Enhanced Resistance to Decay and Mildew for Moso Bamboo (*Phyllostachys edulis*) through *in-situ* Metal Particle Impregnation

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Bamboo has become increasingly attractive for applications in construction and engineering due to its rapid growth, renewability, and a high strength-to-weight ratio. However, the poor natural resistance to mold limits its potential in the building industry. Conventional antifungal and decay-resistant treatments developed by domestic and international researchers often suffer from drawbacks such as human and environmental toxicity or poor leaching resistance. In this study, aiming to enhance the decay and mold resistance of moso bamboo (*Phyllostachys edulis*), a high-voltage electrostatic field was employed to excite metallic particles and embed them into the bamboo surface and interior, where they formed stable chemical bonds with active functional groups. White-rot fungi, brown-rot fungi, and *Aspergillus flavus* were used to assess resistance, with environmental scanning electron microscopy (ESEM) and other techniques employed to evaluate antifungal performance. Results indicated that bamboo treated at the voltage of 60 kV for 12 h exhibited decay and mold resistance slightly lower than that of chromated copper arsenate (CCA)-treated bamboo but higher than that of untreated bamboo; while high-voltage electrostatic-treated bamboo possessed superior leaching resistance compared with CCA-treated bamboo.

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Keywords: Bamboo; High-voltage electrostatic treatment; Decay resistance; Mold resistance; Leaching resistance; Environmental scanning electron microscopy

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INTRODUCTION

Moso bamboo (*Phyllostachys edulis*) was originally described as *Bambusa edulis* by Carrière (1866) and was later transferred to the genus *Phyllostachys* by J. Houzeau de Lehaie in 1906, belonging to the Bambusoideae subfamily of the Poaceae family (Huang *et al.* 2023). It is a type of fast-growing and renewable material with excellent mechanical properties (*e.g.*, high strength-to-weight ratio), making it increasingly attractive for construction and engineering applications (Shu *et al.* 2019, 2021, 2022). Although moso bamboo is classified as Class I in natural decay resistance, its mildew resistance is relatively low, with a damage index up to 4 (Ran *et al.* 2021). The cell walls of bamboo are composed of three main structural polymers (cellulose, hemicellulose, and lignin), serving as the primary nutrient source for decay fungi (Li *et al.* 2025). Compared with wood, bamboo contains higher amounts of non-cell wall constituents, such as reducing sugars, starch, and proteins, which increase susceptibility to molds, staining fungi, and soft-rot fungi. Pioneer microorganisms could alter the pH, permeability, and nutrient composition of the surface, which promotes the growth of decay fungi and accelerates deterioration; moreover, the prolonged mildew exposure might further reduce the mass and mechanical strength of bamboo (Bao *et al.* 2025).

Normally, the service life of untreated bamboo is shorter than two years, which can be extended to around seven years by limiting outdoor exposure (Fan *et al.* 2023). For permanent structures, GB 50068 (2018), a minimum design service life of 25 years is required, where effective mildew and decay protection strategies are important. Bamboo preservation methods are largely adapted from wood treatment techniques. Currently, waterborne preservatives, such as CCA (chromated copper arsenate), ACQ (alkaline copper quaternary), and CA (copper azole), are most frequently used (Lee *et al.* 2001; Wang *et al.* 2008; GB/T 27654 2011; LY/T 3195 2020; Chen *et al.* 2025). However, the high toxicity of CCA restricts its application; the less toxic copper-based preservatives exhibit limited leaching resistance and potential environmental risks (Nurdiah 2016; Li *et al.* 2025), which lead to the dilemma. The high longitudinal but poor transverse permeability of bamboo further reduces preservative penetration, making conventional wood preservatives difficult to be employed (Lee *et al.* 2001). Previous studies have proposed various approaches to improve the decay and mold resistance of bamboo. For example, Zhang *et al.* (2024) enhanced the anti-mold performance of bamboo boards through vacuum impregnation combined with an epoxy resin-microcapsule coating process. Liu *et al.* (2023) modified bamboo using a boric acid-borax mixed solution at a 1:2 ratio, thereby improving its decay resistance. Liao *et al.* (2024) pretreated bamboo powder under high-temperature and high-pressure conditions with biological factors, such as sugars and laccase produced by white-rot fungi, which enhanced the mechanical properties of self-bonded fiberboards. Wu *et al.* (2022) applied four anti-mold agents: boric acid, copper sulfate, aluminum phosphate sol, and aluminum silicate sol to bamboo and reported a resistance ranking of copper sulfate > aluminum silicate sol > boric acid > aluminum phosphate sol. Chen *et al.* (2023) showed that deep carbonization treatment at 185 °C enhanced mold resistance, while Fan *et al.* (2023) introduced cinnamaldehyde into bamboo *via* an *in-situ* Mannich reaction and obtained improved anti-mold performance. He *et al.* (2023) removed the waxy coating from the outer epidermis of bamboo using alkaline and copper salt solutions to open the surface pores, thereby improving mold resistance. However, these studies have not addressed the leaching resistance of anti-decay agents, and some of the materials used may pose environmental concerns.

High-voltage electrostatic (HVE) excitation can generate nanometer-sized metal particles that are capable of penetrating bamboo pits (Liu 2017; Ju *et al.* 2020). Previous studies demonstrated that silver particles effectively enhance fiber material durability (He 2020), while nickel particles, though less antibacterial, are more economical and exhibit bactericidal properties (Ji and Shi 2023). In order to further reduce costs, in this study, HVE impregnation of nickel particles was employed to form stable chemical bonds with bamboo active groups, aiming to develop a low-cost, energy-efficient, environmentally friendly, and leach-resistant method to enhance the decay and mildew resistance of bamboo. To evaluate the effectiveness of this treatment and its potential for large-scale application in bamboo construction, a HVE field was employed to impregnate nickel particles into both the surface and interior of bamboo. The prepared particle can form stable chemical bonds with active groups in the bamboo structure, thus enhancing its decay and mildew resistance.

EXPERIMENTAL

Materials

The 5-year-old moso bamboo was collected from Liyang, Changzhou, Jiangsu Province, China. For the untreated control group, bamboo with a wall thickness of 10 ± 0.5 mm^2 was cut into 20 mm-long rings using a sliding table saw, and then further processed into 20 mm × 20 mm × wall thickness specimens using a miniature band saw, to serve as controls.

The nickel source was derived from the electrode material used in the high-voltage electrostatic (HVE) system. The electrodes were fabricated from AISI 304 stainless steel sheets with a thickness of 1 mm (chemical composition: 0Cr18Ni9), in which nickel is present as an alloying element with a typical mass fraction of approximately 8% to 10%. This material provides good electrical conductivity and corrosion resistance, ensuring the stability of the high-voltage electric field during treatment.

For those specimens under HVE treatment, bamboo culms with a maximum outer diameter of 80 mm and a wall thickness of 10 ± 0.5 mm^2 were cut into 800-mm-long segments using a sliding table saw with nodes removed. Before HVE activation treatment, the segments were air-dried and then oven-dried to a moisture content of 5.5 ± 0.5%. After treatment with HVE-excited nickel particles, the bamboo was sawn into specimens measuring 20 mm × 20 mm × wall thickness using a miniature band saw and set aside for testing.

Both HVE-treated and untreated materials were placed at an equilibrium moisture content of approximately 12% for later use.

Test Apparatus and Specimen Treatment

The main instruments and equipment used in this study are listed in Table 1.

Table 1. Test Instruments and Equipment Used in This Study

Equipment Name	Model/Specification	Manufacturer
Panel saw	D-54518 Niersbach	PROXXON (Germany)
HVE corona charging	SPX-150C	Jingcheng Electronic Co., Ltd. (Zhaoqing, Guangdong)
High-voltage electric field control unit	SPX-150A	Jingcheng Electronic Co., Ltd. (Zhaoqing, Guangdong)
Circulating water vacuum pump	SHB-3A	David Science & Education Equipment Co., Ltd. (Hangzhou)
Micro band saw	MBS240/E	PROXXON (Germany)
Vernier caliper	150T	Mynatec (Germany)
Digital constant-temperature water bath	HH-4	Guohua Electric Appliance Co., Ltd.
Constant temperature and humidity chamber	HWS-250	Jinghong Experimental Equipment Co., Ltd. (Shanghai)
Environmental scanning electron microscope (ESEM)	Quanta200	FEI Company (Netherlands)
Electronic balance	BS423S	Meiyingpu Instrument Manufacturing Co., Ltd. (Shanghai)

A HVE generator (manufactured by Jingcheng Electronics Co., Ltd., Zhaoqing, Guangdong, China) was used for the treatment. A custom HVE setup was designed for the node-removed bamboo specimens (see Fig. 1).

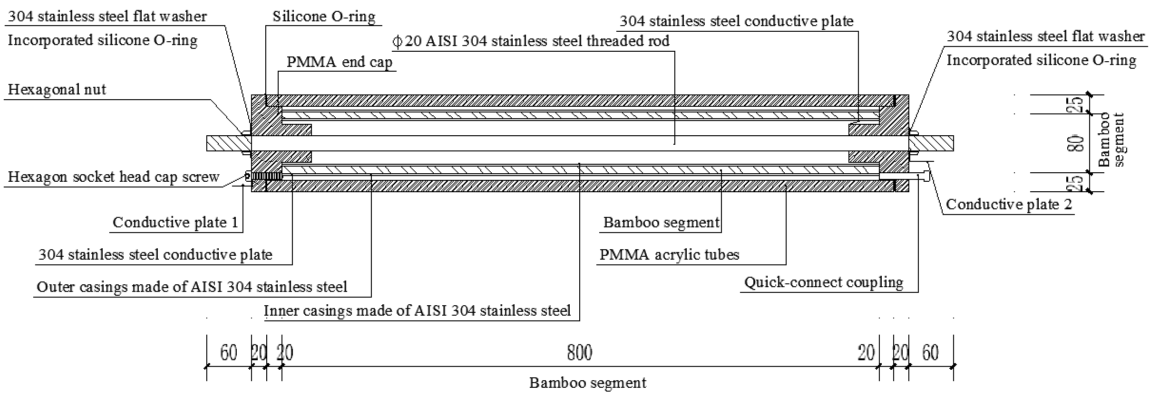


Fig. 1. High voltage static test device

A 1-mm-thick AISI 304 stainless steel sheet (chemical composition: 0Cr18Ni9) was tightly wrapped around the inner and outer surfaces of each bamboo segment. The outer sheet was secured with 2-mm soft steel wires at 100 mm intervals to ensure intimate contact. Conductive plate 1 was connected to the high-voltage generator, while conductive plate 2 was grounded, inducing the movement of metal particles from the outer to the inner bamboo surface. Silicone O-rings were used to seal the end caps with the acrylic tube, and hex nuts and screws secured the assembly. A quick connector linked the vacuum generator, which was activated prior to the high-voltage treatment to evacuate air from the acrylic tube to -0.080 ± 0.010 MPa. Vacuum was maintained until the end of the electrostatic treatment.

To ensure a uniform electric field distribution during HVE treatment, the electrode spacing must be kept constant and the high-voltage power supply stable during the test. At the same time, the sample should be placed in the center of the electrode, and an appropriate distance should be maintained between the electrode and the sample to prevent local electric field concentration or discharge phenomena. The experimental setup photo is shown in Fig. 2.

Fig. 2. Setup of high-voltage static test

Based on previous research (He *et al.* 2020), two factors were investigated: (1) applied voltage: 40, 50, 60, and 70 kV for 12 h each; (2) treatment duration: 6, 12, 18, and 24 h at 60 kV. After treatment, specimens were equilibrated under indoor conditions (25 °C, 65% relative humidity) for 4 weeks. Six replicates per treatment condition were prepared with six specimens per bamboo segment, with a total of 36 specimens per condition for decay and mildew testing. Additionally, 36 specimens under the treatment of 60 kV voltage for 12 h were used for leaching tests before decay and mildew assessment.

CCA was selected as a reference preservative due to its widespread use and high resistance to both decay and leaching. The solution concentration was 3%. A total of 72 specimens were prepared: 36 of them were directly subjected to decay and mildew tests, while the other 36 specimens were first subjected to leaching tests before decay and mildew evaluation. An additional 36 untreated specimens were used as controls.

The CCA treatment was performed using a vacuum-pressure method. Specimens were weighed (± 0.001 g), immersed in the preservative, and subjected to vacuum at -0.080 to -0.085 MPa for 20 min, followed by 5 min at atmospheric pressure. Specimens were removed, wiped with filter paper to remove excess solution, and weighed to determine an average retention of 15.7 ± 1.1 kg/m³. Treated specimens were air-dried under indoor conditions (25 °C, 65% relative humidity) prior to testing.

Methods

Leaching test

Leaching tests were conducted following the GB/T 29905 (standard 2013) and AWPA E11 (2016). Both HVE-treated and CCA-treated specimens (36 of each) were submerged in 180 mL deionized water in 500-mL beakers and stirred with a magnetic bar. Deionized water was replaced at 6, 24, 48, 96, 144, 192, 240, 288, and 336 h (nine times in total). Specimens were then air-dried at 25 °C and 65% relative humidity.

Decay resistance test

Decay tests were carried out according to GB/T 13942.1 (2009) and BS EN 113 (1997). White-rot fungus (*Phanerochaete chrysosporium*) and brown-rot fungus (*Gloeophyllum trabeum*) were used. Cultures were prepared on 90-mm Petri dishes containing 25 mL of malt agar (1.5% agar, 4% malt by weight) and sealed with parafilm. Then they were incubated at 28 ± 2 °C and 75 to 85% relative humidity for 10 days. The cultivation processes of white-rot fungus and brown-rot fungus are illustrated in Fig. 3(a) and Fig. 3(b), respectively.

(a) White-rot fungus (b) Brown-rot fungus (c) *Aspergillus flavus*

Fig. 3. Anti-biodegradation and anti-fungal culture

Twelve specimens were prepared for each strain. After random numbering, the specimens were placed in an oven at 103±2 ℃ and dried to constant weight. After weighing each specimen, it was wrapped in absorbent paper and kept in a steam sterilizer at normal pressure for about 30 minutes to bring the moisture content of the sample to the range 40 to 60%. After cooling, it was ready for use.

Every 2 weeks, specimens were removed, mycelia cleared, oven-dried to constant weight, cooled, and reused. The test continued for 12 weeks. Mass loss was calculated as,

$$\text{Mass loss (\%)} = (m_1 - m_2)/m_1 \times 100 \quad (1)$$

where m_1 and m_2 are the oven-dry weights (g) before and after testing, respectively. Decay ratings are summarized in Table 2.

Table 2. Decay Ratings

Mass Loss	Decay Resistance Grade	Decay Ratings
0 ~ 10 %	Highly resistant	I
11 ~ 24 %	Resistant	II
25 ~ 44 %	Moderately resistant	III
＞45 %	Non-resistant	IV

Mildew Resistance Test

Mildew tests followed the GB/T 18261 (2000) standards. The procedure was to inoculate the mycelium into a petri dish and cover the dish with Parafilm sealing film. The next step was to incubate in an environment with a temperature of 25 to 28 °C and a relative humidity of 85% for about 7 days.

A total of 12 specimens were randomly numbered and placed in an oven at 103±2 ℃ to dry to constant weight. After weighing each specimen, it was wrapped in absorbent paper and kept in a steam sterilizer at normal pressure for about 30 min to make the moisture content of the sample reach 40 to 60%. After cooling, it was ready for use.

The culture of *Aspergillus flavus* is shown in Fig. 3(c). After 4 weeks, infection areas were visually assessed and damage values calculated according to Table 3. Fungicidal efficiency was determined as,

$$\text{Efficiency (\%)} = (1 - D_t/D_0) \times 100 \quad (2)$$

where D_t and D_0 represent the mean damage values of treated and untreated specimens, respectively.

The infection area of the specimens was scored visually as five grades: 0, 1/4, 1/2, ¾, and 1.

Table 3. Damage Value of Specimen Mildew

Deterioration Rating	Hyphal Coverage Area
0	No visible mycelium on specimen surface, no apparent color alteration
1	Surface colonization < 25%
2	Surface colonization 25% to 50%
3	Surface colonization 50% to 75%
4	Surface colonization > 75%

The schematic diagram of the experimental process in this paper is shown in Fig. 4

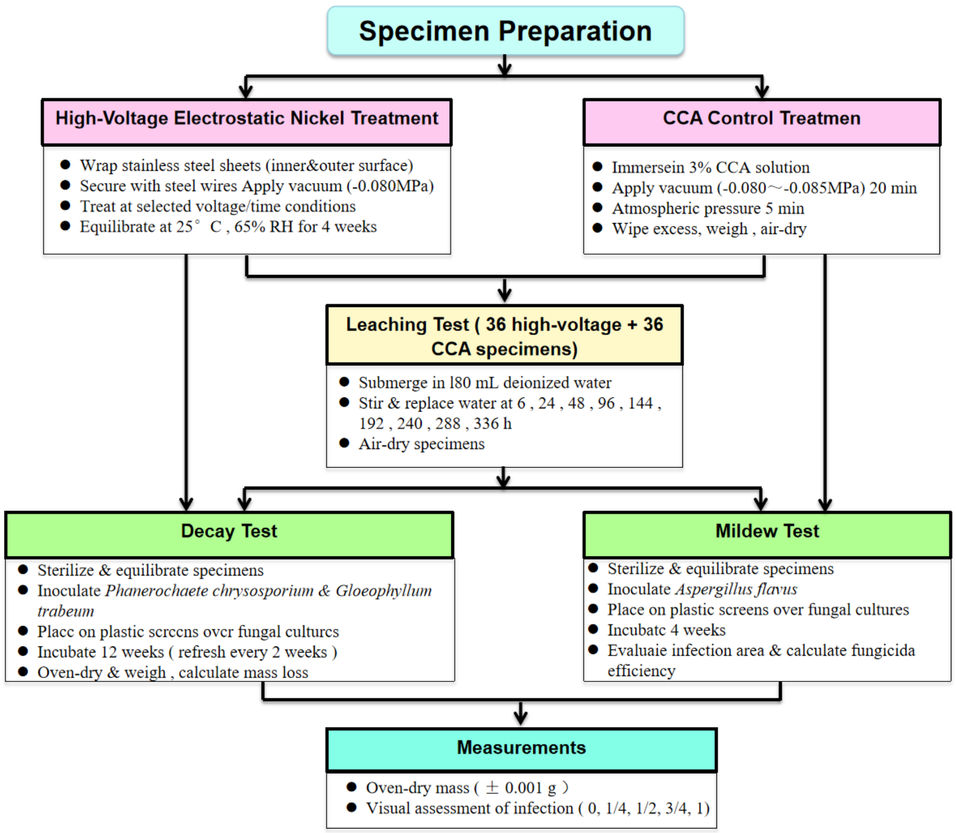


Fig. 4. Schematic diagram of the experimental process

RESULTS AND DISCUSSION

Mechanism of HVE-induced Metal Particles

The surface morphology of bamboo after HVE treatment is shown in Fig. 5. As observed, HVE treatment with metallic Ni resulted in numerous irregular black spots on the surface of bamboo, which may adversely affect its aesthetic appearance. This phenomenon is primarily attributed to the excitation of Ni particles under HVE fields, leading to the deposition of excited-state Ni particles onto the bamboo surface, with some particles forming *in-situ* chemical bonds with oxygen-containing groups in the bamboo cell walls (He *et al.* 2020).

Fig. 5. Surface of bamboo after HVE treatment

An HVE-induced metal particle deposition model was established, as illustrated in Fig. 6. Under increasing voltage, the number of excited metal particles and electrons rose. When these collide with chemical groups in bamboo, more broken and free chemical bonds and ions (*e.g.*, -COOH and -CHO) interact with the material surface (Solodovniko *et al.* 2011; Klarhöfer *et al.* 2010). The authors' previous studies indicated that under suitable HVE treatment duration the content of active groups significantly increases, particularly on the outer bamboo layer (bamboo green) compared to the inner layer (bamboo yellow) (Ju *et al.* 2020; Cui *et al.* 2022). This difference is primarily due to the higher lignin and cellulose content in the bamboo green, which generates more broken chemical bonds, oxygen-containing functional groups, and active sites under high-voltage excitation (Li *et al.* 2014).

The chemical interaction between metal particles and bamboo functional groups significantly enhances the surface coverage of excited Ni particles. Ni particles also exhibit antibacterial properties, disrupting fungal cells and inhibiting their proliferation by penetrating the cell membrane and inducing severe oxidative stress (Dizaj *et al.* 2014). Higher Ni particle concentrations in the material lead to greater damage and dissociation of wood-decaying fungi cells (Kim *et al.* 2012).

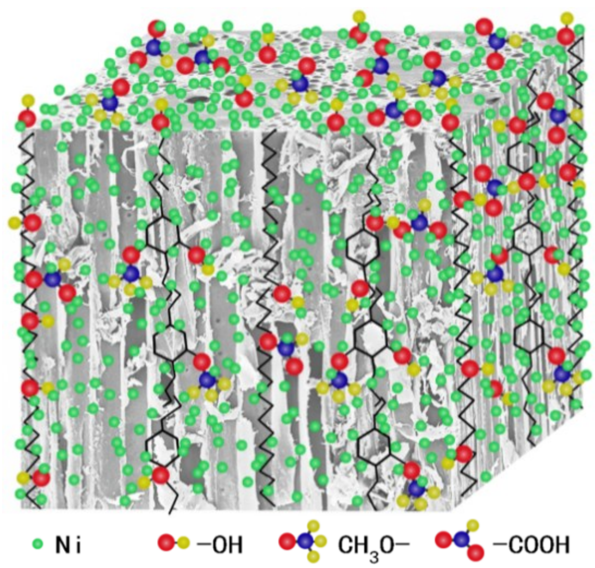


Fig. 6. High-voltage static induced metal particle model

Microscopic Analysis of Decay-Resistant Bamboo

Wood-decaying fungi secrete degrading enzymes that initially utilize small molecular carbon sources and hemicellulose as nutrients for mycelial growth. The mycelium subsequently spreads along cell lumens, further secreting enzymes to degrade hemicellulose and lignin into small acids or lipids, forming grooves under the mycelium (Zhang *et al.* 2012). The enzymatic degradation process is illustrated in Fig. 7 (Wu *et al.* 2021).

According to Li *et al.* (2012), the primary pathway for fungal spread in bamboo is through the secondary xylem vessels, followed by pits in the cell walls. The most severely damaged cells are small parenchyma cells, sieve tubes, and companion cells within vascular bundles, and adjacent parenchyma cells.

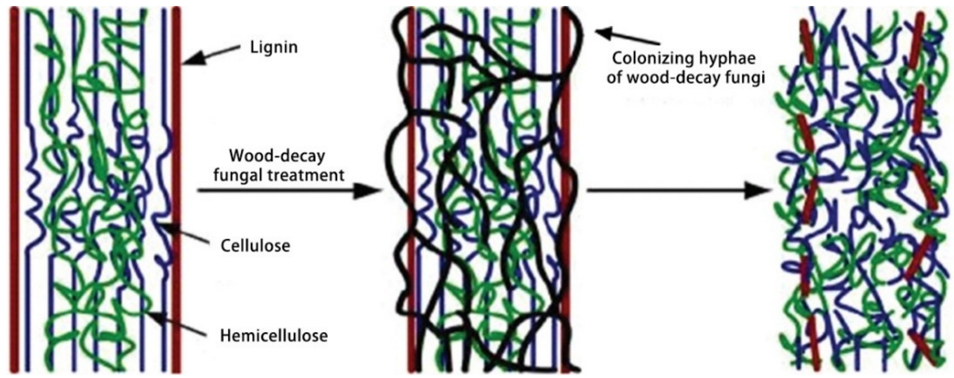
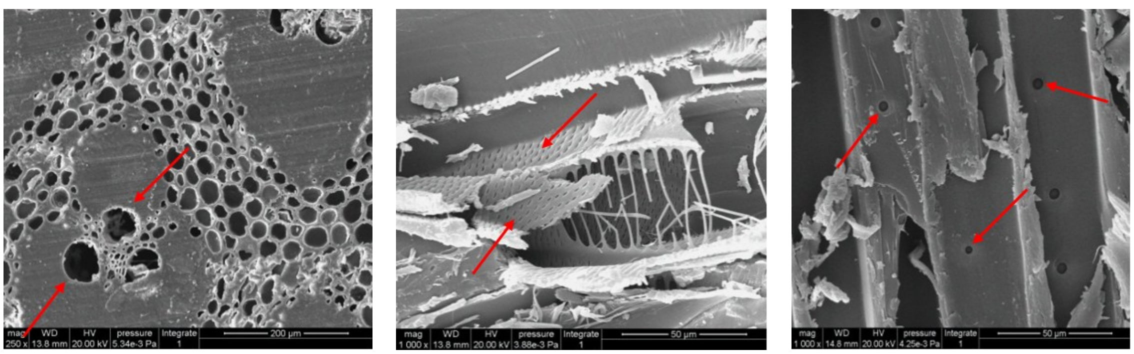


Fig. 7. Physical surface after HVE treatment

In this study, bamboo specimens treated with HVE at 60 kV for 12 h were subjected to decay tests, and their microstructures were examined using environmental scanning electron microscopy (ESEM), as shown in Fig. 8. No fungal hyphae or perforations were observed in the secondary xylem vessels, sieve tubes, or pits, and the lumen walls appeared smooth without significant grooves, indicating good decay resistance at the microscopic level.



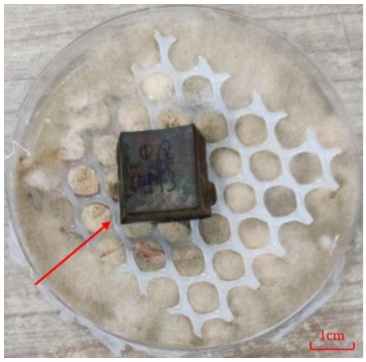
(a) Metaxylem vessels (b) Sieve tubes (c) Pit membranes

Fig. 8. ESEM of bamboo after corrosion resistance test

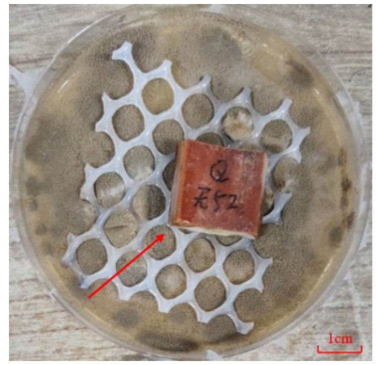
Evaluation of Antifungal Performance

Bamboo antifungal performance was assessed using *Aspergillus flavus* after 4 weeks, following the method described in GB/T 18261 (2000). Typical infection areas of treated specimens are shown in Fig. 9.

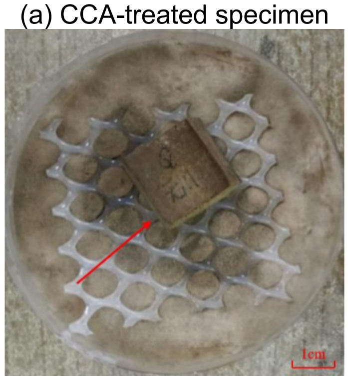
The CCA-treated bamboo exhibited excellent antifungal performance, with only sparse fungal colonies on the longitudinal section. The specimens treated with HVE at the voltage of 60 kV showed slightly more fungal growth than CCA-treated specimens, but infection areas remained small, with damage ratings of 0 to 1. Fungal growth occurred mainly along the longitudinal section of the bamboo, where secondary xylem vessels act as primary fungal pathways (Kim *et al*. 2012). In contrast, those untreated specimens presented poor antifungal performance, with surfaces almost fully covered by fungi and a damage rating of 4. Reducing the voltage to 40 kV increased fungal infection areas compared to the specimens under voltage of 60 kV, but the areas remained lower than those untreated, with damage ratings of 1 to 3.



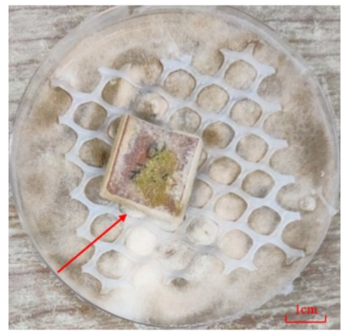
(a) CCA-treated specimen



(b) HVE-treated specimen (60 kV)



(c) HVE-treated specimen (40 kV)

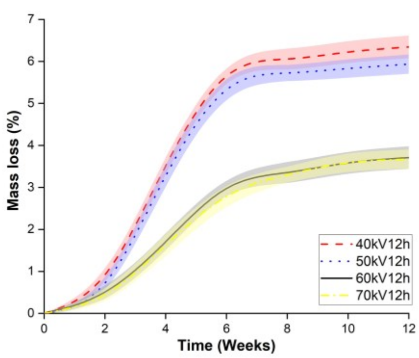


(d) Untreated control specimen

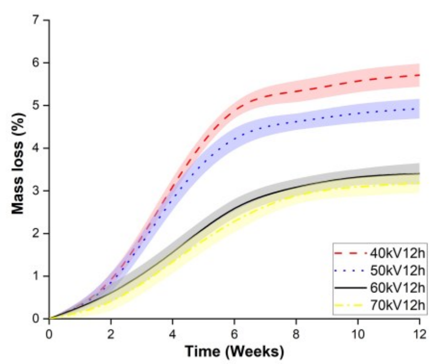
Fig. 9. Infected area of typical processing material specimen

Effect of HVE Parameters on Bamboo Decay Resistance

When under the same HVE treatment duration (12 h), the specimens were treated at the voltage of 40, 50, 60, and 70 kV, respectively. Decay tests were performed by removing fungal hyphae every two weeks, oven-drying, and measuring mass loss values. The mass loss values over time under white-rot fungal exposure are presented in Fig. 10(a).



(a) White-rot fungal

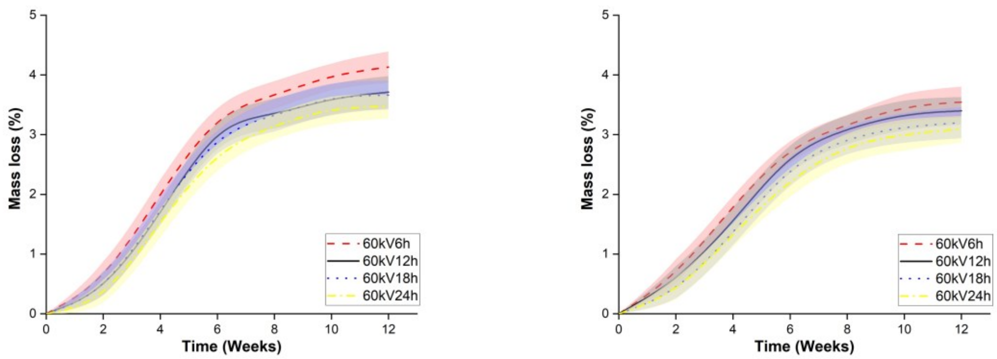


(b) Brown-rot fungal

Fig. 10. Variation of mass loss with voltage under different fungal exposure

As shown in Fig. 10, increasing voltage led to lower mass loss, indicating the enhanced resistance of bamboo to white-rot fungi. Mass loss was relatively low during the first two weeks, increased between 2 to 6 weeks, and stabilized thereafter. The initial low mass loss was attributed to fungal growth consuming nutrients in the medium, while subsequent growth in bamboo vessels required additional nutrients, during which enzymatic degradation of cellulose, hemicellulose, and lignin occurred. Notably, at 60 kV, the mass loss of the specimens decreased significantly, suggesting optimal adsorption and chemical interaction of excited Ni particles with bamboo cell wall functional groups (Liu 2017; Ji and Shi 2023). Similar trends were observed under brown-rot fungal exposure, as shown in Fig. 10(b). Higher voltage enhanced decay resistance. Mass loss values of these specimens were again lower in the first two weeks and then concentrated in weeks 2 to 6.

In this test, bamboo specimens were treated for 6, 12, 18, and 24 h, respectively, at 60 kV. White-rot fungal mass loss results are shown in Fig. 11(a), and brown-rot fungal mass loss percentages are shown in Fig. 11(b). A longer treatment for bamboo slightly decreased mass loss, but reductions were marginal beyond 12 h. Thus, it can be summarized that treatment duration for 12 h under 60 kV voltage represented the optimal HVE treatment method for bamboo of both white-rot and brown-rot decay resistance.



(a) white-rot fungi (b) brown-rot fungi

Fig. 11. Variation of mass loss with time under different fungal exposure

Effect of HVE Parameters on Bamboo Antifungal Performance

In this test, specimens treated for 12 h at the voltages of 40, 50, 60, and 70 kV were evaluated against *Aspergillus flavus*. Damage ratings were used to calculate average antifungal efficacy, as shown in Fig. 12.

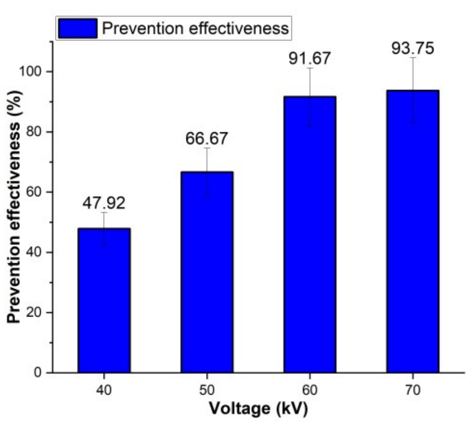


Fig. 12. Variation of prevention effectiveness with voltage

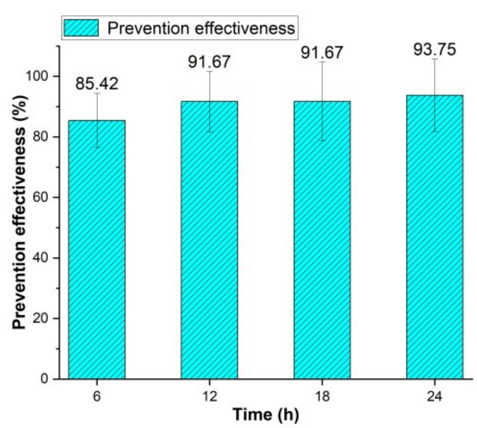


Fig. 13. Variation of prevention effectiveness with time

The results showed that the antifungal efficacy of specimens in this test increased with increased voltage, which reached 91.67% at the voltage of 60 kV. As can be seen from the graph, when the voltage increased from 50 kV to 60 kV, the improvement in the prevention effectiveness of the specimen was much greater than when the voltage increased from 60 kV to 70 kV, which indicated that 60 kV is a more suitable dosage.

In this section, the specimens under the voltage of 60 kV with treatment durations of 6, 12, 18, and 24 h were tested, and the results are shown in Fig. 13. The antifungal efficacy of the specimens improved with the increasing treatment duration. Specifically, the prevention effectiveness exceeding 90% at the group under 12-h treatment. However, as time went on, the improvement in the prevention effectiveness was slight. Taking both the effect and the time cost into consideration, the 12-h duration was an optimal antifungal performance solution.

Performance Evaluation of HVE-treated Bamboo

The mass loss results for bamboo treated at the voltage of 60 kV for 12 h were compared with the untreated and CCA-treated specimens (see Fig. 14). Untreated bamboo exhibited mass loss values of 7.72% (white-rot) and 6.64% (brown-rot), respectively, corresponding to natural decay resistance grade I (Ran *et al*. 2021). HVE treatment could significantly reduce the mass loss of bamboo, although the loss was slightly higher than those under CCA-treated. Furthermore, white-rot fungi caused greater mass loss in the specimens than brown-rot fungi, which is consistent with their broader enzymatic activity (Kim *et al*. 2012).

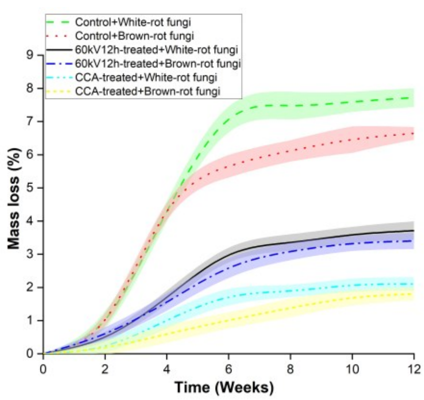


Fig. 14. Mass loss under the action of wood-rot fungi

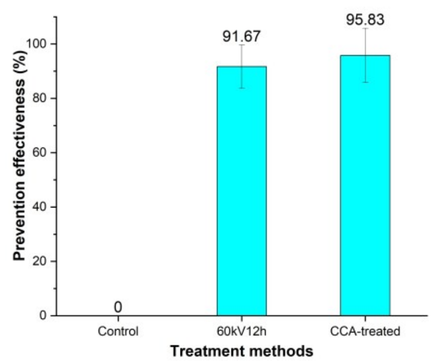


Fig. 15. Prevention effectiveness of each treatment method

Figure 15 shows the prevention effectiveness of each treatment method for the bamboo specimens, where the antifungal efficacy of bamboo under the condition of the 60 kV voltage and 12-h HVE-treated duration was compared with those untreated and CCA-treated specimens. Results showed that the specimens under HVE treatment achieved 91.7% efficacy, which was slightly lower than those CCA-treated specimens (95.8%).

Leaching tests followed GB/T 29905 (2013) and AWPA E11 (2016), with specimens immersed in deionized water for nine cycles up to 336 h. After the leaching test, the bamboo specimens were subjected to a decay resistance test. The mass of the specimens before and after the test was determined by the drying method, and the mass loss was calculated. Post-leaching decay tests showed increased mass loss of specimens (as shown in Fig. 16). The CCA-treated bamboo exhibited an increase of mass loss to 123.7% for white-rot and 98.3% for brown-rot, respectively, while the increase of HVE-treated bamboo specimens was only 32.6% and 2.94%, respectively, indicating superior leaching resistance for HVE-treated specimens. Post-leaching antifungal tests (Fig. 17) revealed increased infection areas on the bamboo specimens, but they were still smaller than the area on untreated bamboo.

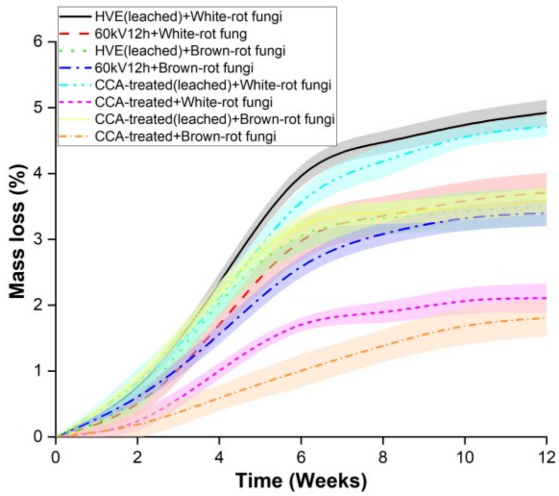


Fig. 16. Mass loss of wood rot fungi after leaching

(a) CCA-treated (b) HVE (60 kV)

Fig. 17. Infected area of specimen after leaching test

Calculated antifungal efficacy (as shown in Fig. 18) of these specimens remained above 80%, with HVE-treated bamboo showed a smaller reduction (6.82%) compared to CCA-treated bamboo (13.04%), demonstrating the better retention of antifungal properties of HVE-treated specimens after leaching.

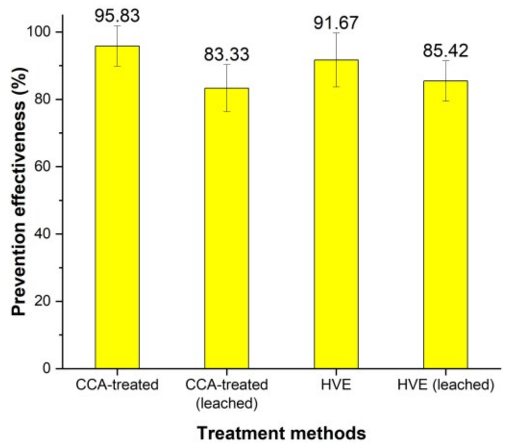


Fig. 18. Prevention effectiveness of each treatment method before and after leaching

CONCLUSIONS

This study evaluated the decay resistance and mold resistance of bamboo subjected to high-voltage electrostatic (HVE) treatment. The mechanism was explored through an HVE-induced metal particle model, and the antibacterial properties were verified at the microstructural level using environmental scanning electron microscopy (ESEM). Mass loss values and control efficacy were measured for both untreated and leached specimens, and the results were compared with untreated and chromated copper arsenate (CCA)-treated bamboo. The main findings are summarized as follows:

1. The HVE treatment with metallic Ni generated multiple irregular black spots on the bamboo surface. These black spots may affect the aesthetic appearance, thereby impacting the commercial/market acceptance of the treated bamboo. Under HVE fields, higher voltages produced more excited metal particles and electrons. Ni particles formed chemical bonds with bamboo chemical groups, increasing the coverage of excited metal particles on the bamboo surface.
2. The ESEM analysis showed that no mycelia or perforations were apparent in the latewood vessels, sieve tubes, or pits-areas that are typically prone to decay. Cell lumen walls were smooth with no evident erosion grooves. Natural bamboo exhibited mass losses of 7.72% and 6.64 % under white-rot and brown-rot fungi, respectively, corresponding to durability Class I. The resistance of bamboo to both fungi increased with higher treatment voltages and longer durations, with voltage having a more pronounced effect than treatment time. A treatment of voltage at 60 kV for 12 h was identified as the optimal HVE decay-resistance process. The decay resistance of HVE treated bamboo was slightly lower than that of CCA-treated bamboo but higher than that of untreated bamboo. Under the same conditions, white-rot fungi caused greater mass loss than brown-rot fungi.
3. Natural bamboo showed poor mold resistance, with a damage rating of 4. Bamboo treated at the voltage of 60 kV for 12 h exhibited only minor mold growth near the latewood vessels of some longitudinal sections, with small surface infection areas of *Aspergillus flavus* and damage ratings of 0 to 1. Bamboo treated at the voltage of 40

kV for 12 h showed damage ratings of 1 to 3. Mold control efficacy increased with both treatment voltage and duration, with voltage having a more pronounced effect. Treatment at the voltage of 60 kV for 12 h achieved a control efficacy of 91.67%, demonstrating good mold resistance.

4. Bamboo treated with HVE-induced Ni particles exhibited superior leaching resistance compared to CCA-treated bamboo. After leaching tests, mass losses of CCA-treated bamboo under white-rot and brown-rot fungi were increased by 123.7% and 98.3%, respectively, whereas those under the voltage of 60 kV for 12 h electrostatically treated bamboo were increased by only 32.6% and 2.9%. The damage rating for mold infection of 60 kV voltage for 12 h treated bamboo was 2. The control efficacy against *Aspergillus flavus* was decreased by 13.0% for CCA-treated bamboo and 6.8% for HVE treated bamboo, with both treatments maintaining control efficacy above 80%.

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Conflict of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Use of Generative AI

No AI tools were used in the paper.

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