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Evaluating the structural endurance of Bamboo Kelarai panels through the application of tensile strength testing methodologies

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ABSTRACT

The long-term performance and durability of bamboo kelarai panels are significantly governed by the mechanical properties of the individual bamboo strips that constitute their interwoven configuration. This research is intended to assess the durability of bamboo kelarai panels through a detailed examination of the influence of moisture content and boron-based preservation treatment on their tensile strength characteristics. An experimental laboratory methodology was implemented, employing Gigantochloa scortechinii (commonly referred to as Semantan bamboo) as the primary material, wherein the specimens were systematically classified into four distinct categories according to moisture condition (elevated and reduced) and treatment status (treated with boron and untreated). Tensile strength evaluation was carried out using a Universal Testing Machine, with peak stress values meticulously measured and documented for subsequent analytical interpretation. The findings reveal a pronounced inverse correlation between moisture content and tensile strength, whereby specimens with reduced moisture levels exhibited superior strength performance alongside greater structural stability. Furthermore, samples subjected to boron treatment demonstrated more uniform tensile behaviour, suggesting an improvement in fibre cohesion and internal structural integrity. Notably, the synergistic combination of low moisture content and boron treatment resulted in the highest recorded tensile strength values among all tested groups. Collectively, these outcomes establish a robust scientific foundation for enhancing the durability of kelarai panels through effective moisture regulation and appropriate preservation techniques, thereby contributing to the advancement of more dependable, resilient, and sustainable bamboo-based construction materials within the field of architecture.

Introduction

Bamboo kelarai panels constitute a significant cultural artefact within the corpus of Malay architecture, esteemed for their refined craftsmanship and complex interlacing geometries. Beyond their visual and ornamental attributes, the functional efficacy of kelarai panels is fundamentally governed by the mechanical behaviour of the bamboo strips employed in their woven assembly. Durability, particularly the capacity to withstand deformation and fibre rupture, remains a critical parameter in ensuring that kelarai panels preserve both their structural integrity and aesthetic quality throughout their operational lifespan. Tensile strength is widely acknowledged as a principal indicator of bamboo durability, as the longitudinal alignment of fibres imparts substantial tensile capacity along the grain, while simultaneously rendering the material susceptible to rupture when fibres are degraded or unevenly conditioned (Amada and Untao 2001; Sharma et al. 2015).

The tensile response of bamboo is significantly affected by a range of intrinsic material parameters, among which moisture content is particularly influential. Elevated moisture levels interfere with hydrogen bonding within the lignocellulosic matrix, induce softening of cellulose microfibrils, and diminish overall fibre cohesion, thereby leading to reduced stiffness and diminished tensile resistance (Cheng, Wang, and Wen 2016; H. Liu et al. 2014; Yu et al. 2014). Conversely, reduced moisture conditions enable bamboo fibres to maintain higher structural rigidity and enhanced tensile performance, exhibiting greater resistance to fibre slippage and fracture under applied loading (Huang, Ji, and Yu 2016). Given that kelarai weaving imposes both bending stresses and tensile forces on slender bamboo strips, inadequate regulation of moisture content directly compromises material reliability during fabrication processes as well as in long-term application.

In addition to hygroscopic effects, the application of chemical preservatives such as boron plays a vital role in sustaining bamboo durability. Boron treatment permeates the cellular structure and safeguards fibres against fungal and insect-induced degradation, thereby preserving the microstructural integrity necessary for consistent tensile performance (Ahmad, Hamid, and Ibrahim 2010). Although boron does not directly enhance the intrinsic strength of cellulose, its capacity to mitigate biological deterioration and stabilise the fibre matrix enables bamboo to retain its inherent mechanical properties over extended periods (Rana et al. 2013; Sudiana & Marsoem 2015). Consequently, a comprehensive understanding of the combined influence of moisture conditions and boron treatment on tensile strength is essential for ensuring the long-term mechanical durability of kelarai panels.

Despite the enduring utilisation of bamboo kelarai panels in traditional Malay architectural practices, their integration into contemporary construction remains constrained due to concerns related to durability and structural reliability. Existing research has predominantly concentrated on engineered bamboo materials, including laminated boards and composite systems, whereas comparatively limited attention has been directed toward woven bamboo assemblies such as kelarai, particularly at the scale of individual bamboo strips. This research gap generates uncertainty regarding the manner in which processing parameters specifically moisture condition and preservation treatment affect the structural performance of kelarai components. As documented in prior studies, untreated bamboo structures are highly vulnerable to rapid environmental degradation, frequently exhibiting service lives of only a few years under exposed conditions, thereby restricting their broader adoption in modern architectural applications (Richard 2013; Rittironk 2009).

The importance of this study resides in its contribution toward bridging traditional artisanal knowledge and empirical material science. By emphasising tensile behaviour as a primary metric of durability, this research provides quantifiable and evidence-based data to inform the enhancement of kelarai production techniques. Furthermore, improving the durability of bamboo kelarai panels carries broader implications for sustainable construction practices, conservation of cultural heritage, and the advancement of rural economies. Enhanced material performance has the potential to increase acceptance within the construction sector, thereby encouraging the utilisation of locally sourced renewable resources while simultaneously preserving traditional weaving expertise and craftsmanship (Preeya 2014; Zulkifli 2016).

Accordingly, the primary objective of this study is to evaluate the durability of bamboo kelarai panels through the analysis of tensile performance across four classifications of bamboo samples: high-moisture sun-dried specimens, lower-moisture oven-dried specimens, boron-treated specimens, and untreated specimens. Through this analytical framework, the research establishes a scientific basis for determining appropriate processing strategies that optimise structural performance, longevity, and overall material quality of bamboo kelarai panels utilised in interior architectural applications.

This study offers a novel contribution by integrating traditional kelarai craftsmanship with rigorous quantitative mechanical assessment at the material scale. In contrast to previous investigations that have focused on engineered bamboo composites or macro-scale structural elements, this research specifically examines the tensile properties of individual bamboo strips employed within woven panels. The novelty of this work lies in its evaluation of the combined effects of moisture conditioning and boron treatment on tensile durability, thereby providing a scientific framework for refining traditional kelarai manufacturing processes. This approach establishes a direct correlation between material preparation techniques and the long-term mechanical reliability of woven bamboo systems, a relationship that remains underexplored in existing scholarly literature.

Methods

In response to the identified research gap, this study is structured around the following hypotheses:

i. Bamboo strips with reduced moisture content will exhibit greater tensile strength compared to those with elevated moisture levels.
ii. Bamboo strips subjected to boron treatment will demonstrate enhanced tensile stability relative to untreated specimens.
iii. The combined condition of low moisture content and boron treatment will yield the highest tensile performance and durability among all sample groups.

These hypotheses provide the conceptual foundation for analysing the extent to which physical conditioning and chemical preservation influence the mechanical behaviour of bamboo utilised in kelarai panel fabrication.

Bamboo Blade sample preparation

The bamboo species employed in this study is *Gigantochloa scortechinii* (Buluh Semantan), selected on the basis of its favourable mechanical properties, linear fibre alignment, and long-established suitability for kelarai production. Bamboo culms were manually processed into uniform strip specimens measuring 30 mm × 250 mm, ensuring consistency in cross-sectional dimensions to facilitate accurate tensile stress calculations. All specimens were derived from a uniform maturity classification to minimise variability in fibre structure.

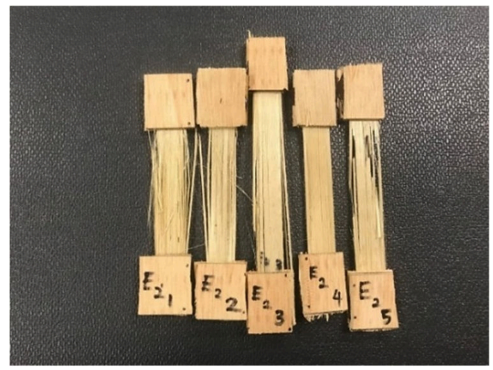

Figure 1. Bamboo blade sample

Moisture content grouping

Specimens were categorised according to their measured moisture content, determined through initial and final mass comparisons obtained from the experimental dataset. Two distinct moisture conditions were defined:

- Higher Moisture Content Group (HMC): Specimens retaining elevated internal moisture due to limited conditioning.
- Lower Moisture Content Group (LMC): Specimens exhibiting reduced moisture levels, forming a comparative low-moisture group.

Moisture values were directly derived from the MC dataset and utilised solely as variables for interpreting tensile performance, without elaboration on drying methodologies.

Boron treatment

Boron treatment was administered to selected specimens to evaluate its influence on tensile durability. A boron-based preservative solution, commonly applied in bamboo preservation, penetrates the cellular matrix, enhancing resistance to biological agents such as fungi and insects while contributing to fibre stabilisation. Treated specimens were designated as "+Boron," whereas untreated specimens were classified under the "non-Boron" category. This classification yielded four distinct specimen groups:

- HMC (non-Boron)
- HMC (Boron)

- LMC (non-Boron)
- LMC (Boron)

Tensile testing procedure

Tensile strength testing was conducted at the Fibre and Biocomposite Development Centre (FIDEC), Malaysian Timber Industry Board (MTIB), utilising a Shimadzu Universal Testing Machine equipped with an extensometer to ensure precise strain measurement. Standardised testing parameters were defined as follows:
- Mode: Tensile
- Speed: 5 mm/min
- Specimen shape: Plate
- Gauge measurement: extensometer

Test direction: longitudinal fiber axis

Each experimental batch comprised five specimens. Recorded tensile parameters included maximum load (N), ultimate tensile stress (MPa), percentage elongation, and displacement at elongation, all extracted from tensile datasets E1, E2, E3, and E4.

Figure 2. Tensile testing machine

In summary, the research methodology follows a systematic experimental framework consisting of four principal stages. Initially, bamboo culms were selected and fabricated into uniform strip specimens to ensure testing consistency. Subsequently, specimens were subjected to controlled conditions defined by two primary variables: moisture content and boron treatment. Moisture levels were quantified through mass comparison, while tensile testing was performed using a Universal Testing Machine to obtain mechanical performance data. Finally, the acquired data were analysed through comparative evaluation of tensile stress values across all specimen groups to determine the relationship between moisture condition, chemical treatment, and durability performance. The procedural sequence can be outlined as follows:

(1) Sample preparation → (2) Moisture conditioning → (3) Boron treatment → (4) Tensile testing → (5) Data analysis → (6) Durability interpretation.

This structured methodology ensures that the influence of each variable is systematically isolated and rigorously evaluated, thereby providing a reliable and scientifically grounded basis for assessing bamboo durability within kelarai panel applications.

Literature review

Tensile behaviour and mechanical properties of bamboo

Bamboo is extensively acknowledged as a natural composite material possessing outstanding tensile capacity, primarily attributed to the longitudinal alignment of its cellulose fibres. A substantial body of research has established that tensile strength serves as one of the most dependable indicators of the mechanical performance of bamboo, particularly in applications involving bending, interlacing, and tension-based structural systems (Amada and Untao 2001; Sharma et al. 2015). The fibre bundles distributed within the bamboo culm contribute significantly to elevated stiffness and strength along the grain direction, frequently enabling bamboo to attain tensile performance comparable to, or even surpassing, that of certain hardwood species. Amada et al. (1997) characterised bamboo as a functionally graded material, wherein fibre density progressively increases toward the outer region of the culm wall, thereby enhancing tensile resistance. This gradation renders bamboo especially suitable for thin-strip applications such as kelarai panels, where tensile resistance is critically required during both fabrication and prolonged service conditions.

Contemporary studies further substantiate that the tensile strength of bamboo is intrinsically linked to its hierarchical microstructure and fibre distribution. Radial variations in fibre density exert a considerable influence on tensile behaviour, with the outer layers demonstrating superior strength due to a higher concentration of vascular bundles (Al-Rukaibawi and Károlyi 2023). In a similar vein, investigations into engineered bamboo systems have revealed that fibre orientation, strip thickness, and lamination arrangements play a decisive role in determining tensile performance and stress distribution characteristics (Wang et al. 2025). Moreover, the favourable strength-to-weight ratio and mechanical efficiency of bamboo have positioned it as a viable alternative to conventional construction materials, particularly within the domain of sustainable architectural applications (Das, Prashant, and Kini 2025; Adebowale and Agumba 2025).

The tensile behaviour of bamboo is also governed by its anatomical configuration and microstructural composition. Liese and Köhl (2015) emphasise that the distribution of vascular bundles, the thickness of fibre cell walls, and the composition of lignin are critical determinants of strength performance. Mao, Guan, and Yu (2019) further demonstrated that bamboo exhibits nonlinear tensile characteristics, where fibre rupture is controlled by cell-wall deformation and shear interactions within the parenchyma matrix. At the level of fibre bundles, it has been observed that processing techniques such as extraction methods, thermal modification, and variations in fibre density substantially affect tensile capacity, with chemically treated fibres achieving markedly higher tensile strength than untreated counterparts (Chen et al. 2025). Given that kelarai panels utilise slender, processed bamboo strips rather than intact culm sections, an in-depth understanding of tensile behaviour at the microstructural scale becomes essential. The presence of weakened or deteriorated fibres can initiate crack propagation within woven configurations, ultimately undermining the durability of the panel system.

Beyond immediate strength characteristics, long-term mechanical responses such as creep also influence the performance of bamboo. Owing to its viscoelastic nature, bamboo undergoes progressive deformation over time when subjected to sustained loading, a behaviour influenced by factors including moisture content, fibre orientation, and internal structural composition (Seixas, Cardoso, and Moreira 2025). This time-dependent response underscores the necessity of evaluating not only instantaneous tensile strength but also long-term dimensional stability when assessing bamboo durability in architectural contexts.

Influence of moisture content on tensile properties

Moisture content represents one of the most critical variables affecting the mechanical behaviour of bamboo. As a hygroscopic material, bamboo continuously exchanges moisture with its surrounding environment, thereby influencing its stiffness, strength, and dimensional stability. Extensive research consistently demonstrates an inverse correlation between moisture content and tensile strength, whereby increased moisture levels diminish fibre cohesion and reduce mechanical resistance (Cheng, Wang, and Wen 2016; Yu et al. 2014). The presence of water molecules disrupts hydrogen bonding within the cellulose matrix, leading to reduced crystallinity and enhanced fibre mobility, which collectively contribute to decreased tensile stiffness and premature structural failure (H. Liu et al. 2014).

Further investigations confirm that the hydrophilic nature of bamboo accelerates mechanical degradation under moisture exposure. Interactions between hydroxyl groups in cellulose and water molecules result in swelling, microstructural instability, and a reduction in load-bearing capacity (Han et al. 2025). Additionally, fluctuations in moisture content significantly affect the long-term behaviour of bamboo, particularly in relation to creep deformation, where elevated moisture levels accelerate viscoelastic strain under sustained loading conditions (Seixas, Cardoso, and Moreira 2025). These findings indicate that moisture not only influences immediate tensile properties but also plays a decisive role in long-term structural reliability.

In the context of thin bamboo strips used for kelarai weaving, the impact of moisture becomes even more pronounced. Due to their reduced thickness, such elements are highly susceptible to moisture-induced swelling, deformation, and the formation of microcracks. Huang, Ji, and Yu (2016) reported that bamboo with higher moisture content exhibits a brittle ductile transition under tensile loading, resulting in less predictable failure mechanisms. Furthermore, studies examining the relationship between bamboo density and fibre distribution indicate that moisture interacts with internal structural characteristics, thereby affecting the correlation between vascular bundle concentration and mechanical performance (Z. Liu et al. 2025). This is particularly significant in kelarai systems, where consistent tensile behaviour is essential to maintain the integrity and uniformity of woven patterns.

Overall, the literature underscores the importance of controlling moisture content to preserve tensile strength and ensure durability. In the absence of adequate moisture conditioning, bamboo components are vulnerable to mechanical weakening, dimensional instability, and premature failure, thereby limiting their applicability in both structural and interior architectural contexts.

Effects of Boron Treatment on mechanical and durability performance

Boron treatment is widely recognised as an effective preservation strategy for bamboo, owing to its high diffusibility, relatively low toxicity, and capacity to protect against fungal and insect attack. Traditionally, boron has been applied to enhance durability by mitigating biological degradation; however, recent studies suggest that it also contributes indirectly to mechanical performance by stabilising the internal fibre structure. Ahmad, Hamid, and Ibrahim (2010) observed that treated bamboo maintains superior fibre cohesion over time compared to untreated specimens, particularly when subjected to environmental exposure.

Additional research further corroborates the role of chemical preservation in improving durability and sustaining mechanical integrity. Investigations on treated bamboo strips exposed to aggressive environmental conditions demonstrate that preservation methods significantly reduce structural degradation and improve strength retention over extended periods (Kattumunda, Thai, and Maity 2026). Similarly, Samal, Sahoo, and Badavath (2026) emphasise that untreated bamboo is highly susceptible to biodegradation, which adversely affects its tensile capacity, whereas chemical and thermal treatments can substantially enhance durability performance.

Beyond biological protection, chemical treatments contribute to the stabilisation of bamboo's microstructure. Boron and related modification techniques help mitigate lignin degradation and preserve cellulose integrity, both of which are essential for maintaining tensile strength (Chen et al. 2025). This stabilising effect is particularly important in environments characterised by fluctuating moisture conditions, where untreated bamboo tends to undergo rapid deterioration.

Furthermore, recent advancements in bamboo modification technologies indicate that improvements in surface protection and internal structural stability can significantly enhance both durability and mechanical performance. For instance, biomimetic and composite-based treatments have been shown to increase water resistance, reduce degradation rates, and improve tensile behaviour (Han et al. 2025; Lakshmaiya, Raja, and Yuvarajan 2025). These findings suggest that preservation strategies are not solely protective measures but also critical factors in sustaining long-term mechanical reliability.

In summary, although boron treatment does not directly increase the intrinsic strength of cellulose fibres, its effectiveness in protecting and stabilising the fibre matrix ensures that bamboo retains its mechanical properties over prolonged periods. This makes it particularly suitable for applications such as kelarai panels, where durability and consistent tensile performance are essential requirements.

Structural variability and material consistency in bamboo

In addition to moisture content and chemical treatment, the inherent variability of bamboo as a natural material presents a significant challenge in achieving uniform mechanical performance. Unlike engineered materials, bamboo exhibits natural variations in fibre distribution, density, and structural composition, all of which directly influence tensile behaviour. Research indicates that differences in vascular bundle distribution, the presence of nodes, and the position along the culm can result in substantial variability in strength and stiffness across samples (Al-Rukaibawi and Károlyi 2023; Ji et al. 2025).

Material density has been identified as a key parameter influencing the mechanical properties of bamboo, as it reflects the concentration of load-bearing fibres within the structure. Regions with higher density typically exhibit greater tensile strength, whereas lower-density areas are more susceptible to deformation and structural failure (Z. Liu et al. 2025). Such variability presents challenges for standardisation, particularly in applications such as woven panels, where consistent mechanical performance is required to ensure structural reliability.

Moreover, recent studies on engineered bamboo and composite materials highlight the importance of controlling variability through processing techniques. Manufacturing strategies such as strip selection, grading, and lamination have been shown to enhance consistency and predictability in mechanical performance (Alves, De Araujo, and Christoforo 2025). However, in traditional systems such as kelarai panels, where natural bamboo strips are utilised directly, managing material variability remains a critical concern.

A comprehensive understanding and effective management of this variability are essential for improving the reliability of bamboo-based products. By establishing correlations between material characteristics, such as density, fibre distribution, and treatment conditions, and mechanical performance, researchers and practitioners can develop more consistent and durable bamboo systems suitable for both traditional and contemporary architectural applications.

Overall, the existing body of literature demonstrates that the tensile durability of bamboo is governed by an interplay of microstructural attributes, moisture conditions, and preservation treatments. The naturally aligned fibre architecture of bamboo provides high tensile strength; however, this performance is highly sensitive to moisture variations, which weaken fibre bonding and reduce mechanical stability (Cheng, Wang, and Wen 2016; Yu et al. 2014). Concurrently, chemical treatments such as boron play a crucial role in preserving fibre integrity and enhancing long-term durability by mitigating biological degradation (Ahmad, Hamid, and Ibrahim 2010; Samal, Sahoo, and Badavath 2026). Additionally, factors such as fibre distribution, material density, and inherent structural variability further influence tensile behaviour, underscoring the necessity for controlled material preparation. Despite extensive research on bamboo in structural and engineered contexts, relatively limited attention has been directed toward the tensile performance of individual bamboo strips used in kelarai systems. Accordingly, this study addresses this gap by evaluating the effects of moisture content and boron treatment on tensile strength, thereby directly supporting the research objective of identifying optimal conditions for enhancing the durability of bamboo kelarai panels.

Results and discussion

The tensile test data obtained from the four specimen categories reveal distinct variations in mechanical performance, primarily governed by differences in moisture content and the application of boron treatment.

Table 1. Moisture content grouping of bamboo blade samples

Sample Group	Description	Moisture Condition	Treatment
E1	High-MC samples	Higher moisture content	No boron
E2	High-MC+Boron	Higher moisture content	Boron-treated
E3	Low-MC samples	Lower moisture content	No boron
E4	Low-MC+Boron	Lower moisture content	Boron-treated

Table 2. Summary of tensile stregth results for all sample groups

Batch	Stress Range (MPa)	Mean Stress (MPa)	Notes
E1 (High-MC, Non-Boron)	85.65 – 184.70	133.13	Lowest tensile stability due to moisture softened fibres
E2 (High-MC, Boron)	73.64 – 185.69	128.66	Boron adds stability but moisture still limits strenght
E3 (Low-MC, Non-Boron)	92.14 – 190.36	121.69	Lower moisture improves fibre cohesion
E4 (Low-MC, Boron)	140.79 – 215.16	173.27	Best tensile performance; ideal for kelarai durability

High moisture content – Non-Boron (E1)

The E1 specimen group recorded tensile stress values ranging from 85.65 MPa to 184.70 MPa, with an average value of 133.13 MPa. The presence of elevated internal moisture likely contributed to the softening of inter-fibre bonding, thereby reducing structural stiffness. The considerable variation in recorded values suggests inconsistent fibre cohesion, potentially caused by uneven moisture distribution within the material.

High moisture content – Boron (E2)

The E2 specimens exhibited tensile stress values between 73.64 MPa and 185.69 MPa, with a mean value of 128.66 MPa. Although these samples remained within the high-moisture category, the boron-treated specimens demonstrated slightly improved consistency in elongation behaviour, indicating the beneficial effects of preservation. Nevertheless, elevated moisture content continued to limit overall tensile performance.

Low moisture content – Non-Boron (E3)

The E3 specimen group displayed tensile stress values ranging from 92.14 MPa to 190.36 MPa, with an average of 121.69 MPa. While variability remained evident, the reduced moisture condition contributed to an increase in the upper range of tensile stress, thereby confirming the positive influence of improved moisture regulation on fibre cohesion and mechanical performance.

Low moisture content – Boron (E4)

The E4 specimens exhibited the highest and most consistent tensile performance, with values ranging from 140.79 MPa to 215.16 MPa and an average of 173.27 MPa. This category represents the optimal condition, in which reduced moisture enhances fibre cohesion, while boron treatment contributes to microstructural stabilisation.

Interpretation

The overall dataset indicates that:

- Moisture content exhibits a pronounced inverse relationship with tensile strength.
- Boron treatment enhances tensile reliability, even when moisture is not fully optimized.
- The combined effect of reduced moisture content and boron treatment produces the highest tensile durability, rendering it most suitable for long-term kelarai applications.

A comprehensive interpretation of the tensile data reveals a consistent and well-defined pattern illustrating the combined influence of moisture content and boron treatment on the mechanical durability of bamboo strips utilised in kelarai systems. The findings clearly demonstrate that moisture content functions as a dominant parameter governing tensile behaviour, with a strong inverse correlation observed between internal moisture levels and tensile strength. Specimens with higher moisture content consistently exhibited inferior tensile performance, a phenomenon attributable to the weakening of cellulose fibre cohesion when water molecules disrupt hydrogen bonding within the bamboo microstructure. As moisture levels increase, the fibres become more pliable and susceptible to slippage under tensile loading, resulting in premature rupture and lower stress values. This trend is particularly evident in the E1 and E2 specimen groups, which, despite differences in chemical treatment, both display reduced tensile capacity corresponding to their elevated moisture conditions.

Conversely, specimens characterised by lower moisture content, specifically E3 and, more prominently, E4, demonstrate enhanced and more stable tensile properties. Reduced moisture facilitates the preservation of structural rigidity within the fibre matrix and strengthens intermolecular bonding, thereby producing higher maximum stress values and more predictable failure mechanisms. These observations confirm that moisture reduction directly contributes to improved mechanical durability, consistent with established literature on the hygroscopic behaviour of bamboo and its influence on fibre integrity. However, moisture content alone does not fully account for the observed performance variations, particularly when comparing untreated and boron-treated specimens.

The incorporation of boron treatment introduces an additional dimension of mechanical enhancement, which becomes increasingly evident under favourable moisture conditions. Boron-treated specimens, particularly within the low-moisture category (E4), achieved the highest tensile strength among all sample groups, exceeding both untreated specimens at comparable moisture levels and treated specimens under high-moisture conditions. This suggests that boron functions as an effective stabilising agent, reinforcing the internal structure of bamboo by inhibiting microbial degradation and preserving cellulose fibre integrity. Even within the high-moisture E2 group, boron-treated specimens exhibited marginally improved consistency relative to untreated counterparts, indicating that preservation treatment provides measurable mechanical benefits even when moisture conditions are not optimal.

Collectively, the data strongly support the conclusion that the most favourable tensile performance, and, consequently, the highest durability potential for kelarai panel applications, is achieved through the synergistic combination of reduced moisture content and boron treatment. The E4 specimen group exemplifies this interaction, demonstrating both high tensile strength and consistent mechanical behaviour across all samples. This combination produces bamboo strips that are not only stronger but also more reliable, rendering them particularly suitable for long-term interior applications where kelarai panels must maintain dimensional stability and resistance to fibre failure. Accordingly, the findings confirm that optimising both moisture condition and chemical preservation is essential for enhancing the mechanical durability of bamboo materials used in kelarai production.

Discussion

The tensile test results derived from the four specimen categories provide significant insight into the manner in which moisture content and boron treatment affect the mechanical durability of bamboo strips employed in kelarai panel applications. The data consistently indicate that moisture content serves as a primary determinant of tensile behaviour, influencing both fibre cohesion and failure mechanisms. Specimens with elevated moisture levels exhibited reduced tensile performance, confirming that internal water disrupts the microstructural bonding of cellulose and hemicellulose components. This observation aligns with established principles of material science for lignocellulosic materials, wherein moisture acts as a plasticising agent that reduces stiffness and facilitates premature fibre slippage under tensile loading. Consequently, bamboo strips with high moisture content are unable to sustain the tensile forces required for weaving processes or long-term installation.

Beyond the influence of moisture, the comparison between boron-treated and untreated specimens introduces an additional dimension to the analysis. Boron treatment is commonly applied as a preservation technique due to its capacity to penetrate the vascular structure and protect against biological agents such as fungi and insects. However, the tensile test results indicate that boron may also contribute to mechanical stability by preserving fibre integrity. Within the high-moisture groups, boron-treated specimens exhibited slightly improved consistency in tensile behaviour, suggesting that the preservative may mitigate certain aspects of structural weakening associated with moisture. Nevertheless, boron treatment alone is insufficient to offset the detrimental effects of excessive moisture, as demonstrated by the relatively moderate tensile performance of the E2 group. This finding reinforces the notion that boron enhances durability most effectively when combined with favourable physical conditions.

The low-moisture specimen groups, particularly E4, illustrate the synergistic advantages of combining controlled moisture conditions with boron treatment. These specimens achieved the highest maximum stress values and the most uniform tensile performance. Reduced moisture strengthens the cellulose fibre matrix, thereby enabling boron treatment to preserve a structurally sound material rather than one compromised by internal moisture. The superior performance of the E4 group highlights the necessity of addressing both physical and biochemical factors in bamboo preparation. When moisture is effectively controlled and fibre integrity is preserved, bamboo exhibits optimal performance under tensile loading, indicating enhanced long-term durability for kelarai applications.

An additional observation derived from the dataset concerns variations in elongation behaviour across specimen groups. High-moisture specimens tended to exhibit greater elongation percentages, reflecting increased flexibility but reduced structural strength. Such elasticity is undesirable in kelarai applications, where the woven configuration requires rigidity and minimal deformation to maintain geometric stability. In contrast, low-moisture boron-treated specimens demonstrated more controlled elongation behaviour, indicating a balanced mechanical profile suitable for weaving and sustained use. This stability is essential for preventing loosening, distortion, and fibre rupture within woven panels subjected to indoor environmental fluctuations.

Overall, the discussion confirms that enhancing the mechanical durability of bamboo for kelarai production necessitates careful control of both moisture content and chemical preservation. Moisture directly influences fibre stiffness and tensile reliability, while boron treatment contributes to structural stability and resistance to biological degradation. The results reinforce the understanding that durability is governed not by a single factor, but by the interaction between internal moisture conditions and preservation chemistry. From a practical perspective, this implies that bamboo intended for kelarai fabrication must undergo adequate moisture conditioning and consistent boron treatment to ensure long-term dimensional stability and mechanical performance.

The findings of this study directly address the research problem concerning the limited scientific understanding of durability in bamboo kelarai panels. The results confirm that tensile strength is significantly affected by both moisture content and boron treatment. Specifically, reduced moisture enhances fibre cohesion and mechanical stability, while boron treatment improves structural integrity through the preservation of fibre quality. The interaction between these two factors produces the most durable bamboo condition, thereby fulfilling the research objective of identifying optimal preparation strategies for improving kelarai panel performance.

In terms of contribution, this study offers a meaningful advancement in both scientific knowledge and practical application. From a scientific perspective, it establishes a clear relationship between moisture regulation, chemical preservation, and tensile durability in bamboo materials. From a practical standpoint, it provides valuable guidance for craftsmen, manufacturers, and conservation practitioners in selecting appropriate processing techniques to enhance kelarai durability. Furthermore, the study contributes to sustainable construction by promoting bamboo as a reliable material while reinforcing the preservation of traditional weaving practices within contemporary architectural contexts.

Conclusions

This study establishes that the mechanical durability of bamboo strips utilised in kelarai panels is profoundly affected by two principal parameters: moisture content and boron treatment. The tensile testing carried out on four distinct categories of bamboo specimens indicates that reduced moisture levels are strongly associated with increased tensile strength, demonstrating that effective moisture control is essential for preserving fibre cohesion and ensuring overall structural stability. Concurrently, boron treatment enhances fibre preservation and improves tensile consistency, particularly when applied under conditions of reduced moisture content. These outcomes are consistent with established understandings of bamboo material behaviour and provide empirical validation of the structural significance of both moisture regulation and chemical stabilisation.

In summary, the integration of low moisture content with boron treatment produced the most favourable performance among all specimen groups, yielding the highest tensile strength and the most stable mechanical response. This synergistic interaction underscores the importance of adopting integrated preparation strategies that address both physical and chemical parameters in the fabrication of bamboo components for woven kelarai panels. The practical application of these findings enables craftsmen, manufacturers, and conservation practitioners to produce bamboo panel systems that are more durable, mechanically dependable, and capable of sustaining long-term performance in interior architectural environments.

This research effectively demonstrates a coherent relationship between the identified research problem, the defined study objectives, and the resulting findings. The initial concern regarding the limited durability and insufficient scientific validation of bamboo kelarai panels has been addressed through a systematic experimental investigation of tensile performance under varying conditions. The objective of evaluating the influence of moisture content and boron treatment on durability has been successfully achieved, as the results clearly indicate that controlled moisture reduction, in combination with appropriate preservation treatment, significantly enhances tensile strength. Accordingly, the study concludes that improvements in the durability of bamboo kelarai panels can be attained through methodical material preparation, offering both a practical and scientifically grounded approach to support their broader implementation in contemporary architectural construction.

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Mohd Jaki Bin Mamat contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

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