization	0.986	3.48	72%
Sales and usage stage	−2.0	0.0	200%
Abandonment stage	−0.2	3.69	105%
Total life cycle	−6.441	14.671	144%

(1) Raw material production stage

Bamboo powder composite materials are primarily composed of bamboo powder, and their production process effectively sequesters carbon (−7.8 kg CO₂ eq/kg) through bamboo forest photosynthesis. While the production and transportation of chemicals such as sodium hypochlorite and ZnO contribute to emissions, the overall carbon footprint remains low at 2.023 kg CO₂ eq. In contrast, traditional plastic chairs are predominantly derived from petrochemical sources, with polyethylene (PE) or polypropylene (PP) having a production emission factor of approximately 2.5 kg CO₂ eq/kg. This results in an estimated carbon footprint of 7.5 kg CO₂ eq per plastic chair. Therefore, outdoor seating made from bamboo powder composite materials demonstrates a 73% reduction in carbon emissions compared to conventional plastic alternatives.

(2) Product processing and utilization stage

The seat made of bamboo powder composite material and welded to a 304 stainless steel frame, as well as the fabric anti-slip pad, are processed and manufactured using various techniques. The carbon footprint during the processing stage is 0.986 kg CO₂ eq. By contrast, the injection molding process of traditional plastic chairs has a carbon footprint of 3.48 kg CO₂ eq under electricity consumption, resulting in higher energy consumption. Outdoor seats based on bamboo powder composite materials achieved a 72% reduction in emissions compared to traditional plastic materials.

(3) Sales and usage stage

Bamboo powder composite outdoor chairs have a lifespan exceeding 10 years, during which each chair can achieve a carbon sequestration effect of −2.0 kg CO₂ eq. In contrast, plastic chairs have a lifespan approximately 5 years shorter than that of bamboo powder composite chairs and do not exhibit any carbon sequestration during use. As a result, the bamboo powder composite outdoor chair achieves a 200% reduction in emissions over its service life, significantly enhancing its sustainability.

(4) Abandoned landfill stage

The outdoor seats made from bamboo powder composite materials demonstrate significant environmental benefits during the disposal phase. Approximately 70% of the material can be reused or recycled, entering the next lifecycle, while the remaining 30% naturally degrades or is landfilled, resulting in an emission of only −0.2 kg CO₂ eq. In contrast, plastic chairs are primarily disposed of through incineration (70%) and landfill (30%), which generates a total carbon footprint of 3.69 kg CO₂ eq. Consequently, bamboo powder composite materials achieve a 105% reduction in emissions during the waste stage.

compared to plastic chairs. Compared with the commonly used plastic outdoor seats, the outdoor seats prepared in this study showed a 144% increase in carbon reduction effect.

Therefore, the sustainability indicators of the modified bamboo powder composite outdoor chair, including carbon footprint, energy consumption, and recyclability, were analyzed across its entire lifecycle. The results demonstrated a significant reduction in emissions, further confirming the environmental benefits of the material. This not only validates the sustainable development potential of the design but also provides a scientific foundation for its future industrial application.

The preparation process of bamboo powder-based composite materials, such as delignification treatment and the blending of bamboo powder with ZnO and EP, has been maturely applied in multiple industrial fields and has the potential for future industrial production. According to the cost standards of the Chinese market, the production cost of bamboo powder and the energy consumption cost generated during the processing of bamboo powder composite materials are estimated to be lower than those of PE or PP. According to the sustainability indicators of the carbon footprint of outdoor chairs made of bamboo powder composite materials throughout their entire lifecycle, the high recycling rate of modified bamboo powder materials for outdoor furniture directly increases the environmental value of the material during the disposal stage. The equipment and machinery used in the early material preparation and production process of the product have minimal wear and tear, and do not require large-scale modifications; and during the injection molding process of chair surface materials, the use of existing machinery also reduces a lot of process cost losses, as production can be directly integrated into existing outdoor furniture production lines. Based on the economic cost analysis of large-scale production above, the feasibility of its industrial application has been verified.

4. Conclusions

In this study, a bamboo powder-based material with a three-dimensional network structure, exhibiting enhanced bonding strength and durability, was developed for outdoor chair design. This material was prepared through the delignification and activation of bamboo powder, combined with physical and chemical modification via zinc oxide dispersion treatment. Based on the results and discussions presented, the following conclusions can be drawn:

- (1) According to FTIR and TGA, the 1.5% ZnO-Board exhibited the best overall performance across multiple indicators. As the ZnO content increased to 1.5%, the surface activity of the modified bamboo powder was enhanced, the number of bubbles was reduced, and the interface interactions between the materials were improved. The average UV absorbance of the 1.5% ZnO-Board in the 275–400 nm range was slightly lower than that of the 0.5% ZnO-Board. However, the compressive strength of the 0.5% ZnO-Board was significantly weaker, well below that of the 1.5% ZnO-Board. After compressive testing, no cracks were observed on the surface of the 1.5% ZnO-Board. Additionally, the 1.5% ZnO-Board exhibited good thermal stability and water absorption resistance, demonstrating its potential for applications in outdoor furniture design.
- (2) The 1.5% ZnO-Board was applied in the design and manufacturing of outdoor chairs. Following the principles of “less is more” and green sustainable development in modern design, a functional bamboo powder-based outdoor seat was created with a simple shape that harmonizes with outdoor environmental colors. In practical testing, the chair demonstrated excellent mechanical strength, durability, UV resistance, and waterproof performance.
- (3) The outdoor seats prepared by our research institute also demonstrated good carbon reduction effects. Compared to commonly used plastic outdoor chairs, the outdoor chairs prepared in this study achieved a 144% improvement in carbon emission reduction.

The functional modification approach proposed in this study offers an effective solution for the use of bamboo-based composite materials in outdoor furniture. By preparing bamboo powder-based composites and integrating them into outdoor seat designs, the materials exhibit enhanced UV resistance, thermal stability, hydrophobicity, and significantly improved mechanical properties. These advancements enable the chairs to better meet the demands of complex outdoor environments. The findings open up new possibilities for the development and application of sustainable bamboo-based materials, facilitating the broader use of composite, environmentally friendly materials in the outdoor furniture sector. The research holds substantial theoretical value and practical significance, advancing the field of sustainable material innovation.

Author Contributions: Conceptualization, Y.F.; Methodology, Z.Z.; Software, Y.F.; Resources, Y.L.; Data curation, J.L.; Writing-original draft, Y.F.; Writing-review & editing, Z.Z.; Supervision, J.L.; Visualization, Y.L.; Project administration, Y.F.; Funding acquisition, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Project of the Ecological Habitat Academic Committee of the Chinese Architectural Society: CEH-ASC-2023-04.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Modarress, B.; Ansari, A.; Ansari, A. Sustainable Development and Ecological Deficit in the United Arab Emirates. *Sustainability* **2020**, *12*, 6180. [\[CrossRef\]](#)
2. Parkar, S.; Mulukh, R.; Narhari, G.; Kulkarni, S.J. An Insight Into Treatment, Reuse, Recycle and Disposal of Biodegradable and Non-biodegradable Solid Waste. *SSRN Electron. J.* **2021**. [\[CrossRef\]](#)
3. Cobirzan, N.; Muntean, R.; Thalmaier, R.A. Recycling of Mining Waste in the Production of Masonry Units. *Materials* **2022**, *15*, 594. [\[CrossRef\]](#)
4. Chainey, S.; Shijagurumayum, C.; Thokchom, S. Review on the Use of Bamboo as A Construction Material. *SAMRIDDHI J. Phys. Sci. Eng. Technol.* **2022**, *14*, 47–51. [\[CrossRef\]](#)
5. Nilsson, B.; Peterson, B.; Omtanke, D.M.; Gotaland, V. Sweden Design Med Omtanke: Participation and sustainability in the design of public sector buildings. *Design Stud.* **2011**, *32*, 235–254. [\[CrossRef\]](#)
6. Namaki, P.; Vegesna, B.S.; Bigdellou, S.; Chen, R.; Chen, Q.; Li, M.E. An Integrated Building Information Modeling and Life-Cycle Assessment Approach to Facilitate Design Decisions on Sustainable Building Projects in Canada. *Sustainability* **2024**, *16*, 4718. [\[CrossRef\]](#)
7. Bovea, M.D.; Vidal, R. Materials selection for sustainable product design: A case study of wood based furniture eco-design. *Mater. Des.* **2004**, *25*, 111–116. [\[CrossRef\]](#)
8. Dilik, T.; Gursoy, S. Effect of Wood Based Materials on Current Use and Production of Outdoor Furniture from the Perspective of Human Dimension. *J. Eng. Appl. Sci.* **2016**, *2*, 35–44.
9. Clark, G.; Kosoris, J.; Hong, L.N.; Crul, M. Design for Sustainability: Current Trends in Sustainable Product Design and Development. *Sustainability* **2009**, *1*, 409–424. [\[CrossRef\]](#)
10. González-García, S.; Gasol, C.M.; Lozano, R.G.; Moreira, M.T.; Gabarrell, X.; Pons, J.R.I.; Feijoo, G. Assessing the global warming potential of wooden products from the furniture sector to improve their ecodesign. *Sci. Total Environ.* **2011**, *410*, 16–25. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Fu, L.N.; Tan, M.Y.; Shi, R.K.; Wang, H.B.; Fu, J.J. Insights into high temperature pretreatment on cellulase processing of bamboo. *Therm. Sci.* **2012**, *16*, 1524–1528. [\[CrossRef\]](#)
12. Li, C.Y.G.Y. Effects of different management approaches on soil carbon dynamics in Moso bamboo forest ecosystems. *Catena Interdiscip. J. Soil Sci. Hydrol. Geomorphol. Focus Geoecol. Landsc. Evol.* **2018**, *169*, 59–68. [\[CrossRef\]](#)
13. Borchani, K.E.; Carrot, C.; Jaziri, M. Untreated and alkali treated fibers from Alfa stem: Effect of alkali treatment on structural, morphological and thermal features. *Cellulose* **2015**, *22*, 1577–1589. [\[CrossRef\]](#)
14. Jin, C.N.S. Effect of bamboo fibers with different coupling agents on the properties of poly(hydroxybutyrate-co-valerate) biocomposites. *J. Appl. Polym. Sci.* **2019**, *136*, 47533. [\[CrossRef\]](#)
15. Xie, Y.; Hill, C.A.S.; Xiao, Z.; Militz, H.; Mai, C. Silane coupling agents used for natural fiber/polymer composites: A review. *Compos. Part A Appl. Sci. Manuf.* **2010**, *41*, 806–819. [\[CrossRef\]](#)

16. Ma, Y.; Qian, S.; Hu, L.; Qian, J.; Lopez, C.A.F.; Xu, L. Mechanical, thermal, and morphological properties of PLA biocomposites toughened with silylated bamboo cellulose nanowhiskers. *Polym. Compos.* **2019**, *40*, 3012–3019. [[CrossRef](#)]
17. Niu, S.; Han, G.; Chen, X.; Liu, J.; Wang, C. Changes in Physical Properties and Microstructure of Bamboo-Plastic Composites with Different Bamboo Powder/Polybutylene Succinate Ratios, Polypropylene, and Polyethylene. *Forests* **2024**, *15*, 478. [[CrossRef](#)]
18. Gruell, G.; Tscherne, F.; Spitaler, I.; Forsthuber, B. Comparison of wood coating durability in natural weathering and artificial weathering using fluorescent UV-lamps and water. *Eur. J. Wood Wood Prod.* **2014**, *72*, 367–376. [[CrossRef](#)]
19. Liufu, S.C.; Xiao, H.N.; Li, Y.P. Thermal analysis and degradation mechanism of polyacrylate/ZnO nanocomposites. *Polym. Degrad. Stabil.* **2005**, *87*, 103–110. [[CrossRef](#)]
20. Yu, Y.; Jiang, Z.; Wang, G.; Tian, G.; Song, Y. Surface functionalization of bamboo with nanostructured ZnO. *Wood Sci. Technol.* **2012**, *46*, 781–790. [[CrossRef](#)]
21. Du, H.; Mao, F.; Li, X.; Zhou, G.; Zhou, Y. Mapping Global Bamboo Forest Distribution Using Multisource Remote Sensing Data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote. Sens.* **2018**, *11*, 1458–1471. [[CrossRef](#)]
22. Ferreira, E.; Kalliola, R.; Ruokolainen, K. Bamboo, climate change and forest use: A critical combination for southwestern Amazonian forests? *Ambio* **2020**, *49*, 1353–1363. [[CrossRef](#)]
23. Feng, X.; Tan, S.; Dong, Y.; Zhang, X.; Xu, J.; Zhong, L.; Yu, L. Mapping Large-Scale Bamboo Forest Based on Phenology and Morphology Features. *Remote Sens.* **2023**, *15*, 515. [[CrossRef](#)]
24. Dong, J.; Xiao, X.; Menarguez, M.A.; Zhang, G.; Qin, Y.; Thau, D.; Biradar, C.; Moore, B. Mapping paddy rice planting area in northeastern Asia with Landsat 8 images, phenology-based algorithm and Google Earth Engine. *Remote Sens. Environ.* **2016**, *185*, 142–154. [[CrossRef](#)] [[PubMed](#)]
25. Liu, X.; Zhang, Z.F. Study on the Design of Outdoor Furniture Made of Recombinant Bamboo. *Appl. Mech. Mater.* **2013**, 397–400, 907–910. [[CrossRef](#)]
26. Zhou, Z.; Wei, Y.; Wang, J.; Wang, G.; Chen, S. Experimental study on the feasibility of using innovative biomass bamboo aggregate for cementitious materials. *Ind. Crop Prod.* **2024**, *217*, 118864. [[CrossRef](#)]
27. Hubbell, C.A.; Ragauskas, A.J. Effect of acid-chlorite delignification on cellulose degree of polymerization. *Bioresour. Technol.* **2010**, *101*, 7410–7415. [[CrossRef](#)] [[PubMed](#)]
28. Cui, C.W.; Yang, C.; Bao, J.; Huang, X.J.; Zeng, X.F.; Chen, J.F. Monodispersed ZnO Nanoparticle-Poly(methyl methacrylate) Composites with Visible Transparency for Ultraviolet Shielding Applications. *ACS Appl. Nano Mater.* **2020**, *3*, 9026–9034. [[CrossRef](#)]
29. Calvo, M.E.; Castro Smirnov, J.R.; Míguez, H. Novel approaches to flexible visible transparent hybrid films for ultraviolet protection. *J. Polym. Sci. Part B Polym. Phys.* **2012**, *50*, 945–956. [[CrossRef](#)]
30. Zhang, Y.; Yu, Y.; Lu, Y.; Yu, W.; Wang, S. Effects of heat treatment on surface physicochemical properties and sorption behavior of bamboo (*Phyllostachys edulis*). *Constr. Build. Mater.* **2021**, *282*, 122683. [[CrossRef](#)]
31. Liu, C.; Wang, S.; Shi, J.; Wang, C. Fabrication of superhydrophobic wood surfaces via a solution-immersion process. *Appl. Surf. Sci.* **2011**, *258*, 761–765. [[CrossRef](#)]
32. Zhang, H.; Chu, X.; Ding, Q.; Zhao, G.; Li, H. Study on the UV aging resistance of ZnO-modified epoxy resin by experiments and MD simulation. *Polym. Eng. Sci.* **2024**, *64*, 5903–5914. [[CrossRef](#)]
33. Șomoghi, R.; Semenescu, A.; Pasăre, V.; Chivu, O.R.; Nițoi, D.F.; Marcu, D.F.; Florea, B. The impact of ZnO nanofillers on the mechanical and anti-corrosion performances of epoxy composites. *Polymers* **2024**, *16*, 2054. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.