

Preservative treatment of the bamboos *Dendrocalamus giganteus*, *Bambusa vulgaris* and *Gigantochloa nigrociliata*

Rabeya Khatun^a, Ershad Ahmmed^{b,*}, Samina Ferdousi^c, Md. Abu Rayhan Khan^{c,d},
Md. Obaidullah Hannan^a, Md Ashaduzzaman^a, Arif Sikder^e, Atanu Kumar Das^{f,*}

^a Forestry and Wood Technology Discipline, Khulna University, Khulna 9208, Bangladesh

^b Department of Sustainable Bioproducts, Mississippi State University, MS 39762-9820, USA

^c Department of Chemistry, Mississippi State University, MS 39762-9573, USA

^d Chemistry Discipline, Khulna University, Khulna 9208, Bangladesh

^e Department of Textile Engineering, National Institute of Textile Engineering and Research (NITER), Technology Unit, Dhaka University, Bangladesh

^f Cellulose Technology, Department of Sustainable Materials and Packaging, RISE Research Institutes of Sweden, Hörneborgsvägen 10, Domsjö, Örnsköldsvik 892 50, Sweden

ARTICLE INFO

Keywords:

Bamboo
Physical properties
Preservative
Chromated copper arsenate
Full cell or bethel process

ABSTRACT

Bamboo is crucial as a woody primary raw material for various products in tropical regions. It is also one of the strongest structural materials used in rural areas of developing countries. However, bamboo is susceptible to biodegradation, leading to the need for frequent replacement, which increases costs. Preservative treatment is essential to extend its lifespan. This study evaluated the feasibility of preservative treatment for three bamboo species: *Dendrocalamus giganteus*, *Bambusa vulgaris* and *Gigantochloa nigrociliata*. The Full-Cell (Bethel) process was used to treat bamboo samples with chromated copper arsenate (CCA) ($\text{As}_2\text{CrCuO}_9$). The effectiveness of the treatment was assessed by measuring penetration and retention efficiency in both green and dried bamboo. Results showed that dried bamboo exhibited higher penetration and retention efficiency compared to green bamboo. The average penetration efficiency of dried bamboo was 92.9 %, 91.0 % and 93.9 % for *D. giganteus*, *B. vulgaris* and *G. nigrociliata*, respectively. The retention efficiency was 1.7, 1.5 and 1.8 kg m^{-3} for *D. giganteus*, *B. vulgaris* and *G. nigrociliata*, respectively. These findings indicate that all three bamboo species can be treated effectively with CCA.

1. Introduction

Sustainable materials are becoming increasingly important due to the energy crisis and growing environmental concerns. Non-wood resources, such as bamboo, are being explored as alternatives to wood-based products to help reduce deforestation. Bamboo plays a crucial role as a primary woody raw material for various products, particularly in tropical regions. It is native to nearly every continent except Europe and thrives in tropical and subtropical areas, such as Southeast Asia (Suhaily et al., 2013). Bamboo is especially abundant in the tropics, with over 75 genera and 1250 species, ranging from small grasses to towering giants exceeding 40 m in height and 0.3 m in diameter (Tewari, 1993). Often regarded as one of nature's most valuable gifts, bamboo is widely used for diverse applications. Despite its potential, bamboo remains underutilized in some tropical countries, such as Indonesia and

Malaysia, whereas it contributes significantly to the economies of China and Japan. According to Jinyi and Fawei (2022), China dominates the global bamboo trade, and the target is to contribute to the economy valued at approximately USD 137 billion in 2035 by Chinese bamboo industries. One of bamboo's most remarkable advantages is its rapid growth. It reaches maturity in less than four years, whereas most woody plants take up to 20 years. Its exceptional growth rate, combined with its versatile properties, has made it a sought-after material, particularly in tropical countries. Bamboo has similar characteristics to wood, making it an attractive alternative for various applications. However, due to its unique growth structure and microstructure, specialized techniques are required to fully harness its diverse uses. Advances in technology and scientific research have further enhanced the development of bamboo-based bio-composite products, increasing its relevance as a sustainable material (Bhat et al., 2011).

* Corresponding authors.

E-mail addresses: ershadahmmed85@gmail.com (E. Ahmmed), atanu.kumar.das@ri.se, atanufwt03ku@yahoo.com (A.K. Das).

<https://doi.org/10.1016/j.bamboo.2025.100163>

Received 15 November 2024; Received in revised form 8 April 2025; Accepted 14 April 2025

Available online 15 April 2025

2773-1391/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

A major drawback of bamboo is its low durability against microorganisms (Liese, Tang, 2015; Mehramiz et al., 2021). Bamboo and its components serve as a food and energy source for various microorganisms (Chavan, Attar, 2013). The starch in bamboo attracts some beetles and termites which break down the cellulose and damage the material (Kaminski et al., 2016). As a result, bamboo used for structural purposes in rural and tribal housing often deteriorates within a few years, leading to the need for frequent replacements and increased pressure on bamboo resources. This high demand for replacements negatively impacts the supply of bamboo, even in regions where it is abundant. Extensive research has been conducted in bamboo-producing countries across Asia to enhance the service life of bamboo. In its natural state, most bamboo species have an average durability of less than two years without any protective treatment. However, when stored under cover, untreated bamboo can last between four and seven years (Xu et al., 2013). Several factors influence bamboo's durability, including culm length, wall thickness, harvesting time (Dhawan and Mishra, 2005) and species (Wei et al., 2013). Dhawan and Mishra (2005) also studied bamboo's inherent resistance to termites in relation to the lunar phase and season at the time of harvest. Their findings indicate that bamboo harvested during the moon phase exhibited lower durability against termites compared to bamboo felled during the dark phase.

Bamboo stems, also known as culms, are typically bright green when young and gradually become dull green or yellow as they age. Bamboo is primarily composed of cellulose, hemicellulose and lignin, with minor constituents including resins, tannins, waxes and inorganic salts (Reardon et al., 2013). Additionally, parenchyma cells, which store energy in the form of starch and are essential for the formation of new culms, make up nearly half of the culm's cells (Okahisa et al., 2005). The composition of bamboo varies by species, typically containing around 40 % fibre and 8–10 % (cross-sectional area) conducting tissues such as vessels and sieve tubes (Jiang, 2007; Shibata, 2012). Approximately 10–20 % of the vascular bundles are found in the inner third of the culm wall, while the remaining 50–80 % are located in the outer third (Silva et al., 2006). The vascular bundles towards the edges of the culm are more closely spaced (Li et al., 2007). Most bamboo species have distinct fibre strands positioned on the inner and outer sides of the vascular bundle or both (Silva et al., 2006). Additionally, Silva et al. (2006) observed that vascular bundles are larger at the base of the culm and gradually decrease in size toward the top. Vessels play a crucial role in sap transportation, and their efficiency depends not only on intervessel-bordered pits but also on vessel size and perforation plates (Shibata, 2012). The high starch content in bamboo makes it particularly susceptible to mould, fungi (especially blue-stain fungi) and wood-boring insects such as termites and powder-post beetles (Huang et al., 2014). These may cause significant damage during drying, storage and use. Unlike the heartwood of many trees, bamboo culms do not develop toxic compounds over time, making the entire culm susceptible to degradation and removal (Huang et al., 2014). Bamboo consists of 50–70 % hemicellulose, 30 % pentosans and 20–25 % lignin. The lignin content is unique and influences culm growth. Additionally, bamboo is rich in silica (0.5–4 %), though most of it is concentrated in the outermost 1 mm layer, with very little present in the rest of the culm wall (Sulaeman et al., 2018). Hossain et al. (2022) studied the impact of age and height position on the chemical properties of *Melocanna baccifera* (Roxb.) Kurz and found that the highest holocellulose content (74.66 %) was present in the top portion of three-year-old bamboo, while the bottom portion had the highest lignin (27.83 %) and extractive (5.24 %) content. Similarly, Hossain et al. (2024a) examined the chemical composition and solubility characteristics of *Bambusa bambos* (L.) Voss at different ages and heights, finding that as *B. bambos* aged, its solubility in cold water, hot water and NaOH decreased, while its holocellulose, lignin and extractive content increased. On average, three-year-old *B. bambos* contained 70.5 % holocellulose, 27.6 % lignin and 4.54 % extractives (Hossain et al., 2024). Although bamboo contains trace amounts of waxes, resins and tannins, none of these

compounds are toxic enough to provide significant natural durability (Febrianto et al., 2014). Therefore, bamboo treatment is essential for improving its longevity and resistance to degradation.

Applying the appropriate treatments can extend bamboo's lifespan to 50 years or more, making it a more cost-effective and sustainable material. Chemicals like chromated copper arsenate (CCA), zinc chloride, sodium pentachloro-phenate and boron-based additives are used as preservatives to shield bamboo from fungal degradation and insect infestation. These substances guarantee bamboo's structural integrity and lengthen its lifespan (Sain et al., 2024). Chemical preservation, with or without specialized equipment, provides long-term protection against decay and pests. Depending on the treatment method, chemical preservatives can offer either short-term or long-term protection. Fixing-type preservatives consist of proportionate mixtures of different salts that chemically interact with each other, becoming permanently fixed within the material. The degree of fixation and effectiveness depends on the nature, combination and concentration of the components. In CCA preservatives, chromium aids in fixation, copper protects against decay fungi and soft rot, and the arsenic targets insects and fungi. The fixation process takes several weeks and slow fixation is preferred as it allows for better diffusion and distribution of the preserving salts. CCA treatment is typically carried out using the Full-Cell process developed by John Bethell in 1838, a widely used vacuum-pressure technique. This method ensures the deepest possible penetration and the highest retention of preservatives, particularly in species that are easily treated. By replacing all the air within the bamboo cells, the Full-Cell process maximizes preservative absorption, significantly enhancing bamboo's durability.

This research examined the impact of the Full-Cell process on the treatability of three different bamboo species with CCA. The primary objective was to evaluate the effectiveness of the Full-Cell process in preserving bamboo and to compare treatability across different species. The study assessed the physical properties, penetration and retention of CCA in both green and dried bamboo. Additionally, the influence of nodes and internodes on CCA treatment was analyzed.

2. Materials and methods

2.1. Raw material preparation

Three-year-old bamboo culms from three species, *Dendrocalamus giganteus* Munro, *Bambusa vulgaris*, and *Gigantochloa nigrociliata* (Buse) Kurz (syn. *Gigantochloa andamanica* (Kurz) Kurz), were collected from the nursery of the Forestry and Wood Technology Discipline at Khulna University, Bangladesh. Samples measuring 152.4 mm in length, including both nodes and internodes, were taken from the base, middle, and top sections of the culms of each species. To assess the impact of moisture content, half of the samples from each height position and species were oven-dried at 40 °C until they reached approximately 7 % moisture content, while the remaining samples were left in their green state. All samples were then stored in plastic bags in preparation for preservative treatment. The CCA, supplied by Worth R.D. Industrial Corporation, located at 188 Manicktala Road, Kolkata, West Bengal, 700054, India, was obtained from the Nordic Woods Ltd. Khulna plant in Bangladesh.

2.2. Preservative treatment

In this study, the Full-Cell (Bethell) process was used to treat bamboo samples with 4 % chromated copper arsenate ($\text{As}_2\text{CrCuO}_9$) (CCA). The bamboo samples were placed inside a pressure cylinder, and the door was tightly sealed. To begin the process, a vacuum of at least 30 cm of mercury was applied and maintained for 30 minutes to remove as much air as possible from the bamboo cells. After the vacuum phase, the preservative solution was introduced into the cylinder. Once the cylinder was filled, the vacuum pump was turned off, and pressure ranging

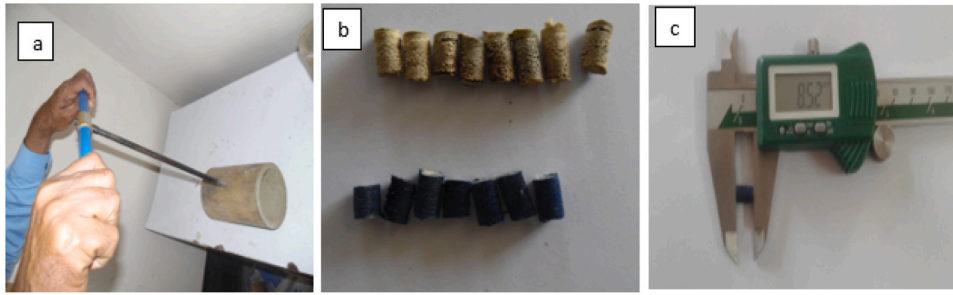


Fig. 1. (a) Bore sample collection, (b) Bore sample and colour-changed bore sample, and (c) Measuring the length of the coloured portion of the bore sample.

from 3.5 to 7.0 kg cm⁻² was applied for 60 minutes to ensure deep penetration of the preservative. Following the pressure treatment, a final vacuum of 33 cm of mercury was applied for approximately 15 minutes to remove any excess preservative from the bamboo surface. This procedure was carried out for both green and dried samples. The treatment parameters were determined through a trial-and-error approach to optimize preservation efficiency.

2.3. Characterization

2.3.1. Physical properties

The density, moisture content (MC), shrinkage along diameter (SD) and shrinkage along thickness (ST) of *D. giganteus*, *B. vulgaris*, and *G. nigrociliata* were measured. The density was measured for the sample with a dimension of 4 cm × 2 cm × bamboo thickness. The bamboo thickness was 0.7–1.9 cm. The density of the air-dried samples was measured with an MC of 18 %. The length and diameter of the samples for, MC, SD and ST were 4 cm and 0.7–11.5 cm, respectively. The density (Eq. 1), MC (Eq. 2), SD (Eq. 3) and ST (Eq. 4) were calculated using the following equations.

$$\text{Density}(\text{gcm}^{-3}) = \frac{\text{ADW}}{\text{ADV}} \quad (1)$$

$$\text{MC}(\%) = \frac{\text{GW} - \text{OD}}{\text{OD}} \times 100 \quad (2)$$

$$\text{SD}(\%) = \frac{\text{GD}_m - \text{OD}_m}{\text{GD}_m} \quad (3)$$

$$\text{ST}(\%) = \frac{\text{GT}_n - \text{OT}_n}{\text{GT}_n} \quad (4)$$

where, ADW = Air dry weight (kg), ADV = Air dry volume (m³), GW = Green weight (g), OD = Oven dry weight (g), GD_m = Green diameter (mm), OD_m = Oven dry diameter (mm), GT_n = Green thickness (mm) and OT_n = Oven dry thickness (mm).

2.3.2. Penetration

A bore was extracted along the thickness of each bamboo sample (Fig. 1a, b) and subsequently soaked in a cromazole indicator which reacts with the copper component of CCA, changing colour to signal that the material has been treated with this preservative (Fig. 1b). This indicator evaluates the uniformity and depth of CCA treatment, particularly in assessing how effectively different bamboo species uptake the preservative. Due to the chemical reaction between the preservative and the indicator, the treated portion of each sample changed colour from greenish to bluish-purple. After sun drying, the bluish-coloured section of each sample was cut, and its length was measured using slide calipers (Fig. 1c) to determine the extent of preservative penetration. Then the following equation (Eq. 5) was used to calculate penetration (PT).

$$\text{PT}(\%) = \frac{L_{cp}}{T_b} \times 100 \quad (5)$$

where, PT = Penetration, L_{cp} = Length of coloured part and T_b = Thickness of the respective bamboo sample.

2.3.3. Retention

The retention of preservative-treated bamboo was determined using the acid digestion method, following the AWP (American Wood Protection Association) U1 standard. Instead of a weight-based approach, the entire sample was used, and its volume was measured for calculation. The sample was ground using a Wiley mill for further analysis.

A 1 g ground bamboo bore sample was placed into a 250 ml Erlenmeyer flask along with three glass beads. Then, 15 ml of nitric acid (70 %, 15.8 M) was added to the flask. The mixture was heated at 50 °C for 30 minutes, followed by heating at 70 °C until the solution became clear. After cooling to 30 °C, 5 ml of hydrogen peroxide (50 %) was added dropwise. The digested sample was then transferred to a volumetric flask for further analysis. A blank digestion was prepared alongside the samples.

For the determination of chromium (CrO₃), a 20 ml sample solution was placed in a 500 ml Erlenmeyer flask, and 180 ml of water was added to bring the total volume to approximately 200 ml. Then, 3 ml of phosphoric acid and 6 ml of 1:1 sulfuric acid were added, followed by thorough stirring. Next, 10 ml of ferrous ammonium sulfate and 10 drops of barium diphenylamine sulfonate solution were added. The solution was then titrated with a standard 0.2 N potassium dichromate solution until the endpoint was reached, indicated by a deep purple or deep greenish colour change. The amount of CrO₃ in the sample was calculated using the following equation (Eq. 6).

$$\text{CrO}_3(\text{kgm}^{-3}) = \frac{\Delta T \times N \times C \times DS}{100} \times BW \quad (6)$$

where, ΔT = Titration difference (ml), N = Normality, C = A liquid factor (3.334), DS = Density of bamboo sample and BW = 20 % weight of the bore sample.

For the determination of copper, a 20 ml sample solution was poured into a 300 ml wide-mouth Erlenmeyer flask, followed by the addition of 10 ml of water, 10 ml of concentrated hydrochloric acid, a few glass beads and 15 ml of alcohol. The mixture was then boiled until the yellowish-green colour changed to a clear bluish-green, confirming the complete reduction of chromium. The solution should appear clear and bluish-green. After cooling, the pH was adjusted to slightly basic using concentrated ammonium hydroxide. Concentrated sulfuric acid was then added dropwise until the solution became acidic, after which it was boiled down to a volume of 30 ml. Once cooled to below 20 °C, the solution was diluted to 125 ml. Next, 10 ml of 20 % potassium iodide solution and 5 ml of 20 % sodium thiocyanate solution were added and mixed thoroughly by rotating the flask. The solution was then titrated with 0.05 N sodium thiosulfate solution. Just before the brownish iodine colour disappeared, 2 ml of starch solution was added. The titration was stopped when the colour changed from dark blue to light green. For ammoniacal copper zinc arsenate, the endpoint colour change was from dark blue to cream. The amount of copper was determined using the following equation (Eq. 7).

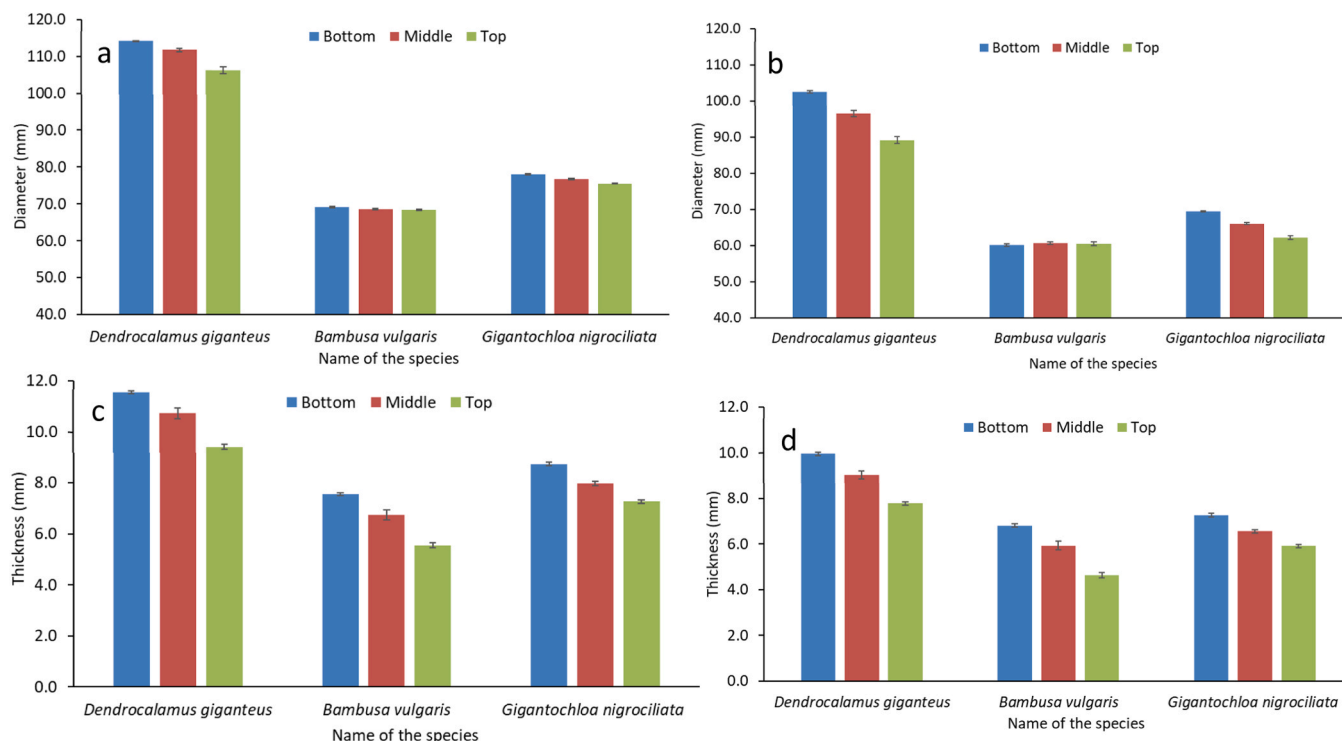


Fig. 2. Diameter of green (a) and dry (b) and thickness of green (c) and dry (d) samples from the three bamboo species.

$$CuO(kgm^{-3}) = \frac{\Delta T \times N \times C \times DS}{100} \times BW \quad (7)$$

where, ΔT = Titration difference (ml), N = Normality, C = A liquid factor (7.96), DS = Density of bamboo sample and BW = 40 % weight of bore sample

For the arsenic measurement, a 20 ml sample solution was placed in a 250 ml wide-mouth Erlenmeyer flask, and 30 ml of water was added to bring the total volume to approximately 50 ml. Then, 50 ml of hydrochloric acid and 20 ml of hypophosphorous acid were added and mixed thoroughly. The solution was then warmed until a precipitate formed, followed by boiling for 15 minutes. The mixture was filtered using a 10 ml Gooch crucible containing a Whatman 934 AH glass microfibre filter. The flask and precipitate were thoroughly washed with water. The

collected precipitate was transferred back into the flask, and 10 ml of sulfuric acid was added. The mixture was then heated over an open flame with constant agitation until copious fumes evolved. After cooling, 100 ml of water was slowly and carefully added, followed by 5 ml of hydrochloric acid and 2 drops of methyl orange solution. The solution was then titrated with a standard potassium bromate solution until it became colourless, indicating the endpoint. The amount of arsenic was determined using the following equation (Eq. 8).

$$AsO_5(kgm^{-3}) = \frac{\Delta T \times N \times C \times DS}{100} \times BW \quad (8)$$

where, ΔT = Titration difference (ml), N = Normality, C = A liquid factor (5.746), DS = Density of bamboo sample and BW = 40 % weight

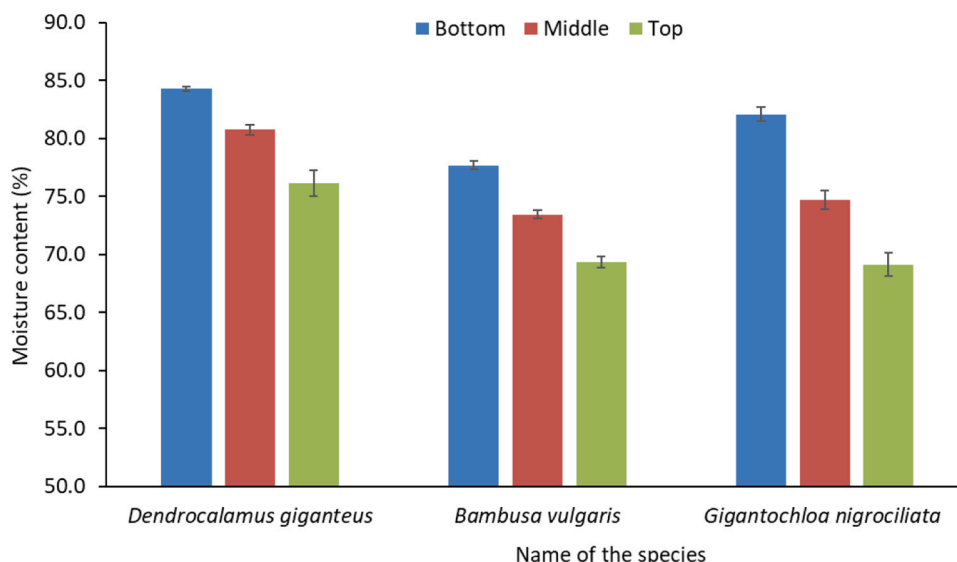


Fig. 3. Moisture content of three bamboo species.

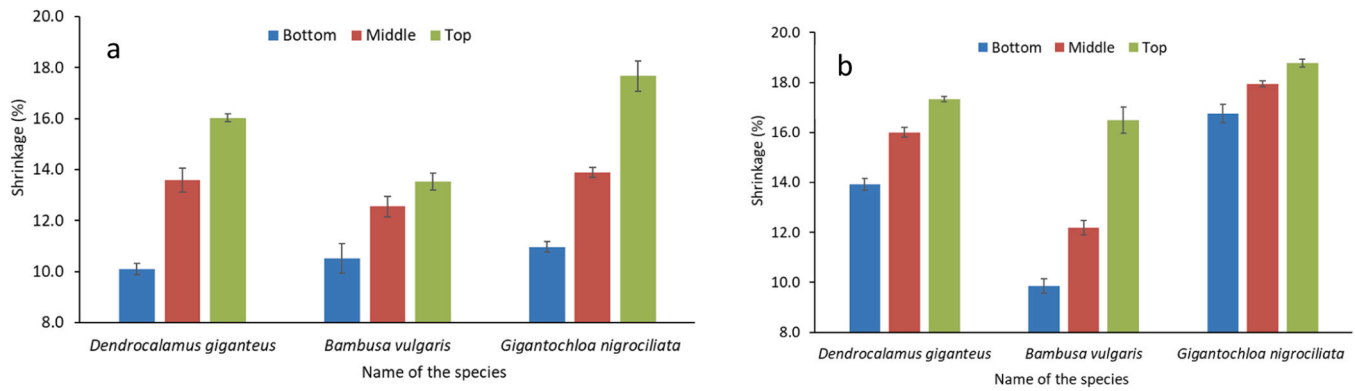


Fig. 4. Shrinkage along diameter (a) and thickness (b) of the three bamboo species.

of the bore sample.

The total retention of preservatives was calculated using the following equation (Eq. 9).

$$T \text{ (kg m}^{-3}\text{)} = A_{\text{CrO}_3} + A_{\text{CuO}} + A_{\text{AsO}_5} \quad (9)$$

where, T = Total amount of retention (kg m⁻³), A_{CrO₃} = Amount of CrO₃ (kg m⁻³), A_{CuO} = Amount of CuO (kg m⁻³) and A_{AsO₅} = Amount of AsO₅ (kg m⁻³)

3. Results and discussion

3.1. Physical properties

3.1.1. Density and thickness

The average basic density of *G. nigrociliata*, *D. giganteus*, and

B. vulgaris was 0.56, 0.65 and 0.71 kg m⁻³, respectively. The diameter and thickness of the bamboo in both green and dry conditions are presented in Fig. 2. The green diameter (Fig. 2a) and thickness (Fig. 2c) of all three species were higher than those in the dried state (Fig. 2b, d), indicating shrinkage during drying. Among the three species, *D. giganteus* had the greatest diameter and thickness in both green and dry conditions, while *B. vulgaris* had the smallest. Although the diameters of the three species varied, they remained relatively consistent between green and dry samples at different height positions. In contrast, thickness varied both among species and at different height positions in both conditions. The reduction in diameter and thickness after drying was attributed to shrinkage. Additionally, the thickness at the bottom of the bamboo culm was higher than at the top. Growth variations among species were also observed in this study.

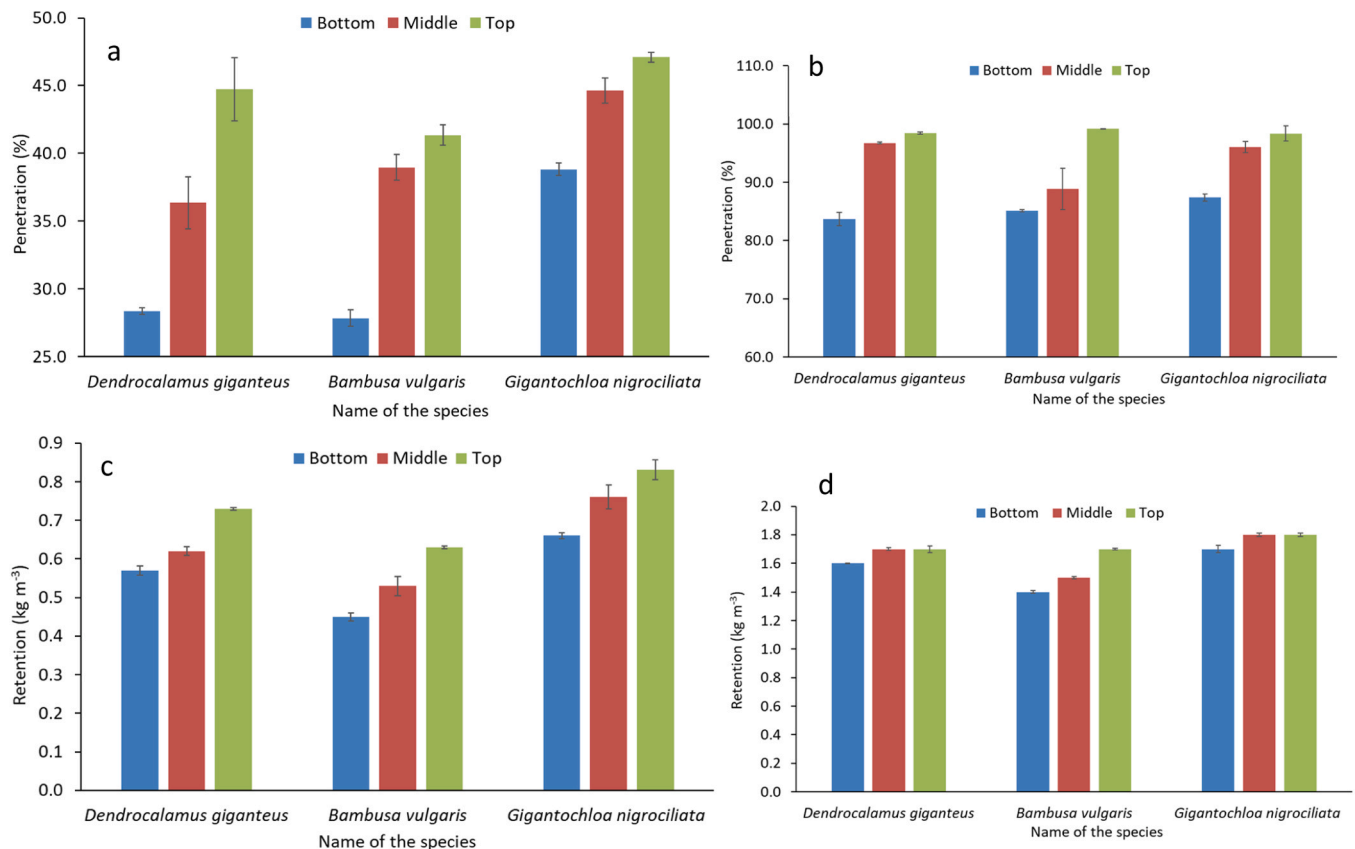


Fig. 5. Penetration efficiency of green (a) and dry (b) and retention efficiency of green (c) and dry (d) samples of the three bamboo species.

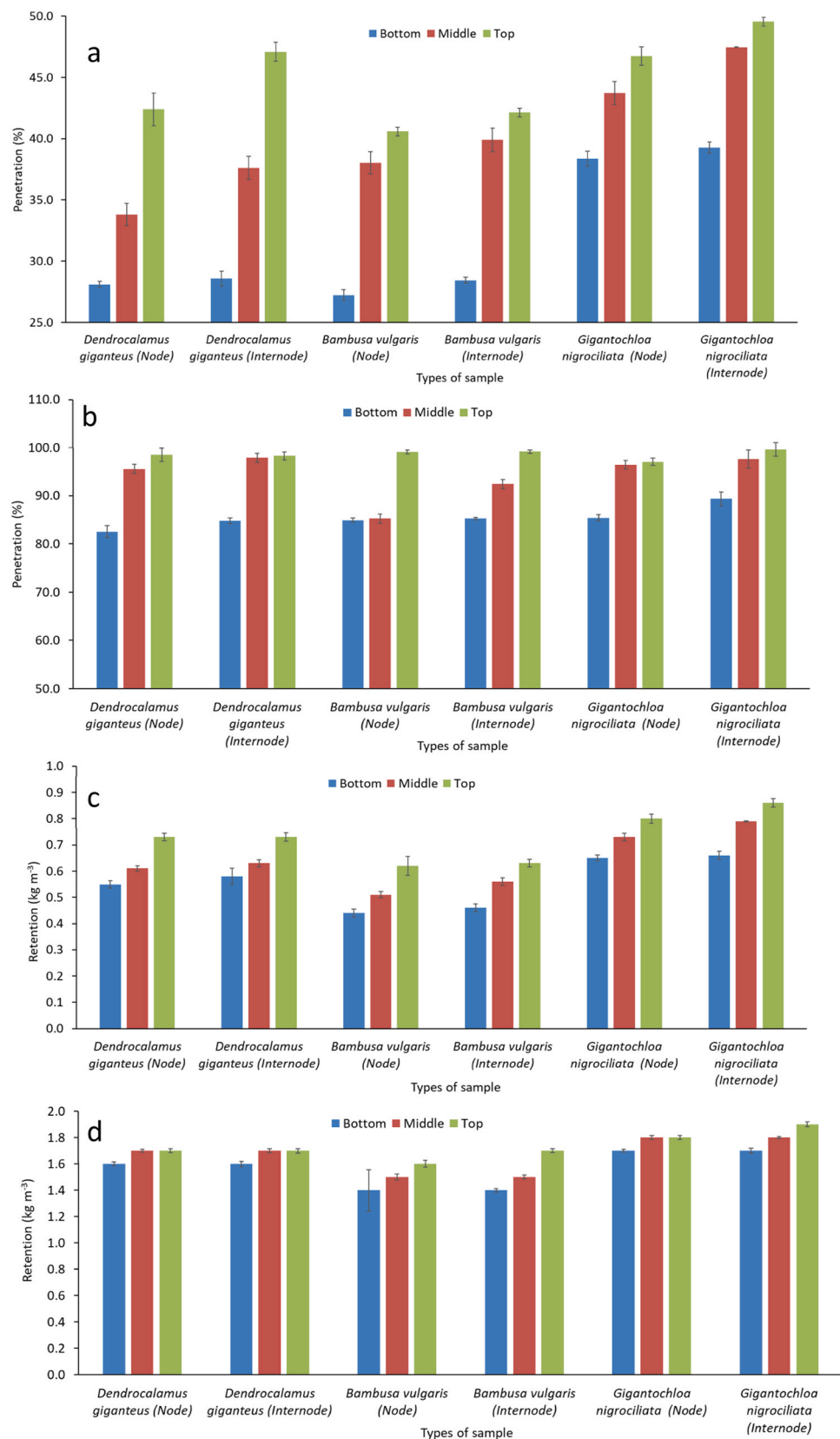


Fig. 6. Effect of node and internode on the penetration efficiency of green (a) and dry (b) and retention efficiency of green (c) and dry (d) samples according to the height positions of the three bamboo species.

3.1.2. Moisture content

The highest moisture content was measured for the bottom part of *D. giganteus* at 84.29 %, while the lowest was 69.12 % for the top part of *G. nigrociliata* (Fig. 3). Moisture content varied among species as well as across different height positions within each species. This variation can be attributed to differences in thickness, as *D. giganteus* had the greatest thickness and *B. vulgaris* the least (Fig. 3). Moisture content exhibited a trend similar to that of thickness. As bamboo matures, xylem tissue develops more at the base, enhancing structural strength and water transport capacity. Consequently, thicker bamboo sections contain a higher proportion of xylem cells, leading to increased moisture content. Since thickness varied among species and at different height positions, moisture content also exhibited corresponding variations. Overall, moisture content decreased towards the upper parts of the culms of each species, following the trend: *D. giganteus* > *G. nigrociliata* > *B. vulgaris*.

3.1.3. Shrinkage

The shrinkage in diameter and thickness for the three bamboo species is shown in Fig. 4. The average shrinkage in both directions followed the trend: *G. nigrociliata* > *D. giganteus* > *B. vulgaris* (Fig. 4a, b). Shrinkage varied across species, height positions and the chemical composition of cells (Hossain et al., 2022, 2024a, 2024b). Vascular bundle density is higher at the top of the bamboo culm than at the bottom. Consequently, the bottom section undergoes less shrinkage than the top. Differences in chemical composition and cellular structure among species also contribute to variations in shrinkage.

3.2. Penetration and retention efficiency

The penetration efficiency (Fig. 5a, b) and retention (Fig. 5c, d) of CCA for *G. nigrociliata*, *D. giganteus* and *B. vulgaris* are presented in Fig. 5. The average penetration efficiency of dried bamboo was 92.9 %, 91.0 % and 93.9 % for *D. giganteus*, *B. vulgaris* and *G. nigrociliata*, respectively. Actual average retention efficiency of dried bamboo was 1.67, 1.53 and 1.77 kg m⁻³ for *D. giganteus*, *B. vulgaris* and *G. nigrociliata*, respectively, which were 20.6 %, 19.3 % and 22.4 %, respectively, of target retention (8 kg m⁻³). In both green and dry conditions, penetration and retention followed the trend: *G. nigrociliata* > *D. giganteus* > *B. vulgaris*. On average, penetration in dried bamboo was 2.6, 2.6 and 2.2 times higher than in green bamboo for *D. giganteus*, *B. vulgaris* and *G. nigrociliata*, respectively. Similarly, retention in dried bamboo increased by 2.6, 2.9 and 2.4 times, respectively, compared to green bamboo for the same species. According to a study by Lee et al. (2001), actual CCA retentions in Moso bamboo (*Phyllostachys edulis* (Carrière) J.Houz.) were 0.88 and 1.49 kg m⁻³ for 4.0 and 6.0 kg m⁻³ target retentions, respectively. This was only 22–23 % of the target retention, whereas using the same treatment procedures for southern pine resulted in 7.12 and 4.61 kg m⁻³, respectively, which were 11–15 % higher than the target. The findings show that compared to southern pine, bamboo is far more challenging to treat. Baysal et al. (2016) also observed a similar difference in retention for bamboo and wood. Bamboo differs from wood in its structure and lacks radial transport systems, which significantly affects the preservation treatments (Sun et al., 2012).

The variation in chemical composition also affects the preservative treatment of bamboo. The holocellulose content increases from the bottom to the top of a bamboo culm (Hossain et al., 2022, 2024a, 2024b). The top section also contains a higher density of vascular bundles (Li et al., 2007), providing more space for chemical penetration. Consequently, the bottom part exhibited lower CCA penetration than the top. Again, extractive content can hinder the bonding between fibres and preservatives, leading to lower retention in the bottom section. The moisture content in green bamboo inhibits preservative penetration by occupying the cell lumen, preventing effective interaction with cellular structures. In contrast, dried bamboo, with empty cell lumens, allows for better preservative uptake and retention. While the air in the dried bamboo lumen could obstruct penetration, the vacuum process used

before treatment removes air, facilitating deeper penetration. Since vascular bundle density increases with height, the top sections of the bamboo exhibited higher preservative penetration.

The effect of nodes and internodes on penetration and retention efficiency at different height positions and for different bamboo species is presented in Fig. 6(a-d). The internode exhibited higher penetration efficiency than the node at all height positions for both green (Fig. 6a) and dried (Fig. 6b) bamboo species. Similarly, retention efficiency was also higher for the internode compared to the node at all height positions for both green (Fig. 6c) and dried (Fig. 6d) bamboo species. The node region of bamboo species is more compact than the internode, which inhibits the penetration of preservatives. As a result, the internode showed higher penetration and retention efficiency than the node in this study.

4. Conclusion

This paper presents the physical properties and the efficiency of preservative penetration and retention in *D. giganteus*, *B. vulgaris* and *G. nigrociliata*. Physical properties and preservative treatability were evaluated for both green and dried bamboo samples. The efficiency of CCA penetration and retention was influenced by species, height position and the distinction between nodes and internodes. Penetration and retention were higher in dried bamboo than in green bamboo. The internode demonstrated a greater capacity for preservative penetration and retention than the node at all height positions across the three bamboo species. Dried bamboo exhibited good CCA treatability. Further studies are needed to explore the impact of preservative treatment on the physical and mechanical properties and durability of these bamboo species.

CRedit authorship contribution statement

Das Atanu Kumar: Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Khatun Rabeya:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Ahmed Ershad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **Ferdousi Samina:** Writing – review & editing. **Khan Md. Abu Rayhan:** Writing – review & editing. **Hannan Md. Obaidullah:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Ashaduzzaman Md:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Sikder Arif:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank Nordic Wood Limited, Khulna, Bangladesh, for providing the facilities to treat the bamboo on their premises.

Data availability

Data will be made available on request.

References

- Baysal, E., Tomak, E.D., Topaloglu, E., Peşman, E., 2016. Surface properties of bamboo and Scots pine impregnated with boron and copper based wood preservatives after accelerated weathering. *Maderas Cienc. Y. Tecnol.* 18 (2), 253–264. <https://doi.org/10.4067/S0718-221X2016005000023>.

- Bhat, I.U.H., Mustafa, M.T.B., Mohmod, A.L., Khalil, H.A., 2011. Spectroscopic, thermal and anatomical characterization of cultivated bamboo (*Gigantochloa* spp.). *BioResources* 6, 1752–1763.
- Chavan, M.A., Attar, A.C., 2013. Study feasibility of preservative chemicals and its effect on load carrying capacity of bamboo. *Int. J. Sci. Eng. Res.* 4, 1271–1278.
- Dhawan, S., Mishra, S.C., 2005. Influence of felling season and moon phase on natural resistance of bamboos against termite. *Indian For.* 131, 1486–1492.
- Febrianto, F., Gumilang, A., Maulana, S., Busyra, I., Purwaningsih, A., 2014. Natural durability of five bamboo species against termites and powder post beetle. *J. Trop. Wood Sci. Technol.* 12, 146–156.
- Hossain, M.J., Ghosh, R.K., Das, A.K., Maryana, R., Muryanto, Sudiyani, Y., Nath, S.C., Islam, R., 2024a. Chemical composition and solubility properties of *Bambusa bambos* at different ages and height positions. *Adv. Bamboo Sci.* 6, e100062. <https://doi.org/10.1016/j.bamboo.2024.100062>.
- Hossain, M.J., Ghosh, R.K., Das, A.K., Maryana, R., Muryanto, M., Nath, S.C., Islam, R., 2024b. Variability of the chemical composition of *Dendrocalamus giganteus* in relation to growth stage. *Adv. Bamboo Sci.* 9, e100111. <https://doi.org/10.1016/j.bamboo.2024.100111>.
- Hossain, M.J., Ghosh, R.K., Das, A.K., Maryana, R., Nath, S.C., Islam, R., Sarker, S.C., 2022. Effect of age and height on the chemical properties of Muli bamboo (*Melocanna baccifera*). *ACS Omega* 7 (43), 39370–39374. <https://doi.org/10.1021/acsomega.2c05684>. PMID: 36340150; PMCID: PMC9631737.
- Huang, X.Y., Xie, J.L., Qi, J.Q., Hao, J.F., Jiang, X.Q., Hu, W.H., 2014. Investigation of the physical and mechanical properties and chemical composition of *Bambusa rigida* before and after accelerated aging. *BioResources* 9, 3174–3184.
- Jiang, Z., 2007. Bamboo pulp and paper making. In: Janssen, J. (Ed.), *Bamboo and Rattan in the World*. China Forestry Publishing House, China, pp. 214–226, pp. 178–198.
- Jinyi, Z., Fawei, L., 2022. China's bamboo industry contributes to global green development. *People's S. Dly., China's Bamboo Ind. Contrib. Glob. Green. Dev.* (<http://en.people.cn/n3/2022/0811/c90000-10134173.html>).
- Kaminski, S., Lawrence, A., Trujillo, D., King, C., 2016. Structural use of bamboo: Part 2: Durability and preservation. *Struct. Eng.* 94 (10), 38–43. <https://doi.org/10.56330/TRBW8039>.
- Lee, A.W.C., Chen, G., Tainter, F.H., 2001. Comparative treatability of Moso bamboo and Southern pine with CCA preservative using a commercial schedule. *Bioresour. Technol.* 77 (1), 87–88. [https://doi.org/10.1016/S0960-8524\(00\)00145-0](https://doi.org/10.1016/S0960-8524(00)00145-0).
- Li, X.B., Shupe, T.F., Peter, G.F., Hse, C.Y., Eberhardt, T.L., 2007. Chemical changes with maturation of the bamboo species *Phyllostachys pubescens*. *J. Trop. For. Sci.* 19, 6–12.
- Liese, W., Tang, T.K.H., 2015. Preservation and drying of bamboo. In: Liese, W., Köhl, M. (Eds.), *Bamboo: The Plant and its Uses*. Springer International Publishing, Cham, Switzerland, pp. 257–297. https://doi.org/10.1007/978-3-319-14133-6_9.
- Mehramiz, S., Oladi, R., Efhamisizi, D., Pourtahmasi, K., 2021. Natural durability of the Iranian domestic bamboo (*Phyllostachys vivax*) against fungal decay and its chemical protection with propiconazole. *Eur. J. Wood Wood Prod.* 79, 453–464.
- Okahisa, Y., Yoshimura, T., Imamura, Y., 2005. An application of the alkaline extraction-glucosylase hydrolysis method to analyze starch and sugar contents of bamboo. *J. Wood Sci.* 51, 542–545.
- Reardon, C.L., Strauss, S.L., Mazzola, M., 2013. Changes in available nitrogen and nematode abundance in response to Brassica seed meal amendment of orchard soil. *Soil Biol. Biochem.* 57, 22–29. <https://doi.org/10.1016/j.soilbio.2012.10.011>.
- Sain, A., Gaur, A., Singh Khichad, J., Somani, P., 2024. Treatment of bamboo for sustainable construction practice: A comprehensive review. *IOP Conf. Ser.: Earth Environ. Sci.* 1326, e012049. <https://doi.org/10.1088/1755-1315/1326/1/012049>.
- Shibata, S., 2012. Effects of forming processing conditions on the flexural properties of bagasse and bamboo plastic composites. *BioResources* 7, 5381–5390.
- Silva, E.C.N., Walters, M.C., Paulino, G.H., 2006. Modeling bamboo as a functionally graded material: Lessons for the analysis of affordable materials (<https://doi.org/10.1007/s10853-006-0232-3>). *J. Mater. Sci.* 41, 6991–7004. <https://doi.org/10.1007/s10853-006-0232-3>.
- Suhaily, S.S., Abdul Khalil, H.P.S., Nadirah, W.O.W., Jawaid, M., 2013. Bamboo based biocomposites: Material, design and applications. In: Mastai, Y. (Ed.), *Materials Science – Advanced Topics*. InTech, UK, pp. 489–517.
- Sulaeman, A., Dungani, R., Nurudin, N., Hartati, S., Karliati, T., Aditiawati, P., Hadiyane, A., Suhaya, Y., Sulistyono, 2018. Review on quality enhancement of bamboo utilization: preservation, modification and applications. *Asian J. Plant Sci.* 17, 1–18. <https://doi.org/10.3923/1jps.2018.1.18>.
- Sun, F., Chen, A., Duan, X., Bao, B., Ma, L., 2012. Mould-resistance of bamboo treated with the compound of chitosan-copper complex and organic fungicides. *Wood Sci. J.* 58, 51–56. <https://doi.org/10.1007/s10086-011-1223-9>.
- Tewari, D.N., 1993. A Monograph on Bamboo. International Book Distributors, Dehra Dun.
- Wei, D., Schmidt, O., Liese, W., 2013. Durability test of bamboo against fungi according to EN standards. *Eur. J. Wood Prod.* 71, 551–556. <https://doi.org/10.1007/s00107-013-0707-2>.
- Xu, G., Wang, L., Liu, J., Hu, S., 2013. Decay resistance and thermal stability of bamboo preservatives prepared using camphor leaf extract (<https://doi.org/10.1016/j.ibiod.2012.12.001>). *Biodeterior. Biodegrad.* 78, 103–107. <https://doi.org/10.1016/j.ibiod.2012.12.001>.