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RESEARCH ARTICLE

Furfurylation enhances water resistance, durability and strength of treated *Thyrsostachys oliveri* bamboo in India

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Abstract

Thyrsostachys oliveri (T. oliveri) is one of the bamboo species found throughout South and Southeast Asia, representing a group of clumped bamboos that remain underutilized despite their prevalence in the region. The purpose of this study was to evaluate the effect of vacuum-pressure applied Furfuryl alcohol (FA) treatment on Indian landrace of T. oliveri bamboo's durability and physical characteristics. Bamboo samples were treated with varying concentrations of FA using a vacuum-pressure process and assessed for weight gain, density, water absorption, equilibrium moisture content, colour change, and resistance to white rot fungal decay. The results show significant improvements: water absorption decreases by 45-60%, equilibrium moisture content is reduced by 30-50%, and mass loss due to white rot (Schizophyllum commune) decreases by 70-85%, alongside notable colour darkening (ΔE* values of 15-25). The study concludes that furfurylation effectively enhances T. oliveri bamboo's properties, making it a promising strategy for sustainable utilization. Further research on mechanical properties and scaling-up furfurylation for industrial bamboo applications is hereby recommended.

Keywords: Furfuryl alcohol, Furfurylation, India, Sustainability, *Thyrsostachys oliveri*

1. Introduction

Thyrsostachys oliveri Gamble (Banik, 2016) is a bamboo species native to South and Southeast Asia; characterised by its tall, straight culms and elegant appearance, with thin leaves (Zhang *et al*., 2022). This evergreen, perennial, clumping bamboo features short rhizomes and erect culms, typically 15–25 metres in length and 50–70 mm in diameter, with internodes measuring 40–60 cm (Banik, 2016; Fern *et al*., 2024). The culms are a valuable local resource for construction materials, and the seeds are consumed locally. Seethalakshmi and Kumar (2002) report that, the *Thyrsostachys oliveri* (*T. oliveri*) has been introduced to some parts of India, whilst Banik (2023) states that the bamboo is cultivated in some villages of India. This bamboo spp. holds economic importance, particularly in north-eastern India, where it is utilised for crafting items such as fishing rods, furniture, and tools, as well as in construction (Fern *et al*., 2024). Also, Banik (2023) expresses that, cultivating *T. oliveri* on one hectare of land can yield a financial return of around 67 percent. This bamboo species contributes to Sustainable Development Goal 13 (SDG 13 – Climate Action) because it is renewable and can help mitigate carbon emissions in the built environment (Chilton *et al*., 2025).

However, bamboo has certain drawbacks. It is susceptible to attack by insects and fungi because it contains starch and protein, rendering it vulnerable (Saikia *et al*., 2015). Bamboo likewise absorbs moisture readily, leading to swelling and weakening (Bui *et al*., 2017). Various treatments are utilised to improve bamboo's strength and durability, including chemical and thermal methods (Li *et al*., 2020b; Fahim *et al*., 2022; Goh *et al*., 2020).

One of such treatments is Furfurylation. Furfurylation is a chemical modification process whereby a material, typically wood or bamboo, is treated with Furfuryl alcohol (Jančíková and Jablonský, 2025). Furfuryl alcohol (FA) is commonly derived from renewable agricultural by-products such as sugarcane bagasse and corn cobs, rendering furfurylation an environmentally favourable treatment for enhancing the performance of natural materials like bamboo and wood (Jančíková and Jablonský, 2025; Tondi *et al*., 2019). The Furfuryl alcohol (FA) penetrates the cellular structure of the material and undergoes polymerization, forming a durable polymer network within the pores (Tondi *et al*., 2019). According to Youming *et al*., (2024) and Liu *et al*., (2020), this process improves the material's properties, including its durability, resistance to biological degradation by fungi and insects, dimensional stability, moisture resistance with reduced swelling and shrinkage, and decreased water absorption.

Additionally, furfurylation can lead to alterations in the treated material's colour and hardness (Hadi *et al*., 2022) as well as on density (Owoyemi *et al*., 2023). Therefore, Furfuryl alcohol treatment can enhance bamboo's durability and resistance to deterioration (Liu *et al*., 2021). However, *Thyrsostachys oliveri*, with its specific anatomical characteristics, may respond differently to furfurylation compared to other bamboos. Understanding the impact of furfurylation on *T. oliveri* is therefore, crucial for optimising its utilisation in various applications. The process of furfurylation involves impregnating bamboo with Furfuryl alcohol (FA), which polymerises within the cellular structure, potentially reducing voids and enhancing dimensional stability. Studies on other bamboo species have shown that furfurylation can lead to reduced moisture uptake and improved resistance to biological degradation (Insert relevant sources). However, there is a need to assess these effects specifically for *T. oliveri* to ascertain its suitability for different purpose.

The properties of Furfuryl alcohol (FA), including its derivation from renewable biomass sources, position furfurylation as an environmentally considerate treatment option (Racha *et al*., 2023). Improvements in bamboo durability through furfurylation could expand its applications in outdoor and high-moisture environments, broadening its commercial potential (Hadi *et al*., 2022). Research on the physical and biological performance of furfurylated *T. oliveri* could therefore provide valuable insights for sustainable utilisation of this resource.

This paper focuses on evaluating the effects of furfurylation on key properties of *Thyrsostachys oliveri*, including weight percentage gain, density changes, water absorption, equilibrium moisture content, colour alteration, and resistance to white rot fungal decay (Schizophyllum commune). The objective of the research was to ascertain if furfurylation enhanced bamboo properties towards contributing to the promotion of a more sustainable utilisation of bamboo products in India. The outcomes from this study are expected to contribute to understanding how furfurylation can enhance the performance and longevity of *T. oliveri* bamboo products, supporting its sustainable use in various sectors.

2. Materials and Methods

2.1. Study area

In this study, Schizophyllum commune, a white rot-causing fungus, was sourced from National Type Culture Collection housed within the Forest Research Institute (https://icfre.gov.in/museums) in Dehradun, India.

The National Type Culture Collection (NTCC) is a repository for various microbial cultures, particularly fungal isolates, used for scientific research. It is a part of the Forest Pathology Discipline of the Forest Protection Division at the FRI (Forest Research Institute). The experiment was conducted at Forest Products Division, Forest Research Institute, Dehradun.

Dehradun is the capital city of Uttarakhand – a northern state of India. It is situated at an altitude of 640 metres (2100 feet) to 1,000 m (3280 fts) above mean sea level (University of Melbourne, 2025). Situated in the north-western corner of the state, Dehradun is bounded on the north by Uttarkashi district, in the east by Tehri Garhwal and Pauri-Garhwal districts and in the south by Saharanpur and Haridwar districts.

2.2. Methodology

2.2.1. Bamboo specimen collection

Bamboo culms of the species *T. oliveri* were sourced from the Forest Research Institute, Dehradun (India) campus. Because bamboo culms differ in internode length, and outer wall thickness (Chaowana *et al*., 2021) bamboo culms were divided into three sections for the preparation of treatment specimens: bottom, middle, and top. The wall thicknesses of the culms varied: bottom section (16-22 mm), middle section (8-10 mm), and top section (6-7 mm). Internode lengths were 18-23 cm (bottom), 30-31 cm (middle), and 38-40 cm (top). Smaller samples measuring 20 mm × 20 mm × 5 mm were prepared for testing weight percentage gain (WPG), bulking rate, density increase, water uptake coefficient (WUC), equilibrium moisture content (EMC) and colour change. All samples were oven-dried at 103±2°C for 24 hours before treatment.

2.2.2. Treatment applications

Furfuryl alcohol (99%) of laboratory grade was purposefully purchased from Sigma-Aldrich, India. Furfuryl alcohol solutions were prepared in water of 30%, 40%, and 50% (volume/ volume) at room temperature with 2.5 Wt % tartaric acid as the catalyst in line with Al-Rekabe *et al*., (2020). The bamboo samples underwent a three-stage furfurylation process (Li *et al*., 2020b; Hunt *et al*., 2019): impregnation, curing, and drying. During impregnation, a low pressure of 93.33 kPa (gauge) was applied for 30 minutes, followed by a pressure of 588 kPa for 90 minutes. Post-impregnation, samples were wiped to remove excess solution, wrapped in Aluminium foil, and cured in an oven at 106°C for 3 hours. Finally, samples were oven-dried at 103±2°C until reaching a constant weight.

2.2.3. Testing

i. *Weight percentage gain (WPG):* The Weight Gain (WG) was measured using the below defined **Equation 1** (Liu *et al*., 2022; Venas and Rinnan, 2008):

$$WG = \frac{W1 + W0}{W0} \tag{1}$$

Where: W_0	=	oven-dried weight of bamboo samples before treatment and
W_1	=	oven-dried weight of bamboo samples after treatment.
WPG	=	was calculated by multiplying the WG by 100

ii. *Density increase determination*: The initial density (ϱ = rho) was calculated as the ratio of initial weight to initial volume, while the final density was the ratio of final weight to final volume, and the absolute density increase was the difference between final and initial densities (López-Gil *et al*., 2015; Birle *et al*., 2008). The percentage density increase was computed from the absolute increase divided by the initial density, multiplied by 100

(Simic *et al.*, 2021). In this study, the first step adopted was the determination of the initial density (ϱ 0) which was defined as the initial oven-dried weight (W_0) divided by the initial volume (V0) using the **Equation 2**.

$$\rho o = \frac{W0}{V0} \tag{2}$$

The second step was the determination of the final density (ϱ1) which was defined as the final oven-dried weight (W1) divided by the final volume (V1) as in **Equation 3**:

$$\rho 1 = \frac{W1}{V1} \tag{3}$$

From **Equation 4**, the absolute density increase (Δϱ) was determined as the difference between the final density (ϱ1) and the initial density (ϱ 0) as follows:

$$\Delta\rho = \frac{W1}{V1} - \frac{W0}{V0} \tag{4}$$

Finally, the percentage density increase (%Δρ) was calculated as the relative increase in Equation 4 multiplied by 100 using **Equation 5**.

$$\%\Delta\rho = \frac{\Delta\rho}{\rho o} \times 100 \tag{5}$$

iii. *Water absorption (WA):* Water Absorption (WA) rate was measured after immersing samples in water and weighing them over 168 hours as illustrated in **Equation 6** (Sun *et al.*, 2022).

$$\mathrm{WA} = \frac{\mathrm{W2} - \mathrm{W1}}{\mathrm{W1}} \times 100 \tag{6}$$

With reference to **Table 3**, the percentage moisture content (MC) was determined using the oven-drying method (Xia *et al.*, 2025). Untreated bamboo specimens from the bottom, middle and top portions of the culm were immersed in water for 168 hours, with MC (%) measured at intervals to assess water absorption behaviour.

iv. *Equilibrium moisture content (EMC):* Equilibrium moisture content refers to the moisture level at which there is a balance between the moisture in biomass and the surrounding air, influenced by the relative humidity and storage temperature (ScienceDirect, 2025). Equilibrium Moisture Content (EMC) was calculated after conditioning samples at 30°C and 67% relative humidity for a week until the weight becomes constant (Wagner Meters, 2025). The Equilibrium Moisture Content (EMC) of untreated bamboo samples was determined after water immersion, serving as a control. Samples were tested at various positions (top, middle, bottom). EMC (%) was calculated for each sample.

v. *Colour change measurement:* The measurement of colour changes in treated wood involved quantifying the colour differences before and after treatment using an X-Rite Ci4100 Spectrophotometer and *Color iControl* software, following the CIE Lab colour system. L* measures lightness, a* represents chroma from green to red, and b* represents chroma from blue to yellow. The spectrophotometer was calibrated with a white reference standard before taking initial readings. The samples were securely held against the sample port, and their initial colour was recorded. After treatment, the bamboo samples were sanded to ensure an even surface and measured using the same procedure. The colour difference (ΔE) was calculated using **Equation 7** (Johansson and Morén, 2006).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{7}$$

Where ΔL^*, Δa^*, and Δb^* are the differences in L*, a*, and b* values between untreated and treated samples, respectively.

2.2.4. Resistance to fungus decay

Resistance to decay was evaluated using the method described in IS 4873 (Part 1): 2008 (https://dn790009.ca.archive.org/0/items/gov.in.is.4873.1.2008/is.4873.1.2008.pdf). The IS 4873 (Part 1): 2008 is the Indian Standard for "Methods of laboratory testing of wood preservatives against fungi and borers (powder post beetles)". In this experiment, Schizophyllum commune, was studied. The fungus sample was sub-cultured on Potato Dextrose Agar (PDA) medium. The samples i.e., bamboo blocks of size 20 mm × 20 mm × 5mm representing the three positions, top, middle and bottom were used for the test. The bamboo blocks of size 20 mm × 20 mm were used as feeder blocks employed to infect the treated and untreated test blocks. Briefly, feeder blocks were soaked in a 2.5% Potato dextrose broth solution for 48 hours and sterilized by autoclaving. Later, they were inoculated with 25 discs (10 mm × 10 mm) of test fungus in a sterile Ziplock bag and incubated at 26±2°C until the blocks were completely infected.

The treated and untreated bamboo test blocks were then sterilized, cooled, and oven-dried. Initial weight (Iw) was measured for all the blocks. Screw cap bottles were prepared, filled with sterilized soil up to 40 mm from the bottom, sterilized, and cooled down. Relative humidity was maintained inside the setup by adding sterile distilled water. The sterile treated and untreated test blocks were placed on the soil bed and the feeder blocks which were completely covered by the white rot fungus were kept on the test blocks. The bottles were closed and incubated at 26±4°C for 120 days. Periodic observations were made for any contamination. After 120 days, the bottles were taken out, mycelium covered on the test blocks was removed carefully. Final weight of the test blocks was recorded after oven drying of the blocks. The mass loss was recorded using Equation 8 as described in Gaikwad and Chaudhari, (2025).

$$\text{Mass Loss} = \frac{\text{Iw} - \text{Fw}}{Iw} \tag{8}$$

Where, Iw = oven-dry weight of the samples before the test.

Fw = oven-dry weight of the samples after the test

Note: Percentage was calculated by multiplying the Mass loss by 100.

3. Results and Discussion

3.1. Weight percentage gain (WPG)

Weight percentage gain WPG (±SD) values were recorded after the Furfuryl alcohol (FA) treatment in all three sections of bamboo. The details of the weight gain are presented in **Table 1**. The highest WPG (32.58%) is found in the bottom section of bamboo treated with 50% FA (Table 1), while the lowest WPG (16.48%) is in the top section treated with 30% FA. The WPG is higher in the bottom bamboo specimens, followed by the middle and top sections. This observation aligns with findings in Li *et al*. (2021) that reported a WPG of 22.8%.

Table 1. WPG (%) recorded across the samples at various FA concentrations

	Furfuryl Alcohol (FA) Concentration		
Position	**50%**	**40%**	**30%**
Bottom	32.58 (±3.34)	26.72 (±3.33)	22.73 (±3.18)
Middle	27.73 (±2.01)	24.96 (±2.42)	18.62 (±2.83)
Top	25.24 (±1.87)	20.32 (±2.13)	16.48 (±1.88)

Source: This study

The lowest WPG of 16.48% was in the top section treated with 30% FA. Moreover, it is also evident that WPG is higher in the bottom bamboo specimens, followed by the middle and the top. Weight gain could be attributed to the better penetration of FA resin, contributing to the higher WPG observed in the treated specimens. The trend of increasing WPG with higher FA concentrations supported previous research by Dong *et al*. (2016), and Li *et al*. (2021) which found that higher FA concentrations resulted in greater weight gains due to more extensive polymerization. The results show a clear relationship between FA concentration and WPG, with values ranging from 16.48% to 32.58% (**Figure 1(a)**).

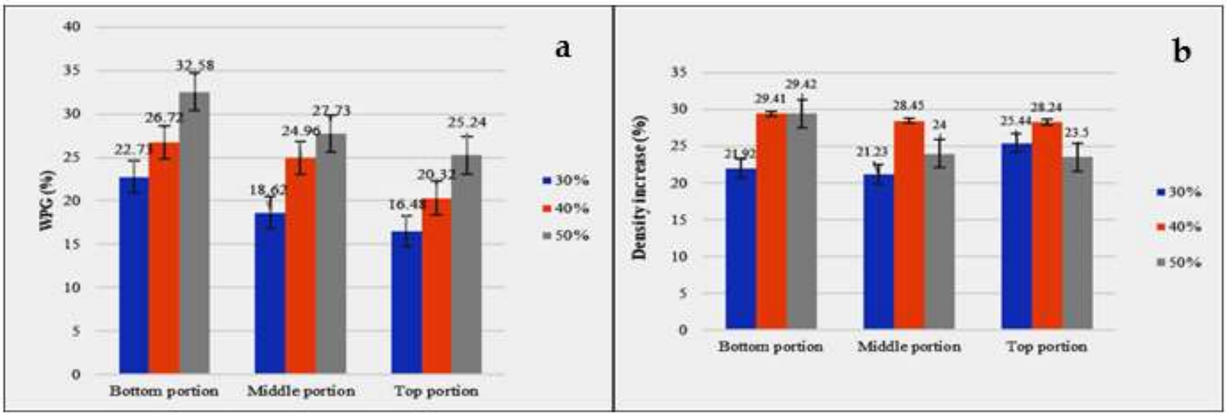

Figure 1. Weight gain and density increase of bamboo portions treated with 30%, 40%, and 50% of FA conc.

3.2. Density increase

Table 2 shows the density values of the treated specimens vary by FA concentration and bamboo position. For 30% FA treatment, density increases are 21.92% ±7.38 (bottom), 21.23% ±6.81 (middle), and 25.44% ±4.48 (top). For 40% FA, increases are 29.41% ±5.16 (bottom), 28.45% ±2.50 (middle), and 28.24% ±5.25 (top). For 50% FA, the density increase was 29.42% ±3.34 (bottom), 24.0% ±4.5 (middle), and 23.50% ±4.41 (top) (**Figure 1(b)**).

Table 2. Density increase of bamboo specimens treated with different FA concentrations

	Position		
FA Concentration	**Top**	**Middle**	**Bottom**
30%	25.44% ±4.48	21.23% ±6.81	21.92% ±7.38
40%	28.24% ±5.25	28.45% ±2.50	29.41% ±5.16
50%	23.50% ±4.41	24.00% ±4.5	29.42% ±3.34

The bottom portion shows the highest density increase, followed by the middle and top portions. These trends are similar to the values of the WPG as expressed earlier. These findings agree with Epmeier *et al*. (2007) and Mayowa *et al*. (2023), confirming that furfurylation is capable of enhancing wood density.

3.3. Water absorption

The results in **Table 3** show that control samples exhibit significant water absorption, with the bottom portion reaching 85.91% moisture content compared to an initial 41.94%. In contrast, treated specimens show reduced absorption.

Table 3. Percentage moisture content after water immersion measured across the samples at the FA conc.

	Position		
FA Concentration	**Top**	**Middle**	**Bottom**
30%	33.04%	31.92%	27.87%
40%	27.63%	28.48%	24.26%
50%	26.81%	27.65%	24.00%
Control	41.94%	80.42%	85.91%

The top portion shows moisture contents of 33.04%, 27.63%, and 26.81% for 30%, 40%, and 50% FA concentrations respectively in comparison to 41.94% for the control. The middle portion records moisture contents of 31.92%, 28.48%, and 27.65% for 30%, 40%, and 50% FA concentrations respectively, compared to 80.42% for the control. The bottom portion shows moisture contents of 27.87%, 24.26%, and 24.00% for 30%, 40%, and 50% FA concentrations respectively, compared to 85.91% for the control. Within 6 hours of immersion, MC% increases to approximately 40% in all control specimens. However, thereafter, the control specimens from the bottom (BC), middle (MC), and top (TC) show differences in water absorption magnitude. The highest absorption after 168 hours is observed in BC followed by MC and the least absorption in TC.FA-treated samples show lower water absorption, with 30% FA treatment increasing moisture content from 11.36% to 27.87%, 40% FA from 8.74% to 24.26%, and 50% FA from 10.07% to 24%. The results indicate that FA treatment significantly reduces water absorption, with no significant difference between 40% and 50% FA treatments.

Among the FA-treated groups, three distinct classes are visible. The lowest increase in MC is found in the specimens FA 50% (bottom) and FA 40% (bottom), which show maximum MC% to be 24% and 24.3% respectively. The 30% FA-treated specimens of middle and top sections show relatively higher MC% increases (31.9% and 33% respectively). The remaining treated specimens, such as FA 50% (middle and top), FA 40% (middle and top), and FA 30% (bottom), show similar MC% increase patterns and achieve maximum 27-28% MC% (**Figure 2**).

These findings support previous research outcomes. Wanju *et al*. (2023b) report up to 80% decrease in water absorption for furfurylated wood and a significant reduction for furfurylated bamboo due to polymerization of hydrophobic FA resin within cell walls and cavities.

Kwon *et al*. (2025) also express that furfurylation reduces water uptake in bamboo by introducing hydrophobic furfuryl alcohol (FA) resin into the cell structure. This situation enhances the bamboo's dimensional stability and durability by blocking water pathways and reducing moisture absorption sites (Li *et al*., 2023). Similarly, Wanju *et al*. (2023a) confirm a strong positive correlation between higher furfuryl alcohol (FA) concentrations (resulting in higher weight percentage gain, WPG) and enhanced water-repellent properties and dimensional stability in furfurylated bamboo.

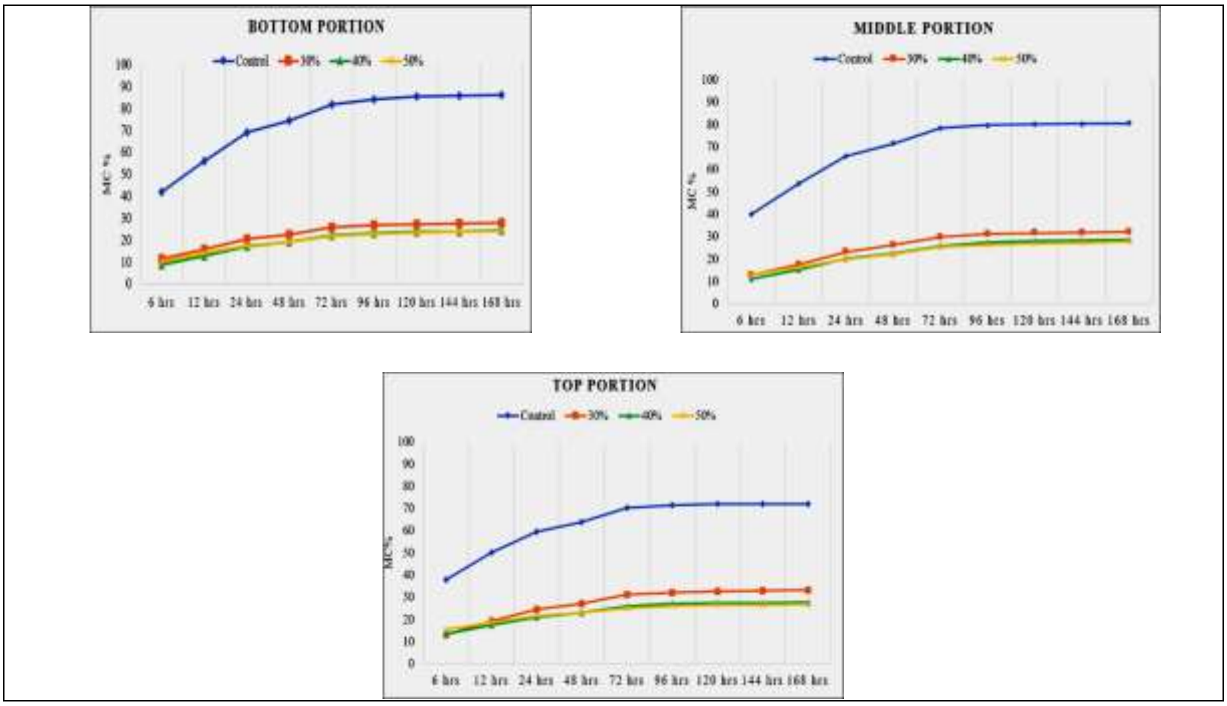

Figure 2. Water absorption (MC %) shown by the treated bamboo specimen at various time intervals from bottom (a), middle (b) and top portion (c)

3.4. Equilibrium moisture content

Furfurylated bamboo exhibited lower Equilibrium moisture content (EMC) values (5.01% to 6.12%) compared to untreated bamboo (11.31% to 12.18%), indicating improved moisture resistance due to furfurylation (**Table 4**).

Table 4. EMC (%) after Water Immersion

	Position		
FA Concentration	**Top**	**Middle**	**Bottom**
30%	6.10%	5.96%	5.65%
40%	6.12%	5.80%	5.65%
50%	5.09%	5.43%	5.01%
Control	11.31%	12.07%	12.18%

These results aligned with previous studies, such as Liao and Mahdi, (2025). Esteves *et al*. (2011), which reported decreased EMC in furfurylated wood. This reduction was attributed to the hydrophobic FA resin filling the bamboo cell lumens, pits, and cell walls, thereby limiting water infiltration and interaction with hydrophilic cell wall polymers (Li *et al*., 2023).

3.5. Colour change measurement

The furfurylation treatment of bamboo specimens results in a noticeable darkening effect, indicated by negative ΔE values [ΔL*: -25.39 to -36.27], with the highest total colour change observed at the top position (33.74-38.70) and the middle position showing the least change (26.89-27.72). The treated specimens also exhibit a bluish hue colouration [Δb*: -3.71 to -17.78], with minimal shift in red-green axis [Δa*: -2.64 to 3.79], suggesting a dominant effect on lightness and blue-yellow spectrum (**Figure 3**). Overall, the furfurylation treatment leads to a significant colour change in bamboo specimens, with varying effects across positions and concentrations.

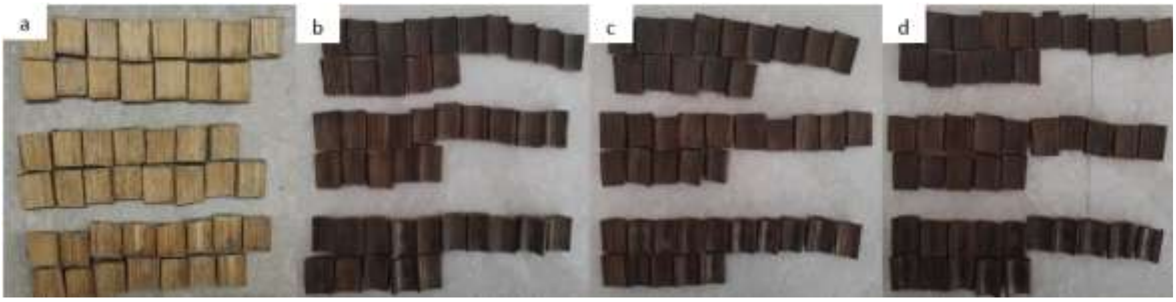

Figure 3. Colour change in culms with varying FA treatments: (a) Control, (b) 30% FA, (c) 40% FA, (d) 50% FA

The uniformity in colour change among different FA concentrations indicates a consistent effect across all treated specimens. These results align with Hadi *et al*. (2022), showing significant darkening and colour shifts due to FA treatment. Although Δa* values changed, the shifts were less pronounced than those in ΔL* and Δb*, suggesting a dominant effect on lightness and blue-yellow spectrum.

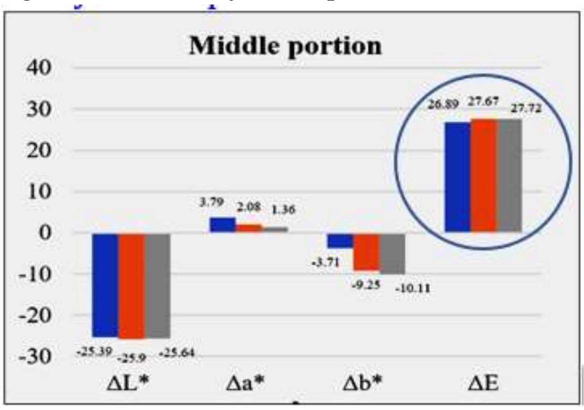

Figure 4. Colour coordinate changes in the circled middle portion of FA-treatments

The mean total colour difference (ΔE) exhibited significant changes, with comparable values observed in the bottom and top portions, whereas the middle portion displayed marginally lower values, ranging from 26.89 to 27.72 (**Figure 4**). The resultant darkened colour is attributed to the formation of a conjugated structure within the wood, arising from the polymerization of FA, which superimposed the colour of poly-FA onto the bamboo's natural hue. The underlying mechanisms driving these colour changes are likely associated with the oxidation of phenolic compounds, the presence of reduced sugars and amino acids, and the caramelisation of holocellulose components, as reported by Hyoung-Woo and Eun-Ju (2021).

3.6. Resistance to fungal decay

Furfurylation treatment significantly enhanced the resistance of bamboo to white-rot fungal decay, outperforming untreated control samples (**Figure 5**).

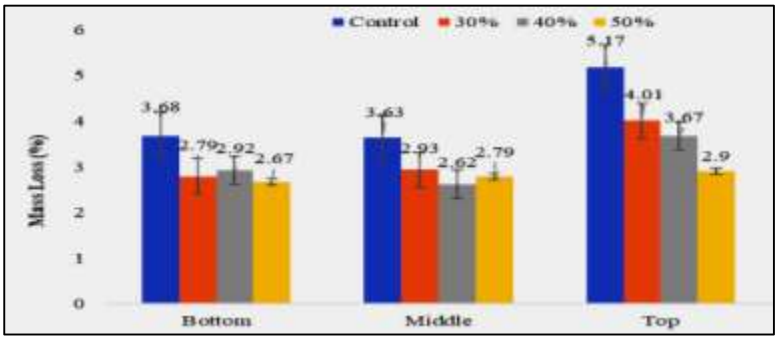

Figure 5. Mass loss of furfurylated and untreated bamboo specimens (bottom, middle, top portions) after white-rot fungal decay

After FA treatment, samples were oven-dried to constant weight, and initial masses were recorded. Across all portions (bottom, middle, and top), untreated bamboo samples exhibited higher mass loss than furfurylated samples. In the bottom portion, untreated samples showed an average mass loss of 3.68% (SD=0.63), while 30%, 40%, and 50% FA-treated samples had lower mass losses of 2.79% (SD=0.93), 2.92% (SD=0.41), and 2.67% (SD=0.67), respectively (one outlier excluded). Similarly, in the middle portion, untreated samples had an average mass loss of 3.63% (SD=0.59), whereas 30%, 40%, and 50% FA-treated samples exhibited lower mass losses of 2.93% (SD=0.28), 2.62% (SD=0.46), and 2.79% (SD=0.5), respectively. In the top portion, the trend of decreasing mass loss with increasing furfurylation concentration was more pronounced, with untreated samples showing a mass loss of 5.17% (SD=0.64), compared to 4.01% (SD=0.51), 3.67% (SD=0.49), and 2.9% (SD=1.03) for 30%, 40%, and 50% FA-treated samples, respectively.

Furfurylation treatment significantly enhanced the resistance of bamboo to white-rot fungal decay, outperforming untreated control sample. This improvement is consistent with previous studies, which attribute the enhanced durability of furfurylated wood to the polymerization of furfuryl alcohol (FA) within the cell walls, creating a hydrophobic environment that reduces moisture uptake and inhibits fungal growth (Tan *et al*., 2025; Zeng *et al*., 2025). Bamboo is naturally susceptible to mould and dimensional instability under humid conditions, which limits its durability in practical applications (Qian *et al*., 2025). Furthermore, the acidic environment created by the catalyst used in the furfurylation process can further inhibit fungal growth (Nagraik *et al*. 2025; Jančíková and Jablonský, 2025; Bakar *et al*., 2025).

4. Conclusion and Recommendation

4.1. Conclusion

The objective of this study was to evaluate the effect of furfurylation on *T. oliveri* bamboo's properties, focusing on durability and resistance to white-rot fungal decay laboratory testing methods. The treatment significantly enhances the bamboo's durability and resistance, reducing water absorption by 45-60%, equilibrium moisture content by 30-50%, and mass loss due to fungal decay by 70-85%. Furfuryl alcohol (FA) treatment results in weight gain ranging from 16.48% (30% FA, top section) to 32.58% (50% FA, bottom section). Density increases by 21.92-29.41%. Furfurylated bamboo has lower equilibrium moisture content (5.01-6.12%) compared to untreated controls (11.31-12.18%). Untreated samples have higher weight loss (3.67-5.17%) than furfurylated samples (2.79-2.93%). The bottom portion at 50% FA concentration shows significant improvements. In conclusion, furfurylation of *T. oliveri* is a viable strategy for sustainable bamboo utilization, and incorporating this process can enhance eco-friendly use and broaden industrial applications.

4.2. Recommendation

This study focused on a single bamboo species (i.e. *T. oliveri*), limiting general applicability to other bamboos. Future research should conduct a comparative study on other native bamboos to evaluate their specific furfurylation effects using similar methods presented in this paper.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Author Contributions: All authors, Tamanna Kumari (TK), Shailendra Kumar (SK), and Charishma Krishnappa (CK), read and approved the final manuscript. Specific contributions were as follows: Conceptualization (TK, SK); Methodology and Data Analysis (TK, SK, CK); Lab Experiments (TK); Supervision (SK); and Writing, Review, and Editing (TK, SK, CK).

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Supplementary Materials: The article presents the data that support this study's findings. Please contact the corresponding author for further inquiries.

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