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Strength, Sustainability, and Design Applications of Bambusa vulgaris in Uganda

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Abstract

Bambusa vulgaris, a fast-growing bamboo species abundant in Uganda, offers significant potential as a sustainable construction material due to its quick regeneration, high biomass yield, and competitive mechanical properties. This study presents a comprehensive evaluation of the mechanical properties and material sustainability of Bambusa vulgaris grown in Uganda's Lake Victoria agroecological zone. Mechanical testing, conducted according to BS ISO 22157:2019 and ASTM D1037-12, assessed bending, tensile, shear, and compressive strengths parallel to the fibres, alongside corresponding moduli of elasticity. The influence of moisture content on the strength and stiffness properties and node presence on compressive strength was evaluated. Results revealed characteristic bending strength values comparable to C16 timber, with mean compressive strengths reaching 33 MPa. Results indicate that bamboo offers significantly higher strengths than the equivalent timber class. However, the lower strength/stiffness to density ratio makes timber a better choice than bamboo for lightweight construction. Correlation analyses confirmed the typical trend of increasing material strength with decreasing moisture content, though some variations in the bending strength suggest further investigation. The results also indicate that the presence of nodes decreases the compressive strengths, although the effect is not significant. Embodied carbon analysis using a modular bamboo housing design demonstrated a significant 74.2% reduction in embodied carbon emissions compared to conventional construction materials and practices in Uganda, underscoring bamboo's potential contribution to climate-friendly building practices. Despite promising findings, limitations include narrow scope of life cycle assessment stages considered and smaller sample sizes. The study recommends broader environmental impact assessments, further investigations into the factors affecting the different strength and stiffness properties and supports the integration of Bambusa vulgaris into local building codes to encourage its uptake as a renewable, low-carbon alternative in Ugandan construction.

Keywords: Bambusa vulgaris; mechanical properties; sustainable construction; Edge software

1. Introduction

Bamboo is a long tubular plant that grows in Asia, South America and parts of Africa (Sharma et al., 2015). The plant has good strength properties along the length of the stem but poor perpendicular to the stem (Estrada et al., 2019). Bamboo is a more renewable resource than steel or concrete or even timber used structurally because of its quick growth rate. It is thus becoming a more competitive resource than all these for structural engineering (Wu, 2014, Sharma et al., 2015).

Globally, bamboo is increasingly recognized in the construction industry, and its global market is forecasted to grow at an annual compound rate of 5% between 2025 and 2033, reaching a market size of USD 109 billion (Straits Research, 2024; Global Growth Insights, 2024). On average, bamboo structures generate a carbon footprint of 107.17 CO_2-eq/m², approximately 60% lower than the 298.44

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kg CO2-eq/m² for conventional clay brick structures (Rincón et al., 2023). Bamboo construction can reduce energy consumption by 3-5% and CO_2 emissions by 7-20% compared to reinforced concrete structures (Zhao et al, 2023). This not only mitigates greenhouse gas emissions so as to achieve the net zero carbon targets, but also enhances energy efficiency in construction, making bamboo a promising solution to the global demand for sustainable construction materials that has intensified in recent years. However, bamboo is not widely used in Europe and the USA for permanent construction, because it is not officially recognised as a building material due to the lack of standard building codes for it in many places. People still use bamboo in many parts of South and South-East Asia and Central America as scaffolding and for temporary and permanent structures, for flooring, fencing furniture and crafts (Wu, 2014). Despite having almost 30% of the world's bamboo by hectare in 2010, Brazil still does not utilise it as a raw material sufficiently (Rusch et al., 2019).

In Africa, bamboo is increasingly recognized as a sustainable alternative in the construction sector, offering rapid growth, low carbon footprint, and cost-effectiveness (Xu, 2025). In Ethiopia, bamboo contributes significantly to the bioeconomy, though its utilization remains underdeveloped (Alemayehu, 2023). Similarly, Nigeria's bamboo industry faces challenges in policy and infrastructure (Okokpujie, 2020). In South Africa, species like Bambusa balcooa show promise for structural applications, yet comprehensive engineering data is lacking (Ross & Alexander, 2022). The International Bamboo and Rattan Organisation (INBAR) emphasizes the need for an enabling environment to mainstream bamboo construction in Africa (Liu et al., 2022). Despite its potential, bamboo faces challenges such as limited processing technology, lack of expertise, and inadequate policy support (Bahru & Ding, 2021). Future prospects hinge on developing standardized design codes, enhancing technical capacity, and fostering public-private partnerships to unlock bamboo's full potential in sustainable construction across Africa

In Uganda, Bambusa vulgaris is among the prioritized species for industrialization due to its fast growth cycle and high biomass production (Zhu&Jin, 2018; Banik 2000). However, there is lack of documented data on the mechanical properties, quantification of sustainability measures, and structural usage of Bambusa vulgaris in Uganda. Previous studies (Carbonari & Carbonari ,2023; Adam & Jusoh, 2019; Sikame et al, 2021; Gomes et al 2021; Trujillo & Lopez, 2020, Mbuge & Gumbe, 2022) among others have characterized Bambusa vulgaris in other parts of the world, but no similar studies have been done in Uganda. These studies often report values obtained under varying test methods, environmental conditions, and maturity levels, making direct comparisons difficult and hindering the development of reliable design codes.

Kalanzi et al (2024) studied the growth properties of Bambusa vulgaris in Uganda and concluded that the Bambusa vulgaris in the L.Victoria agroecological zone of Uganda had the best growth parameters and total above-ground biomass at 3 years. Whereas this short growth cycle and high biomass productivity give Bambusa vulgaris regenerative properties and hence making it a sustainable material, to date, there are no quantitative studies that have assessed the material embodied carbon savings that bamboo offers compared to conventional local construction materials and practices in Uganda.

To represent the research domain and the evolution of this topic's multidisciplinary knowledge, word co-occurrence mapping from abstracts and titles of 41 articles obtained from Scopus that study structural use of bamboo in construction was conducted using VOSviewer. Words occurrence was set to 5 under full counting, and 150 out of 241 words met the threshold for the most relevant keywords. Figure 1 & 2 show the co-occurrence of the keywords with the node size implying the frequency of the word occurrence and the color scale indicating the evolution of the keywords over the years from 2012 to 2025, with Figure 2 showing the interconnected keywords. Figure 1 & 2 show that previously, some topics such as fire reaction, fabrication, bamboo standard, contemporary vernacular architecture, etc were studied. Currently however, present research under the same domain includes keywords such as CO_2 footprint, sustainable construction material, material property, etc. This implies that sustainable construction utilizing bamboo to reduce CO_2 footprint in building construction has gained recent attention and interest to researchers in this area. This study therefore seeks to extend this body of knowledge by focusing on material properties and embodied carbon savings of Bambusa vulgaris.

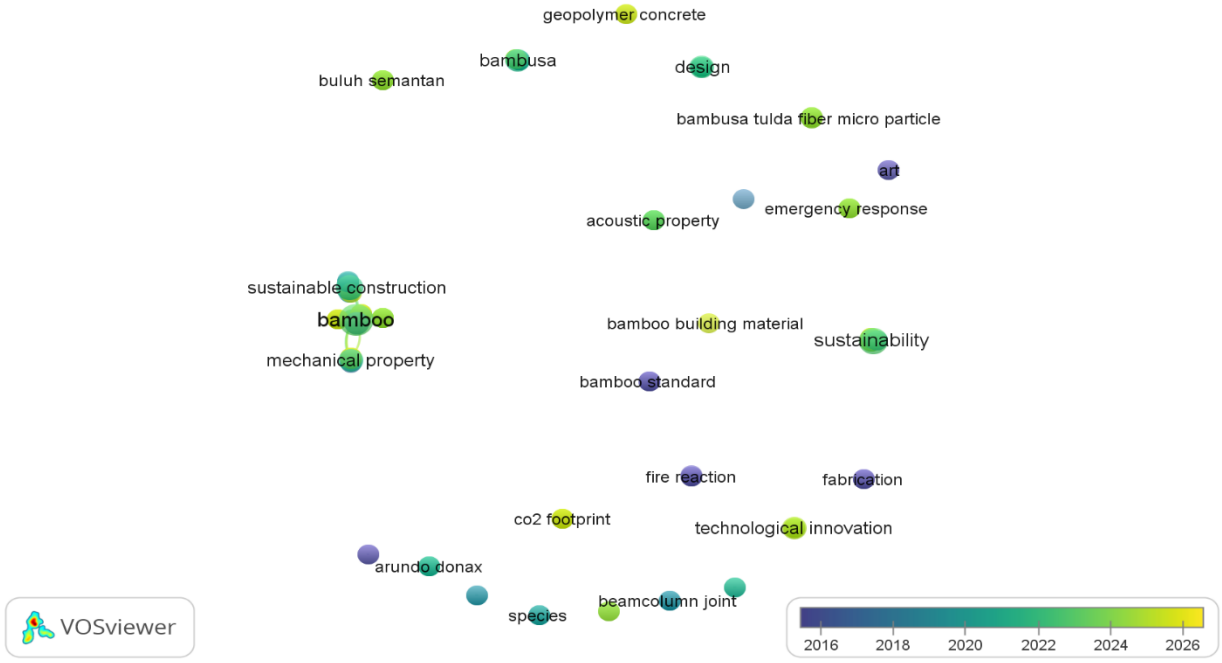


Fig. 1 Scientometric network of co-occurrence and chronological trends of keywords in VOSviewer

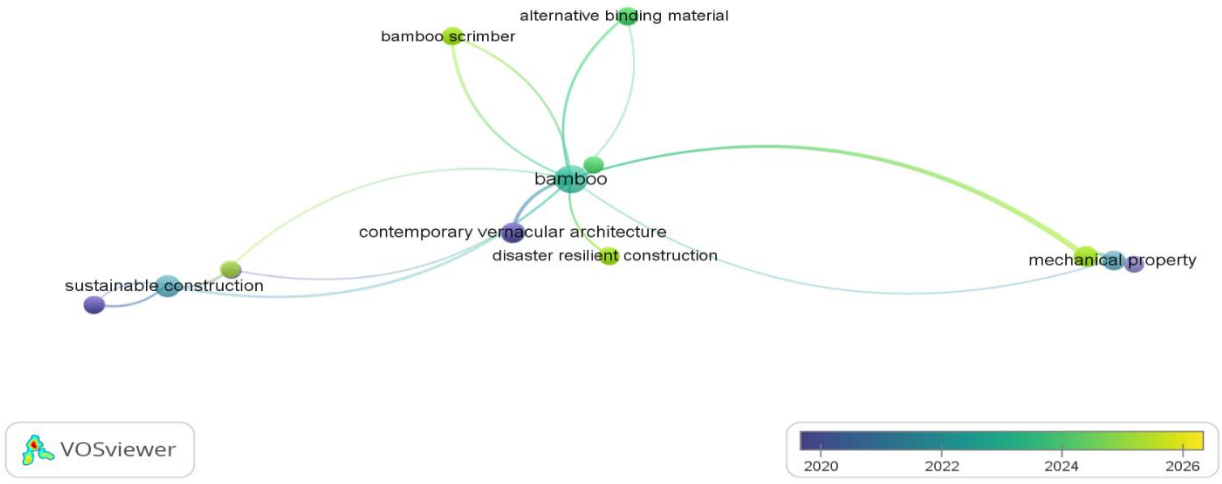


Fig. 2 Scientometric network of co-occurrence connections and chronological trends of keywords in VOSviewer

Given the urgent need for robust, climate-friendly construction materials and the promising attributes of Bambusa vulgaris, a locally contextual evaluation of its mechanical properties is essential. Such characterization will not only inform engineering applications but also support the codification of bamboo in local structural design standards, facilitating its broader adoption in modern construction in Uganda.

This study thus aims to: (1) Assess the strength and stiffness properties of Bambusa vulgaris in the L.Victoria agroecological zone of Uganda; (2) Model the embodied carbon saving in a simple 20.7m^2 house in IFC's Edge tool compared to the typical construction practices in Uganda.

2.0 Materials and Methods

In this study, the research road map is divided into six (6) stages which are demonstrated in Fig. 3.

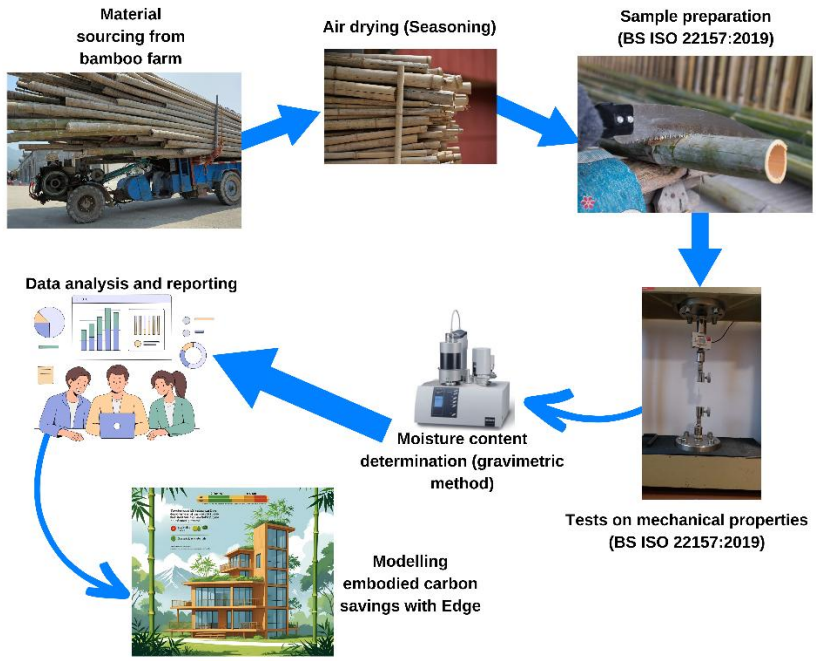


Fig. 3 Methodology schematic of the study

2.1 Material Selection and Sampling

The culms of yellow Bambusa vulgaris used for this study were obtained from a farm in Namasumbi village, in the central part of Uganda, located between latitude 32°E and 33°E, and longitudes 0°N and 1°N, within the L.Victoria agroecological zone. The farm was randomly selected out of a list of 5 farms with the guide of key informants. Juvenile culms of approximately 1 years old were used for the study. The culms were cut at about 15 cm above ground level. The total length of each felled culm was measured and the designated 5th, 10th, 15th, 20th, 25th and 30th internodes were marked and measured for length and diameter.

2.1.1 Sample Preparation

The designated internodes of the culm were utilized for the study. Samples were air dry for two months before testing as per BS ISO 22157:2019.

2.1.2 Materials Testing

The physical and geometric properties tested and measure respectively were; basic density (ρ), density at 12% moisture content (ρ_{12}), moisture content, internode length, culm wall thickness, and culm diameter.

The mechanical properties tested were; bending strength parallel to the fibres ($f_{m,0}$), shear strength (f_v), tensile strength parallel to the direction of the fibres ($f_{t,0}$), compressive strength parallel to the direction of the fibres ($f_{c,0}$), flexural modulus of elasticity parallel to the fibres ($E_{m,0}$), compressive modulus of elasticity parallel to the fibres ($E_{c,0}$), tensile modulus of elasticity parallel to the fibres ($E_{t,0}$).

The samples were treated and tested for the different physical and mechanical properties following the BS ISO22157:2019 (ISO 2019) except for bending strength which was tested by the three points static

bending test in accordance to ASTM D1037-12 (ASTM,2012). The specimen geometric parameters (Length, thickness, diameter) were measured using measuring tape, vernier caliper and micrometer screw gauge. The moisture content at testing of the samples was obtained using a calibrated electrical moisture meter. The specimens were also visually observed for uniformity and also to ascertain the number of nodes. The Computerized Testometric Universal Testing Machine (UTM) at the Department of Mechanical Engineering, Makerere University was used to obtain the ultimate force at (F_{ult}) for each sample, for each test.

2.2 Data Analysis

Statistical analysis was performed using Python (statsmodels library) and Microsoft excel 2019. The physical properties were analyzed to ascertain the descriptive statistics (mean and standard deviation). The objective and scope of the data analysis was to; assess the effect of moisture content on the different mechanical properties, to characterize the strength and stiffness properties of Bambusa vulgaris and compare the strength/stiffness to density ratio with a similar class of timber, and to assess the effect of the number of nodes on the compressive strength of the bamboo parallel to the fibre.

To ascertain the effect of moisture content on the different mechanical properties, Pearson correlation between the moisture content and the different strength and stiffness properties was conducted followed by linear regression model fit based on Analysis of Variance (ANOVA). All tests were done at 5% level of significance. The characteristic values of the material properties were obtained from descriptive statistical analysis (mean, standard deviation and 5th percentile values).

To assess the effect of the number of nodes on the compressive strength, nine (9) cylindrical bamboo specimens were prepared and tested in axial compression parallel to the fibres. For each specimen, three parameters were recorded: node count within the gage length (0, 1, or 2), moisture content (MC, %), and compressive strength (N/mm^2). The analytical approach combined descriptive and inferential methods. Descriptive statistics (means and standard deviations) were calculated for compressive strength within each node group. Analysis of covariance (ANCOVA) was performed with compressive strength as the response variable, node count as a categorical predictor, and MC as a covariate. Robust (HC3) standard errors were applied to account for the small sample size and potential heteroskedasticity. Estimated marginal means (EMMs) of compressive strength were computed for each node level, adjusted to the average MC. Pairwise contrasts were derived to quantify differences between groups. A linear trend model was fitted by treating node count as a numeric predictor to test whether compressive strength decreases linearly with increasing node number. All computations were conducted in Python (Statsmodels library). Graphical analysis, including scatterplots of strength versus MC by node category and boxplots of strength by node group, was used to visualize the effects.

2.3 Embodied Carbon Modelling in Edge

To compute the embodied carbon impact of bamboo in building applications, a simple bamboo housing was designed and modeled in EDGE software.

The housing unit is a 20.7-square-meter, single bedroom residential building constructed using a panelized system as shown in Figure 4.

It comprises six wall panels, two ceiling panels, and two roof panels, all fabricated from bamboo. Tailored bamboo joinery is employed to securely connect these elements, forming a complete, structurally stable unit. The design is modular and fully reversible, allowing for straightforward expansion by adding panels along the gable end without compromising structural integrity.

The wall panels are clad with a breathable mud finish. This breathable wall assembly ensures natural ventilation and thermal regulation while maintaining durability.

By combining prefabricated bamboo elements with reversible connections and modular growth potential, the unit offers a sustainable, adaptable housing solution responsive to changing user needs.

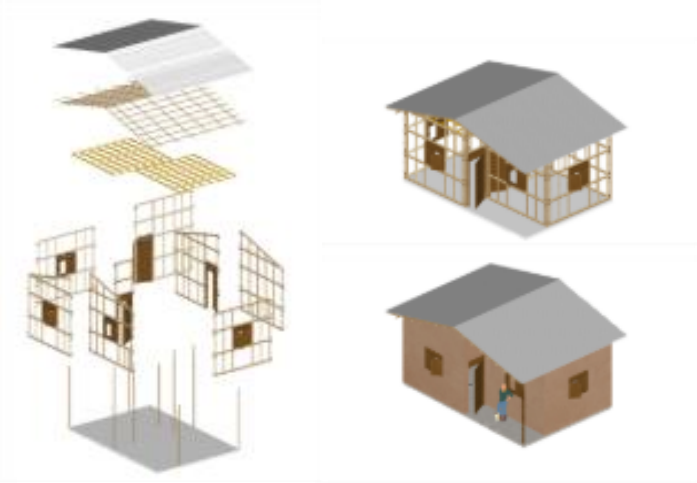


Fig. 4 Building model schematic

EDGE (Excellence in Design for Greater Efficiencies), developed by the International Finance Corporation (IFC), is a software tool used for quantifying energy, water, and embodied carbon footprint of building designs. Critically, the software computes these metrics and compares the results with those of a conventional baseline building with the same size, form, and function in the same geographic region, enabling assessment of sustainability performance relative to typical local construction practices.

The EDGE software calculates the embodied carbon of building materials using a "Cradle to Gate" life cycle assessment (LCA) approach in accordance with Standard EN 15804+A2:2019, measuring Global Warming Potential (GWP) in kg CO2 equivalent. The assessment covers three key stages: A1 (raw material extraction and processing), A2 (transport of raw materials to manufacturing sites), and A3 (manufacturing process emissions), with calculations incorporating regional variations in greenhouse gas emissions across seven geographic regions including Eastern Europe, MENA, Africa, Asia and Australasia, Latin America and the Caribbean, US & Canada, and Western Europe to ensure accurate reflection of location-specific environmental impacts.

A new project was created in the design tab of the application, where the building was classified under the "Homes" category. The project location was set to Kampala, Uganda. Comprehensive building data was input including detailed area allocations, building dimensions and orientation, and the specific material composition of each building element.

The conventional baseline building for comparison utilized typical Kampala construction materials including concrete masonry units for walls, conventional timber or steel framing elements, and standard roofing materials. This baseline comparison enabled quantification of the embodied carbon reduction achieved through bamboo material substitution relative to conventional local construction practices. EDGE combined the region-specific material embodied carbon data for Uganda with the input building specifications to calculate both the absolute embodied carbon of the bamboo building and its performance relative to the conventional baseline, providing both quantitative carbon metrics and percentage reduction compared to typical construction in the region

3.0 Results and discussion

3.1 Physical and morphological properties of the test samples

Table 1 summarizes the scope and values of the physical and morphological properties of the test specimens. The average basic density was approximately 570kg/m^3 with a standard deviation of 81.2kg/m^3. Mbuge & Gumbe (2022) obtained the basic density of Bambusa vulgaris as 590kg/m^3, within the range of 500-700kg/m^3 as per Janssen (1991). These values are within a close range despite the different sources of the samples. This shows that the density values for the same species at the same age are likely not to vary under different geographical conditions.

Furthermore, the internode length and culm wall thickness of approximately 256mm and 11mm ranges closely with that obtained by Kalanzi et al (2024) of 241mm and 0.94mm for a 1 year old Bambusa vulgaris. However, the difference is not expected to be significant given that the species were tested from the same agro ecological zone.

Table 1 Means of the different physical properties tested

Material Property	Mean$\pm$s
ρ (kg/m^3)	568.95 ± 81.2
ρ_{12} (kg/m^3)	542.32 ± 75.32
Moisture Content (%)	17.5 ± 2.3
Internode Length (mm)	255.77 ± 6.03
Culm wall thickness (mm)	10.77 ± 4.84
Outer Diameter (mm)	64.80 ± 12.67

3.2 Mechanical Properties

3.2.1 Effect of Moisture Content on the Mechanical Properties

Table 2 shows the results from the correlation of the tested strength and stiffness properties with moisture content. The trend is as expected, with the strength and stiffness properties increasing as the moisture content decreases, indicated by the negative correlation coefficient. However, for bending strength, the correlation coefficient is high and positive, contrary to the expected trend. This might be as a result of untested confounding factors such as moisture content effect on the plasticity of bamboo, age or the test method. However, this was not part of the scope of the study.

Table 2 Pearson correlation coefficient between moisture content and the tested mechanical properties

Material Property	Pearson Correlation Coefficient (r)	t-Statistic	p-Value
$f_{m,0}$	0.826	3.588	0.012
$E_{m,0}$	-0.750	-2.775	0.032
f_v	-0.796	-3.225	0.018
$f_{t,0}$	-0.931	-3.618	0.069
$E_{t,0}$	-0.292	-0.432	0.708
$f_{c,0}$	-0.226	-0.568	0.591
$E_{c,0}$	-0.414	-1.112	0.309

From Table 2, only $f_{m,0}$ $E_{m,0,}$ and f_v had significant correlation coefficients at 5% level, and the fit for a linear regression model between the moisture content and these properties was tested using Analysis of Variance (ANOVA) as shown in Table 3.

Table 3: Linear Regression Model fit (ANOVA)

Material Property	R^2	F-Statistic	p-Value (ANOVA)

$f_{m,0}$	0.501	7.017	0.033
$E_{m,0}$	0.202	1.773	0.225
f_v	0.622	11.519	0.012

It can thus be concluded that the material strength and stiffness properties generally increase with drying of the bamboo. However, the bending strength seemed to increase with an increase in moisture content and further research is needed to investigate the factors affecting this relationship. The R^2 value for the regression model in Table 3 was highest for shear strength, indicating that moisture content alone is responsible for more than 60% of the shear strength of Bambusa vulgaris.

3.2.2 Characterization of the Mechanical Properties

The material strength and stiffness mean characteristic values are as shown in Table 4. The material strength/stiffness to average density ratio were compared to that of C16 timber, since the characteristic bending strength obtained (16MPa) was close to that of a C16 timber.

The mean compressive strength of the Bambusa vulgaris (33MPa) was almost equal to the bending strength, and about 82% higher than the tensile strength. Similarly, the mean compressive elastic modulus (2326MPa) was very close to the apparent mean flexural elastic modulus (2587MPa) but significantly larger than the mean tension elastic modulus (262MPa). This is attributed to the existence of nodes in the compression test specimens and the absence of nodes (instead using only fibres) in the tension test. The nodes are a stiff zone that increases the compressive strength of bamboo. For this reason, it is recommended that in structural use, compression members should have as many nodes as possible, especially close to the supports.

Compared to a C16 timber, it can be seen that Bambusa vulgaris tested had approximately 10 times lower strength/stiffness to density ratios, except for bending strength. This shows that bamboo that gives the same strength as conventional C16 timber for the same volume would need to be 10 times heavier in shear and axially loaded members. However, for bending, the strength-to-density ratio of C16 timber was twice that of the Bambusa vulgaris. This shows that timber would still be a better choice than bamboo for lightweight construction. However, the characteristic values of the Bambusa vulgaris tested were all significantly larger than the equivalent timber (C16), indicating that Bambusa vulgaris is significantly stronger and stiffer than timber.

Table 4 Average and characteristic strength and stiffness properties

Material Property	Mean±s (MPa)	5th Percentile Value (MPa)	Average Moisture Content (%)	Property to density ratio (MPa/kgm^{-3})	Property to density ratio for C14 timber (MPa/kgm^{-3})
$f_{m,0}$	33.30 ± 12.1	15.94	17.87	0.028	0.043
$E_{m,0}$	2586.87 ± 2081.4	850.97	17.87	1.496	14.595
f_v	6.10 ± 3.10	2.71	17.53	0.005	0.009
$f_{t,0}$	123.63 ± 27.54	86.4	17.7	0.152	0.022
$E_{t,0}$	262.14 ± 60.20	181.62	17.7	0.319	-
$f_{c,0}$	33.13 ± 7.00	24.2	17	0.043	0.046
$E_{c,0}$	2326.32 ± 1013.53	810.3	17	1.424	-

3.2.3 Effect of Nodes on the Compressive Strength Parallel to the Fibres

As per the guidelines from BS ISO 22157:2019, 50% of the specimens used for testing compressive strength had nodes and 50% had no nodes as shown in. From Table 5 and Figure 5, compressive strength declined with increasing node count. Moisture content (MC) varied from 14–21%, but no consistent association with compressive strength was evident within this narrow range.

Table 5 Compressive strength values for specimens with different node configurations

Sample	Number of nodes	Moisture content (%)	$f_{c,0}$ (MPa)

1	0	14	41.647
2	0	14.3	39.775
3	0	14.6	30.18
4	1	14.8	32.184
5	1	15.3	29.459
6	1	16.2	33.162
7	2	21.1	42.877
8	2	21.3	23.091
9	2	21.3	25.831

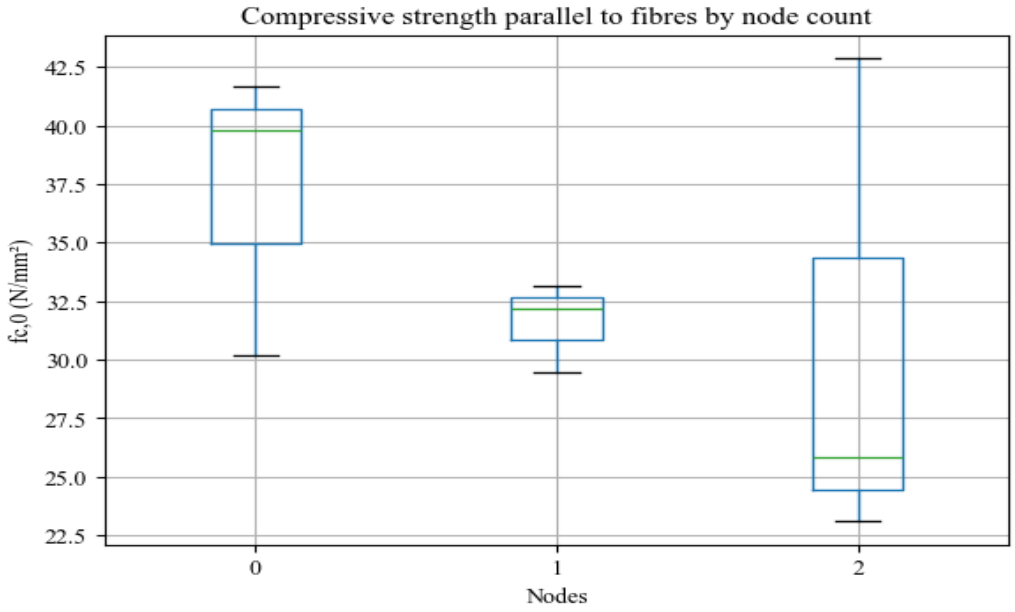


Fig. 51 Box and whisker plot for compressive strength parallel to fibres for different node groups

ANCOVA results confirmed a downward shift in strength associated with the presence of nodes. At the average MC, the estimated marginal means were estimated at: 37.2 N/mm² (0 nodes), 31.7 N/mm² (1 node), 30.3 N/mm² (2 nodes) as per Table 6. The observed reduction from node-free to node-bearing specimens was approximately 15–20%.

Table 6 Estimated marginal means (N/mm²) at average MC (17.5%).

Nodes	EMM (N/mm²)	SE	95% CI Low	95% CI High
0	37.2	~3.5	28.8	45.6
1	31.7	~3.9	22.3	41.2
2	30.3	~4.5	19.9	40.7

Pairwise adjusted differences indicated that node-bearing specimens were weaker than node-free ones (−5.5 to −6.9 N/mm²). However, wide confidence intervals prevented statistical confirmation ($p > 0.05$), reflecting the small sample size. Differences between 1 and 2 nodes were negligible.

Table 7 Pairwise contrasts of compressive strength (N/mm²) at average MC.

Contrast	Difference (N/mm²)	SE	p-value	95% CI Low	95% CI High
1 − 0	−5.5	~4.7	0.3	−17.2	6.2
2 − 0	−6.9	~5.2	0.25	−19.7	5.9
2 − 1	−1.4	~5.0	0.8	−14.2	11.4

3.3 Trend Analysis

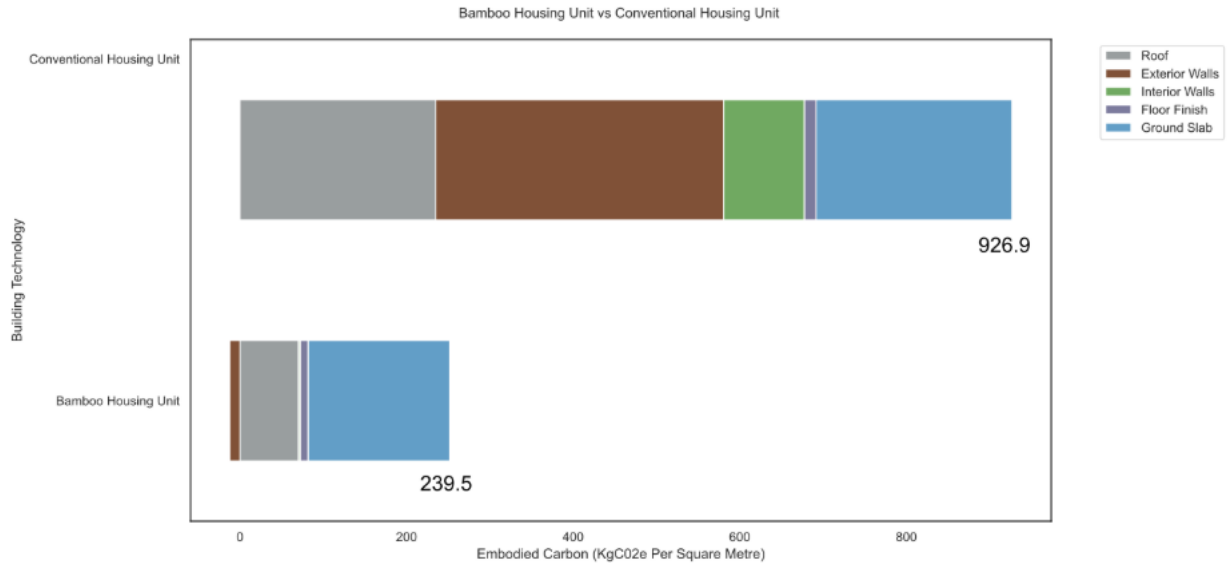
The linear trend model estimated a reduction of −3.4 N/mm² per additional node. While not statistically significant, the negative slope aligns with the mechanical expectation that nodes interrupt fiber continuity, reduce load-sharing capacity, and act as stress risers.

Predictor	Coefficient (β)	SE	95% CI Low	95% CI High	p-value
Intercept	37.2	~3.5	28.6	45.8	<0.01
Nodes	−3.6	~2.1	−9.1	1.9	0.18
Moisture	−0.3	~0.2	−0.8	0.2	0.2

These findings are consistent with the findings of Mbuge & Gumbe (2022) who found out that the compressive strength of Bambusa vulgaris decreases with increasing the number of nodes. However, in their findings still, there was no significant difference between the compressive strength of specimens with nodes and those without nodes. This indicated the presence or absence of nodes was found to have no effect on the compressive strength.

3.4 Material Embodied Carbon Saving from using Bamboo

The EDGE analysis revealed significant embodied carbon reductions when bamboo materials were substituted for conventional construction materials. The bamboo housing unit reported a total embodied carbon of 239.5 kg CO2e/m², compared to 926.9 kg CO2e/m² for the conventional housing unit, representing a major 74.2% reduction in embodied carbon emissions.



At component level, the effect of switching conventional materials with bamboo is observed more clearly. The roof component, where bamboo framing is employed, contributed significantly to carbon reduction, decreasing from 235.1 kg CO2e/m² in the conventional design to 70.5 kg CO2e/m² in the bamboo design, representing a reduction of 164.6 kg CO2e/m² (24.0% of total savings). Interior walls, also framed using bamboo, demonstrated a reduction of 95.1 kg CO2e/m² (from 97.1 to 2.0 kg CO2e/m²), contributing 13.8% to the overall carbon savings. In fact, bamboo-framed exterior walls showed the largest absolute reduction of 357.8 kg CO2e/m² (from 345.5 to -12.3 kg CO2e/m²), accounting for approximately 52.1% of the total carbon savings achieved. The negative embodied carbon value for the exterior walls suggests that material is a net carbon sequestering building material when used in this way, reflecting bamboo's potential for carbon storage during its growth phase. The ground slab, which remained as conventional reinforced concrete in both scenarios with varying thicknesses and steel weight per square meter of slab, showed identical embodied carbon values of 235.1 kg CO2e/m² for the conventional case and 169.8 kg CO2e/m² for the bamboo case.

The overall 74.2% reduction in embodied carbon illustrates the substantial potential of bamboo as a low-carbon building material alternative to conventional brick and concrete construction materials, especially for structural use where most of the building embodied carbon typically resides.

3.5 Limitations and Recommendations

This study was limited to Bambusa vulgaris samples sourced from a single farm in the Lake Victoria agroecological zone, focusing exclusively on juvenile culms of approximately one year in age. Consequently, the findings may not be fully representative of other regions, growth stages, or management practices in Uganda. Mechanical testing was conducted on small, prepared specimens under controlled laboratory conditions and the results may not be generalizable for other regions. The relatively narrow moisture content range, absence of seasonal or environmental variation analysis, and reliance on IFC's Edge tool for embodied carbon modelling, whose datasets may not fully reflect Uganda's local supply chains, further limit the scope of applicability. In addition, long-term durability, resistance to pests and weathering, and economic feasibility were not evaluated. Future research should therefore expand sampling across multiple agroecological zones and age classes, employ full-scale structural testing under realistic load conditions, incorporate durability and life-cycle cost analyses, and validate embodied carbon results using locally verified datasets. Such work would strengthen the basis for developing localized design codes and promoting wider adoption of bamboo as a sustainable construction material in Uganda. Given the unexpected positive correlation between bending strength and moisture content, a dedicated follow-up study should isolate and test likely confounders under controlled conditions. We recommend a factorial experimental design while comparing ASTM D1037-12 and ISO 22157 protocols. Advanced techniques such as strain mapping, microscopy, and finite element modelling should be used to identify the underlying mechanisms and develop moisture-related correction factors for structural design of Ugandan Bambusa vulgaris.

It is important to acknowledge that there are a few limitations that constrain the generalisability of our embodied carbon findings. The analysis employed EDGE's framework for embodied carbon calculations which covers only stages A1-A3 and excludes other life cycle phases such as construction, operational stage impact, and end-of-life considerations. Future research should employ more comprehensive LCA methodologies using specialized software such as OpenLCA, SimaPro, or GaBi that allow for complete customisation of material inputs and full cradle-to-grave analysis including all LCA stages.

3.6 Conclusion

This study provides the first comprehensive characterization of the mechanical properties and sustainability potential of *Bambusa vulgaris* from Uganda's Lake Victoria agroecological zone. The findings demonstrate that the species exhibits competitive strength and stiffness values, with compressive strengths reaching 33 MPa and bending properties comparable to C16 timber. Although its lower strength-to-density ratios limit suitability for lightweight applications, the overall performance confirms *Bambusa vulgaris* as a viable structural material for Uganda's construction sector. Moisture content was shown to significantly influence strength and stiffness, underscoring the need for standardized drying and treatment protocols. The effect of nodes on compressive capacity, though consistent with theoretical expectations, was not statistically significant, suggesting further investigation with larger datasets.

Beyond its mechanical performance, embodied carbon modelling revealed a substantial 74.2% reduction in emissions when bamboo was substituted for conventional construction materials, highlighting its critical role in advancing low-carbon, climate-resilient housing solutions. While limitations related to sampling scope, testing conditions, and the restricted life cycle stages of the embodied carbon assessment constrain the generalizability of the results, the evidence strongly supports the integration of *Bambusa vulgaris* into Uganda's construction practices.

Future work should extend to broader ecological zones, full-scale structural assessments, durability studies, and cradle-to-grave environmental analyses to establish robust design codes and certification frameworks. Overall, this study confirms that *Bambusa vulgaris* holds significant promise as a

renewable, high-performance, and low-carbon alternative to conventional materials, positioning it as a strategic resource for sustainable construction in Uganda and the wider African context.

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