**The Effect of Moisture Content and Density on Steam and Cold Bending Qualities of Two Underutilized Timber Species**

**ABSTRACT**

This study investigated the steam and cold bending properties of sapwood and heartwood from two underutilized timber species, *Azadirachta indica* (Neem) and *Cassia siamea* (Cassia), with the aim of determining their suitability as substitutes for traditional bending species such as *Khaya ivorensis* (African Mahogany) in the furniture and joinery industries. Physical characteristics including moisture content and basic density were determined in accordance with ASTM standards, while bending qualities were assessed using both pegged form and form tool techniques under cold and steam conditions. Descriptive statistics revealed significant variation between species and wood portions. Neem sapwood exhibited the highest moisture content (88.15%), whereas Cassia heartwood showed the lowest (47.50%). Density analysis demonstrated that Cassia heartwood possessed the highest basic density (898 kg/m³), with Neem sapwood recording the lowest (674.61 kg/m³). Mixed ANOVA confirmed statistically significant differences in density and moisture content (F=44.073, p<0.05), and pairwise comparisons highlighted significant differences between most group pairs, except between Neem heartwood and Cassia sapwood.

Bending tests showed that Cassia heartwood performed best under both cold and steam bending,

achieving up to 85% unbroken samples under steam bending with the form tool technique, categorizing it in Quality Class I. Neem sapwood, due to its flexible cellular structure and higher

moisture content, showed superior performance over the heartwood in steam bending, placing it in Quality Class II. Cold bending results indicated generally lower performance of sapwood compared to heartwood, linked to higher moisture content and lower density. The form tool technique consistently outperformed the pegged form, demonstrating reduced bending times and

higher integrity of bent samples. The study established a positive correlation between wood density and bending quality. This study supports the utilization of Cassia and Neem as sustainable alternatives to traditionally exploited species, contributing to forest conservation efforts in Ghana

**Keywords:** Form tool, furniture production, pegged form, curvature, joinery.

**1. INTRODUCTION**

Wood bending is an ancient technique that remains essential in modern joinery and furniture manufacturing, particularly in the production of window and door frames, glue-laminated beams, construction of doors, and various furniture components (Tenório et al., 2024). Curved elements such as chair legs and rails can be produced either by sawing or bending. Among the available methods for shaping curved parts, wood bending is considered the most cost-effective, productive, and material-efficient technique for producing strong and durable components (Ayarkwa et al., 2011). Although wood is naturally straight and rigid, all timber species possess a certain capacity to be bent to a desired radius (Wiedenhoeft, 2010). The bending process involves the simultaneous stretching of fibres on the convex side and compression on the concave side of the curve (Syerko et al 2012).

Wood bending can be performed either cold or using heat and moisture treatments, such as steaming or chemical plasticization with ammonia or urea, when gluing is not applied concurrently. These treatments significantly improve the plasticity of wood materials (Hackenberg et al., 2021). Wood plasticization is typically achieved through atmospheric-pressure steaming, hot or boiling water soaking, or microwave heating (Luan et al., 2022). These processes soften the cell walls, allowing sufficient compressive deformation to accommodate the required curvature. Generally, wood in a heated and moist condition demonstrates greater flexibility compared to cold or dry wood (Börcsök and Pásztory, 2021). Steaming softens the natural wood polymers, rendering them thermoplastic-like and susceptible to reshaping under applied stress and heat Lee et al., 2018). Once shaped and dried while restrained in the desired form, the wood recovers its stiffness and strength, thus permanently retaining the curved configuration.

Anatomically, wood comprises longitudinal cellulose fibres aligned along the tree's axis (Schubert et al., 2022). Transverse fibres and other cellular structures confer additional mechanical stability. Heartwood, composed of dead cells, serves functions related to structural support and water storage, whereas sapwood remains physiologically active, conducting water and nutrients (Kampe and Magel, 2013). Annual fibre layers develop beneath the cambium, with thickness determined by environmental conditions such as moisture availability and mechanical stresses (Rathgeber et al., 2022). Over time, older layers transition into heartwood, characterized by higher density due to lignin deposition and extractives accumulation, whereas the newer sapwood remains less dense and more flexible. Heat treatment causes intrinsic moisture within the wood to vaporize, softening the fibre bonds and facilitating their realignment (Sehlstedt-Persson, 2008). Steam bending exploits this phenomenon to plastically deform and reshape wood fibres, a method commonly employed for hardwood species in the production of furniture and joinery components (Ayarkwa et al., 2011).

Critical factors influencing steam and cold bending processes include specimen size, initial moisture content, steaming duration, bend radius, and the type of equipment used (Mikšik, et al., 2023). For example, 25 mm thick samples require 30–40 minutes of steaming, whereas thinner samples (approximately 15 mm) require less time (Ayarkwa et al., 2011). Optimal moisture content for effective steaming ranges between 18% and 25%; lower moisture levels necessitate extended steaming durations to achieve adequate plasticization (Ratnasingam, 2022). Báder and Németh (2023) demonstrated that plasticized wood can undergo compressive deformation of 25–30% along the grain but only 1–2% tensile extension, underscoring that bending-induced deformation predominantly occurs via compression rather than stretching to prevent structural failure (Ratnasingam, 2022). Post-steaming, the wood can be bent into various curvatures using appropriate jigs or form tools.

Wood species selection for producing components with minor to moderate curvature is typically determined by availability and suitability. However, for applications requiring severe curvature, the wood's intrinsic bending quality becomes the primary selection criterion (Kuljich et al., 2015). Bending properties vary significantly between species and even within individuals of the same species (Bachmann et al., 2012). Thin veneers can be manually bent without prior treatment, whereas bending thicker solid wood sections necessitates softening through heat, or chemical methods.

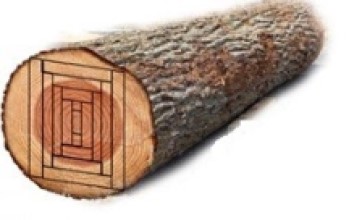
Moisture content noticeably affects wood’s mechanical properties. The distribution of moisture within a tree varies according to species, growth conditions, and environmental influences (Tomczak et al., 2021). Even within the same species, logs harvested under similar conditions may exhibit differences in moisture distribution (Nilsson et al., 2013). Wood density is another critical factor, influences bending performance, with higher density typically correlating with improved bending behaviour (Balboni et al., 2021). Density variations exist between sapwood and heartwood, along the radial and vertical axes of the tree, and between growth rings. Heartwood is denser due to thicker cell walls and reduced lumen size compared to sapwood (Esteban et al., 2024). In some coniferous species, heartwood density can exceed that of sapwood by over 100%, impacting the overall density of the tree (Sillett et al., 2015; Cherelli et al., 2018). A direct relationship often exists between the densities of sapwood and heartwood within individual trees (Bahmani et al., 2020).

For optimal steam bending, defect-free, straight-grained wood is required to prevent failures such as rupture, delamination, or surface checking. Structural defects like knots, irregular grain, cracks, resin pockets, and ingrown bark can compromise bending integrity (Rashidi et al., 2021). In outdoor applications, heartwood is favored for its superior durability (Sandberg, 2009). Other determinants of bending performance include age, growth ring width, cellular structure, resin content, site conditions, and genetic variability among species (Schneeweiß and Felber, 2013). Compared to sawn components, bent elements conserve material, reduce processing waste, and enhance strength due to the preservation of continuous grain orientation, contributing to sustainable forest management practices (Ge et al., 2023). However, excessive bending may lead to mechanical failures categorized as cross-grain tension, splintering, or brashness (Ayarkwa, 2000).

Short-term steaming or hot water soaking improves wood flexibility without adversely affecting its mechanical properties (Yin et al 2011). In glulam production, cold bending is often preferred to avoid moisture interference with adhesive curing. Nonetheless, steam bending of laminated members or gluing post-steam bending is possible. Conventional bending involves heating the wood in steam or hot water followed by shaping on a jig or form tool. Hardwoods generally exhibit superior bending characteristics relative to softwoods (Hassler et al., 2022). In Ghana, limited studies have explored the steam and cold bending behaviors of sapwood and heartwood. This research seeks to evaluate the bending characteristics of Neemand Cassia, underutilized Ghanaian timber species, to inform their potential applications in the furniture and joinery industries and support sustainable forest resource management by the Ghana Forestry Commission in efforts to reduce deforestation and the over-exploitation of primary timber species.

**2. MATERIALS AND METHODS**

Three mature trees, each of *Cassia siamea* (Cassia) and *Azadirachta indica* (Neem) were selected based on their commercial harvesting diameters, ranging from 360 mm to 520 mm, measured at a height of 250 mm above ground level. Logs were carefully marked and sawn (Figure 1) to distinctly separate the heartwood and sapwood portions of each tree. Subsequently, the logs were processed using a horizontal band saw to produce lumber dimensions of 50 mm × 200 mm × 2400 mm. A total of approximately 48 lumber pieces were obtained from the six logs (three per species). From these, test specimens were prepared for the assessment of the various properties described in this study. The moisture content of the specimen before the cold and steam bending test was 18% as used in research by Ayarkwa et al. (2011). In total, eighty specimens comprising both sapwood and heartwood samples were prepared and tested for each property at the Timber Testing Laboratory of the Centre for Scientific and Industrial Research – Forestry Research Institute of Ghana (CSIR-FORIG), located at Fumesua, Kumasi, Ghana.



**Figure 1. The surface of each log was marked for sawing.**

**2.1 Determination of Physical Properties**

**Moisture Content**

Prior to conducting the cold and steam bending tests, the moisture content of the boards was determined using the oven-dry method in accordance with European standard EN 13183-1 (2002). Eighty specimens with dimensions of 20 mm x 20 mm x 30 mm were weighed and placed in a laboratory oven at a temperature of 103°C. The samples were dried until the difference in mass between two successive weightings separated by an interval of two hours was 0.01 g or less as has been done in research by Mitchual et al. (2019). The moisture content (MC) of each specimen was calculated using the following equation: The moisture content of the specimens was then computed as follows:

Moisture content percentage (%) = M1 – Mo × 100

Mo

where M1 and Mo are the masses (g) of the specimens before oven drying and after oven drying, respectively.

**Basic Density**

For determining density, a total of 80 samples of sapwood and heartwood were used. Each specimen, measuring 50 mm × 50 mm × 300 mm, was saturated by soaking in water for 24 hours or by vacuum impregnation to ensure complete swelling as has been done in research by Dadzie et al. (2018) The fully swollen volume of each specimen was determined using the hydrostatic (immersion) method in accordance with ISO 3131 (1975) standard. In this procedure, the mass of a container filled with water was first recorded. Subsequently, each wood specimen was completely submerged in the container, and the combined mass of the container, water, and submerged specimen was measured. According to Archimedes’ principle, the increase in weight (corresponding to the weight of the displaced water in grams) is numerically equivalent to the volume of water displaced in cubic millimeters (mm³), which represents the swollen volume of the specimen. Following volume determination, all specimens were oven-dried at a temperature of 103 ± 2°C to a constant weight, after which their oven-dry masses were measured.

The basic density (kg/m³) of each specimen was then calculated using the following expression:

Basic density = [oven-dry mass kg]

[Mass of water displaced by swollen specimen or volume m3]

For determining density, all samples were weighed using

an electronic balance with accuracy of 0.01g to note their

masses, whereas their dimensions were also determined

with an electronic vernier caliper with accuracy of 0.1mm

as speciﬁed in ISO 3131 at 12 ± 3% air-dry moisture con-

tent. Volumes and density (measured as

mass

volume

) were deter-

mined in accordance with ISO 3131 (1975). In all, a total of

432 samples of stem and branch woods were used for den-

sity estimations {i.e. (6 samples × 2 stem logs × 3 species

× 3 trees × 2 sites = 216) + (6 samples × 2 branch logs × 3

species × 3 trees × 2 sites = 216)}. Moisture contents were

measured with resistance type moisture meter (MO210

designed to measure MC of wood up to 44% as speciﬁed by

manufacturers) and which has been found to have accuracy

of ±2% upon validation with oven-dry method (Dadzie

and Amoah 2015; Dadzie etal. 2016). The use of moisture

meter, including resistance type, is one of the acceptable

means to measure MCs in wood properties studies as has

been done by some researchers, including Beaulieu etal.

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**2.2 Determination of Steam and Cold Bending Qualities**

Test samples for cold and steam bending tests were prepared from clear, straight-grained wood samples with dimensions of 15 mm × 15 mm × 500 mm comprising sapwood and heartwood portions (Figure 2) in accordance with the procedure described by Ayarkwa et al. (2011). In this study, two techniques, pegged form or jig and form tool (Figures 3 and 4), were used for both cold and steam bending tests. In the pegged form method, a 19 mm thick plywood board and wooden dowels were used to prepare the jigs as shown in Figure 3. Holes were drilled along a curvature of 660 mm drawn on the board, and dowels of 12 mm diameter were glued and inserted into the holes. The form tool was made from a 19 mm thick plywood board where curvatures of 660 mm were drawn on the board and cut using a jigsaw to form concave and convex shapes (form tool mould) as shown in Figure 2. Each tool was loaded with one specimen and clamped tightly using sash clamps (Figure 4).

For each species, the number of failed samples and the type of failure in each sample were recorded. The bending time for each sample was measured using a stopwatch. The percentage of unbroken samples was calculated for each species and the most predominant failure type for each species was also recorded. Mahogany (Khaya ivorensis), Danta, and Cedrela were used as controls since they are widely used by furniture manufacturers and their bending qualities are already well documented by Ayarkwa et al. (2011). The species were then classified into three proposed quality classes. In Class I, described as superior-quality species, more than 85 percent of the samples were unbroken. In Class II, representing good-quality species, 50 to 85 percent of the samples were unbroken. In Class III, classified as poor-quality species, fewer than 50 percent of the samples were unbroken. The average bending time for each species was also calculated to determine the relative ease of bending.



**Figure 2 Test** **samples for bending quality tests**.



**Figure 3 Form tool for the bending tests**

**Cold Bending Quality**

A total of 160 specimens comprising both sapwood and heartwood of each species were subjected to cold bending tests following the procedure described by Ayarkwa et al. (2011). The samples were soaked in cold water for a period of 4 hours, after which they were carefully bent by hand using the pegged form and gradually clamped with sash clamps in the form tool designed with a curvature radius of 660 mm (Figures 3 and 4). After bending, the specimens were left to cure for seven days while held in the respective bending apparatus. Upon completion of the curing period, the samples were assessed and classified into the proposed quality classes as previously described.



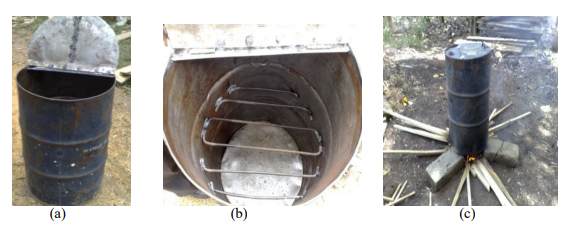
**Figure 4 Pegged form for the cold and steam bending tests**

**Figure 5 Form tool technique for cold and steam bending tests**

**Steam Bending Quality**

A steel barrel was improvised and adapted for use as a steam chamber. The barrel was cut open at the top to create a lid, with the removed cover welded back to the barrel using hinges as shown in Figure 6a. Mild steel rods were welded across the inner circumference of the barrel at a height of 440 mm from the bottom to serve as a platform for holding the wood samples, as illustrated in Figure 6b. The complete steam chamber setup is shown in Figure 6c. Water was filled into the chamber to a designated minimum level of 280 mm and heated to a temperature of 100°C. The test specimens were initially soaked in water for one hour, after which they were placed onto the platform within the preheated steam chamber in batches and subjected to steaming for 30 minutes.

Upon removal from the steam chamber using an improvised wood clipper, the hot steamed samples were immediately clamped with sash clamps in the form tool and hand bent in the pegged form to a curvature radius of 660 mm while still hot and then left to set in the same manner as the cold bending process. The bending time for each specimen was measured using a stopwatch. Following bending, the percentage of unbroken samples was determined for each species, and the predominant type of failure observed for each species was also recorded.



**Figure 6 Improvised steam chamber**

**Source:** Ayarkwa et al. (2011).

**2.3 Data Analysis**

The data collected were subjected to statistical evaluation using mixed analysis of variance (mixed ANOVA) to determine whether there were significant differences in the physical properties between the sapwood and heartwood of the species investigated.

**3. RESULTS AND DISCUSSION**

**3.1 Moisture Content**

Descriptive statistics presented in Table 1 indicate that the sapwood of Neem exhibited the highest mean moisture content of 88.1500, whereas the heartwood of Cassia recorded the lowest mean value of 47.5000. The results from the mixed analysis of variance (F = 126.625, P < 0.05), as shown in Table 2, revealed that there was a statistically significant difference in moisture content between at least two of the examined wood types, namely sapwood and heartwood of the timber species Neem and Cassia. Further analysis using pairwise comparisons (Table 3) confirmed that significant differences existed between each pair of groups assessed. For example, the mean difference of 15.2% observed between the sapwood (88.2%) and heartwood (72.9%) of Neem was statistically significant, indicating that the sapwood of Neem possesses a higher moisture content compared to its heartwood.

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| Table 1. Descriptive statistics of moisture content (MC) of the timber species   |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Wood species | Wood type | N | Min % | Max % | Mean % | Std.Dv |  |  | | Neem | SW  HW | 20  20 | 73.00  57.00 | 99.00  88.00 | 88.15  72.95 | 7.25  9.04 |  |  | | Cassia | SW  HW | 20  20 | 49.00  38.00 | 71.00  57.00 | 60.40  47.50 | 6.41  5.91 |  |  | | Valid N  (listwise) |  | 20 |  |  |  |  |  |  | | | | | |
| **Table 2. The mixed design ANOVA of the moisture content of the timber species** | | | | | | | | |
| Source | | Type III Sum of Squares | df | Mean Square | | F | Sig. | Partial Eta  Squared |
| Moisture content | Sphericity Assumed | 18125.700 | 3 | 6041.900 | | 126.625 | 126.625 | .876 |
| Greenhouse-Geisser | 18125.700 | 2.535 | 7149.246 | | 126.625 | .000 | .876 |
| Huynh-Feldt | 18125.700 | 3.000 | 6041.900 | | 126.625 | .000 | .876 |
| Lower-bound | 18125.700 | 1.000 | 18125.700 | | 126.625 | .000 | .876 |
| Moisture content \*  TIMBER | Sphericity Assumed | 420.700 | 3 | 140.233 | | 2.939 | .041 | .140 |
| Greenhouse-Geisser | 420.700 | 2.535 | 165.935 | | 2.939 | .051 | .140 |
| Huynh-Feldt | 420.700 | 3.000 | 140.233 | | 2.939 | .041 | .140 |
| Lower-bound | 420.700 | 1.000 | 420.700 | | 2.939 | .104 | .140 |
| Error (Moisture content) | Sphericity Assumed | 2576.600 | 54 | 47.715 | |  |  |  |
| Greenhouse-Geisser | 2576.600 | 45.636 | 56.460 | |  |  |  |
| Huynh-Feldt | 2576.600 | 54.000 | 47.715 | |  |  |  |
| Lower-bound | 2576.600 | 18.000 | 143.144 | |  |  |  |

**Table 3. Pairwise Comparison of moisture content of the Timber Species**

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| |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  |  |  | Confidence Interval | | | Timber Species (I) | Wood type | Mean (J) | Mean  Dif. (I-J) | Standard Error | Sig | Lower | Upper | | Neem Sapwood  (Mean 88.1500) | Neem HW | 72.9500 | 15.200\* | 1.870 | .000 | 11.271 | 19.129 | | Cassia SW | 60.4000 | 27.750\* | 2.277 | .000 | 22.966 | 32.534 | | Cassia HW | 47.5000 | 40.650\* | 2.110 | .000 | 36.217 | 45.083 | | Neem Heartwood  (Mean 72.9500) | Neem SW | 88.1500 | -15.200\* | 1.870 | .000 | -19.129 | -11.271 | | Cassia SW | 60.4000 | 12.550\* | 2.192 | .000 | 7.944 | 17.156 | | Cassia HW | 47.5000 | 25.450\* | 2.615 | .000 | 19.957 | 30.943 | | Cassia Sapwood  (Mean 60.4000) | Neem SW | 88.1500 | -27.750\* | 2.277 | .000 | -32.534 | -22.966 | | Neem HW | 72.9500 | -12.550\* | 2.192 | .000 | -17.156 | -7.944 | | Cassia HW | 47.5000 | 12.900\* | 1.963 | .000 | 8.776 | 17.024 | | Cassia Heartwood  (Mean 47.5000) | Neem SW | 88.1500 | -40.650\* | 2.110 | .000 | -45.083 | -36.217 | | Neem HW | 72.9500 | -25.450\* | 2.615 | .000 | -30.943 | -19.957 | | Cassia SW | 60.4000 | -12.900\* | 1.963 | .000 | -17.024 | -8.776 | |

\*. The mean difference is significant at the .05 level.

**3.2 Density**

From the descriptive statistics presented in Table 4, sapwood of Neem recorded the least mean density of 674,61N/mm3 with heartwood of cassia the highest (898.000). Results from the mixed ANOVA analysis (F=44.073, P<.05) as presented in Table 5, suggest that there is a statistically significant difference in density between at least two of the properties (sapwood and heartwood) of the timber species (neem and cassia). The pairwise comparison was conducted to test which pair of the groups had their differences significant, and the results indicate a significant difference between each pair, except for the difference between the heartwood of Neem and the sapwood of Cassia (see Table 6). For instance, the mean difference of -82.129 between the means of sapwood of neem (674.61) and heartwood of Neem (756.7400 N/mm3) is statistically significant, suggesting that sapwood of neem less in density than its heartwood.

The density analysis of the two timber species, Neem and Cassia, revealed notable variations between their sapwood and heartwood portions, as presented in Table 4. The heartwood of Cassia recorded the highest mean density of 898.00 kg/m³, whereas the sapwood of Neem had the lowest mean density of 674.61 kg/m³. Generally, Cassia exhibited higher density values than Neem for both sapwood and heartwood, which suggests that Cassia possesses superior structural integrity and strength compared to Neem. The differences in density between sapwood and heartwood for both species were substantial, reflecting natural variability in wood formation processes, such as cell wall thickening and deposition of extractives in heartwood (Pournou and Pournou 2020; Esteban et al., 2024). The results of the mixed ANOVA (Table 5) confirmed that the differences in density among the four groups (Neem sapwood, Neem heartwood, Cassia sapwood, Cassia heartwood) were statistically significant (F=44.073, p<0.05). This indicates that the density variations observed are unlikely to have occurred by chance and reflect true differences between the wood types and species. The effect size (Partial Eta Squared = 0.846) suggests that the factor "timber property" (sapwood vs. heartwood) accounted for a large proportion of the variance in density. However, the interaction effect between density and timber species was not statistically significant (p=0.644), implying that the pattern of density differences between sapwood and heartwood was consistent across both species.

Pairwise comparisons (Table 6) further revealed that most differences in mean density between the wood types were statistically significant at the 0.05 level. Notably, the mean difference between Neem sapwood and heartwood was 82.129 kg/m³ (p 0.005), indicating that Neem heartwood is significantly denser than its sapwood. Similarly, significant differences were observed between Neem sapwood and Cassia sapwood (mean difference 66.984 kg/m³, p 0.013) and between Neem sapwood and Cassia heartwood (mean difference -223.389 kg/m³, p<0.001). Cassia heartwood was significantly denser than all other wood types, reinforcing its suitability for applications requiring high density and strength, such as steam bending or load-bearing components in joinery and furniture production.

Interestingly, the density difference between Neem heartwood and Cassia sapwood was not statistically significant (p 0.349), suggesting a level of similarity in these specific portions despite being from different species. This overlap, according to Balalau et al. (2015), may have implications for applications where moderate density is sufficient, and cost or availability considerations make either wood a viable option. Overall, the density analysis shows that Cassia, particularly its heartwood, offers superior material characteristics compared to Neem. These differences in density could influence mechanical properties such as bending strength and stiffness, as denser woods generally exhibit better performance in these aspects. The results also indicate that wood part selection (sapwood vs. heartwood) is critical when choosing materials for specific engineering and bending characteristics purposes.

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| **Table 4.** **Descriptive statistics of the density of the timber species** | | | | | |
| |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | | Timber  species | Wood type | N | Mim  Kg/m3 | Max  Kg/m3 | Std. Dev. | | Neem | SW  HW | 20  20 | 630.00  680.00 | 674.51  756.74 | 30.77  59.76 | | Cassia | SW  HW | 20  20 | 664.17  759.00 | 741.59  898.00 | 50.13  61.92 | | Valid N (listwise) |  | 20 |  |  |  | | | | | | | | | |
| **Table 5 The Mixed design ANOVA on the density difference of the timber species** | | | | | | | | |
| **Source** | | Type III Sum of Squares | df | Mean Square | F | | Sig. | Partial Eta  Squared |
| Density | Sphericity Assumed | 264452.392 | 3 | 88150.797 | 44.073 | | .000 | .846 |
| Greenhouse-Geisser | 264452.392 | 2.380 | 111118.943 | 44.073 | | .000 | .846 |
| Huynh-Feldt | 264452.392 | 3.000 | 88150.797 | 44.073 | | .000 | .846 |
| Lower-bound | 264452.392 | 1.000 | 264452.392 | 44.073 | | .000 | .846 |
| Density TIMBER | Sphericity Assumed | 3386.566 | 3 | 1128.855 | .564 | | .644 | .066 |
| Greenhouse-Geisser | 3386.566 | 2.380 | 1422.984 | .564 | | .607 | .066 |
| Huynh-Feldt | 3386.566 | 3.000 | 1128.855 | .564 | | .644 | .066 |
| Lower-bound | 3386.566 | 1.000 | 3386.566 | .564 | | .474 | .066 |
| Error(density) | Sphericity Assumed | 48002.998 | 24 | 2000.125 |  | |  |  |
| Greenhouse-Geisser | 48002.998 | 19.039 | 2521.268 |  | |  |  |
| Huynh-Feldt | 48002.998 | 24.000 | 2000.125 |  | |  |  |
| Lower-bound | 48002.998 | 8.000 | 6000.375 |  | |  |  |

**Table 6**. **Pairwise comparison of density of the timber species**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  |  |  | Confidence Interval | | | Timber Species (I) | Timber section | Mean (J) | Mean  Difference(I-J) | Standard Error | Sig | Lower | Upper | | Neem Sapwood  (Mean 674.61  ) | Neem Heartwood | 756.740 | -82.129\* | 21.700 | .005 | -32.089 | -32.089 | | Cassia Sapwood | 741.595 | -66.984\* | 21.121 | .013 | -18.278 | -18.278 | | Cassia Heartwood | 898.000 | -223.389\* | 22.577 | .000 | -171.326 | -171.326 | | Neem Heartwood  (Mean 756.7400) | Neem Sapwood | 674.61 | 82.129\* | 21.700 | .005 | 132.169 | 132.169 | | Cassia Sapwood | 741.595 | 15.145 | 15.210 | .349 | 50.220 | 50.220 | | Cassia Heartwood | 898.000 | -141.260\* | 14.802 | .000 | -107.126 | -107.126 | | Cassia Sapwood  (Mean 741.5950) | Neem Sapwood | 674.61 | 66.984\* | 21.121 | .013 | 115.690 | 115.690 | | Neem Heartwood | 756.740 | -15.145 | 15.210 | .349 | 19.930 | 19.930 | | Cassia Heartwood | 898.000 | -156.405\* | 22.868 | .000 | -103.671 | -103.671 | | Cassia Heartwood  (Mean 898.0000) | Sapwood Neem | 674.61 | 223.389\* | 22.577 | .000 | 275.452 | 275.452 | | Heartwood Neem | 756.740 | 141.260\* | 14.802 | .000 | 175.394 | 175.394 | | Sapwood Cassia | 741.595 | 156.405\* | 22.868 | .000 | 209.139 | -32.089 | |

\* The mean difference is significant at the .05 level.

**3.3 Cold Bending Quality**

The results of the cold bending tests revealed that 40 percent of the Cassia heartwood samples remained unbroken when subjected to the pegged form technique, as presented in Table 7, while 60 percent of the samples remained unbroken when the form tool technique was employed, as shown in Table 8. In contrast, 25 percent of the Neem heartwood samples remained unbroken using the pegged form technique, whereas 35 percent of the samples were unbroken when bent using the form tool technique.

**Table 7** **Sapwood and heartwood versus cold bending quality pegged form (jig) technique**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Wood  type | N | No of broken  Specimens | % Unbroken  Specimens | Quality classes | Common failure  Type |
| Neem | SW | 20 | 16 | 20 | III | Cross grained tension |
|  | HW | 20 | 15 | 25 | III | Cross grained tension |
| Cassia | SW | 20 | 13 | 35 | III | Cross grained tension |
|  | HW | 20 | 12 | 40 | III | Cross grained tension |

Note: N = Number of specimens, SW = Sapwood, HW = Heartwood

**Table 8** **Sapwood and heartwood versus cold bending quality tool tech**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Wood type | N | No of broken  Specimens | %Unbroken  specimens | Quality classes | Common  failure Type |
| Neem | SW | 20 | 14 | 30 | III | Cross grained tension |
|  | HW | 20 | 13 | 35 | III | Cross grained tension |
| Cassia | SW | 20 | 10 | 50 | II | Cross grained tension |
|  | HW | 20 | 8 | 60 | II | Cross grained tension |

Note: N = Number of specimens, SW = Sapwood, HW = Heartwood

In terms of cold bending performance, the sapwood of both species exhibited lower bending quality compared to their respective heartwood. Specifically, the sapwood of Neem showed a 30 percent unbroken in bending quality, while the sapwood of Cassia demonstrated 50 percent unbroken specimens, as indicated in Table 8. This performance may be attributed to the lower overall strength and higher moisture content of sapwood, which increases its susceptibility to cracking during the bending process. These characteristics suggest that heartwood is more suitable for manufacturing furniture and joinery components that require curved forms. Generally, sapwood tends to display inferior cold bending quality compared to heartwood, although in some wood species the difference between sapwood and heartwood bending performance is less pronounced (Bektaş et al., 2020). To enhance the flexibility of sapwood and reduce the likelihood of breakage, it is recommended that sapwood specimens of both species be soaked for longer durations prior to bending. This according to Bektaş et al. (2020), enhances the sapwood flexibility and reduces breakage because moisture makes the wood more pliable and easier to shape. The most common mode of failure observed during cold bending of Neem was cross-grain tension, as illustrated in Figure 6, whereas the typical failure pattern for Cassia is shown in Figure 7.



**Figure 7 Cross-grained tensile failure of Neem**



**Figure 8** **Cross-grained tensile failure in Cassia**

The results presented in Table 9 suggest that there is a direct relationship between the bending technique employed and the time required to bend each wood sample using the cold bending method, which reflects the relative ease of bending. For instance, the average bending time recorded for Neem using the form tool technique was 0.58 seconds, whereas the pegged form technique required approximately 1.20 seconds, nearly one and a half times longer than the form tool technique. The superior performance of the form tool technique may be attributed to the presence of the concave mould, which provides support to the wood fibres under tension during bending. As the wood bends, the fibres on the outer (convex) side are subjected to stretching, and the form tool effectively restrains these fibres, thereby facilitating easier and more efficient bending.

**Table 9 Cold bending methods and techniques versus average number of cycles (seconds)**

|  |  |  |
| --- | --- | --- |
| Species | Bending technique | Average bending time |
| Neem | Pegged form | 1.20 |
| Form tool | 0.58 |
| Cassia | Pegged form | 1.10 |
| Form tool | 0.46 |

The results presented in Table 8 indicate a strong correlation between wood density and cold bending performance. For instance, Cassia, with a density of 898 kg/m³, yielded 60 percent unbroken samples, whereas Neem, with a lower density of 756 kg/m³, produced only 35 percent unbroken samples. These findings are consistent with those reported by Ayarkwa et al. (2011), who stated that wood density significantly influences the bending performance of timber, with high-density woods generally exhibiting superior bending qualities compared to low-density species (Pham et al., 2021). However, this result contrasts with the assertion made by Riesco et al. (2012), who reported that there is no strong correlation between wood density and bending quality.

**3.4 Steam Bending Quality**

The results presented in Tables 10 and 11 for steam bending qualities followed trends like those observed in the cold bending tests. Cassia exhibited superior performance, with 85 percent of its heartwood samples remaining unbroken when bent using the form tool technique, compared to 50 percent unbroken samples when the pegged form technique was employed. For Neem, the percentage of unbroken sapwood samples was 40 percent with the pegged form technique and 50 percent with the form tool technique. As shown in Table 12, a direct relationship was observed between the bending technique and the time required to bend the samples, reflecting the relative ease of bending using the steam method. For example, Cassia required an average of 0.38 seconds per sample when bent using the form tool, whereas the pegged form technique required 1.05 seconds, approximately two and a half times longer than the form tool technique. However, the ease of bending after steaming can also be influenced by the specific wood species used, as noted by Ratnasingam et al. (2022).

**Table 10 Sapwood and heartwood versus steam bending quality pegged form technique**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Wood type | N | No of broken  Specimens | %Unbroken  Specimens | Quality classes | Common  failure type |
| Neem | SW | 20 | 13 | 40 | III | Cross grained tension |
|  | HW | 20 | 14 | 35 | III | Cross grained tension |
| Cassia | SW | 20 | 10 | 50 | II | Cross grained tension |
|  | HW | 20 | 8 | 60 | II | Cross grained tension |

Note: N = Number of specimens, SW = Sapwood, HW = Heartwood

**Table 11 Sapwood and heartwood versus steam bending qualities from the tool technique**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Wood type | N | No of broken  Specimens | % Unbroken  Specimens | Quality classes | Common failure type |
| Neem | SW | 20 | 10 | 50 | II | Cross grained tension |
|  | HW | 20 | 11 | 45 | III | Cross grained tension |
| Cassia | SW | 20 | 6 | 70 | II | Cross grained tension |
|  | HW | 20 | 3 | 85 | I | Cross grained tension |

Note: N = Number of specimens, WS = Sapwood, HS = Heartwood

**Table 12 Steam bending method and technique versus average time (seconds)**

|  |  |  |
| --- | --- | --- |
| Species | Bending technique | Average bending time |
| Neem` | Pegged form | 1.10 |
| Form tool | 0.43 |
| Cassia | Pegged form | 1.06 |
| Form tool | 0.38 |

Interestingly, the sapwood of Neem demonstrated superior bending quality compared to its heartwood during the steam bending tests. This observation may be attributed to the inherent flexibility of sapwood’s cellular structure, which tends to be more adaptable to deformation under steam conditions than that of heartwood (Dzurenda et al. 2023). Additionally, sapwood generally exhibits fewer defects such as cracks, which are known to compromise the structural integrity of wood during bending operations (Richter 2014). These factors collectively may have contributed to the superior steam bending performance of Neem sapwood, suggesting its suitability for furniture and joinery applications where bending and shaping are required. Figure 9(a) illustrates samples of Cassia after bending, while Figure 9(b) shows the corresponding samples from the Neem wood species.



1. (b)

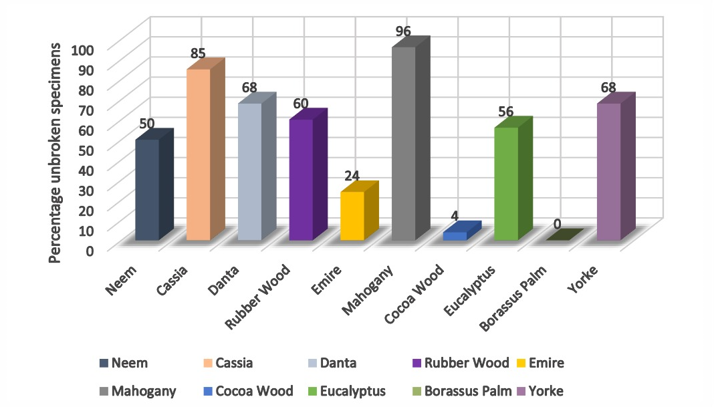
**Figure 9** **Cassia and Neemwoods after cold and steam bending**

Cassia clearly demonstrated superior performance in terms of steam bending, as evidenced by the high percentage of unbroken samples, and can therefore be classified within the proposed Class I category, indicating excellent steam bending qualities. In contrast, Neem was placed within the proposed Class II category, reflecting good steam bending qualities. The outstanding steam bending performance of Cassia may be attributed to its straight wood grain, minimal presence of knots, and fine texture, all of which contribute to its enhanced flexibility during bending. The bending technique employed was also found to influence bending performance, with the form tool technique consistently yielding better results for both species and bending methods. The superior performance associated with the form tool technique may be due to its concave mold, which provides support to the wood fibres under tension; during bending, the fibres on the outer (convex) side of the wood are stretched, and the concavity of the form tool effectively restrains these fibres, thereby reducing the likelihood of failure.

The results further highlight the relationship between the bending method and technique, as well as between the technique used and the time required to bend each sample, reflecting the relative ease of bending. The data presented in Table 11 suggest that, when comparing very high-density species with medium-density species, there is a direct relationship between wood density and steam bending quality. For example, 85 percent of Cassia samples, with a density of 898 kg/m³, remained unbroken, while only 50 percent of Neem samples, with a density of 674.61 kg/m³, remained unbroken. This observation is consistent with the findings of Ayarkwa et al. (2011), who reported that wood density significantly influences bending performance, with high-density timbers generally exhibiting superior bending qualities compared to lower-density species. However, this result contradicts the assertion made by Ratnasingam et al. (2022), who argued that there is no strong correlation between wood density and bending quality.

Although wood is naturally straight and rigid, all wood species are capable of being bent to some extent (Smith 2004). Figure 9 shows that Cassia exhibited superior steam bending qualities compared to all the other species tested, except for Mahogany. This superior performance may be attributed to the effectiveness of the form tool technique used during the bending process. The steam bending characteristics of Cassia and Neem are comparable to those reported by Ayarkwa et al. (2011) for *Khaya ivorensis* (Mahogany) at 96 percent, *Eucalyptus tereticornis* (Eucalyptus) at 56 percent, *Nesogordonia papaverifera* (Danta) at 68 percent, and Cedrela odorata (Cedrela) as presented in Figure 10. These species are widely recognized for their suitability in furniture production, joinery works, and other wood-based applications.

The findings of this study suggest that Neem and Cassia possess favorable steam bending properties, making them suitable for use in furniture manufacturing. In Ghana, most furniture manufacturers and joiners typically saw wood to produce curved components, which are often prone to breakage, thereby encouraging the unnecessary felling of more trees from forest reserves and off-reserve areas. By contrast, cold or steam bending methods are employed to create stronger and more durable components. However, when solid wood is used to produce curved components for furniture and joinery applications, it is commonly subjected to steaming or other treatments such as exposure to ammonia or urea, particularly when gluing is not performed simultaneously, as noted by Tobisch et al. (2023). These treatments considerably improve the properties of various wood species, enhancing their suitability for bending applications as described by Wu et al. (2022). The steam bending quality of both the sapwood and heartwood from Neem and Cassia are comparable to Emire (*Terminalia ivorensis*), Danta (*Nesogordonia papaverifera*), Yorke (*Broussonatia papyrifera*), Cedrela (*Cedrela odorata*) and Mahogany (*Khaya spp)* Eucalyptus (*Eucalyptus tereticornis*), Rubberwood (*Hevea* *brasiliensis*), Cocoa-wood (*Cocos nucifera*) and Borassus palm (*Borassus* *aethiopum*) (Figure 10) reported by Ayarkwa et al. (2011).



**Figure 10. Comparison of the steam bending performance of Neem and Cassia with that of nine other wood species.**

**4. CONCLUSION**

The study comprehensively evaluated the physical properties and bending qualities of sapwood and heartwood from Neem (Azadirachta indica) and Cassia (Cassia siamea) timber species, focusing on their potential applications in furniture and joinery industries. Significant variations were observed in moisture content, basic density, and cold and steam bending performances between the wood species and wood types.

Moisture content analysis revealed a statistically significant difference among the timber species and wood portions, with Neem sapwood exhibiting the highest mean moisture content (88.15%), and Cassia heartwood recording the lowest (47.50%). Higher moisture content in sapwood, particularly in Neem, contributed to reduced stiffness and increased susceptibility to failure under cold bending stresses. Density measurements indicated that Cassia heartwood exhibited the highest mean basic density (898 kg/m³), while Neem sapwood showed the lowest (674.61 kg/m³). The results of the mixed ANOVA analysis (F = 44.073, p < 0.05) confirmed that density differed significantly among at least two timber properties. Pairwise comparisons further indicated that most density differences between wood types and species were statistically significant at the 0.05 level, except for Neem heartwood and Cassia sapwood. These findings highlight the strong influence of wood species and tissue type on basic density, which directly correlates with the bending behavior of the materials.

The bending tests demonstrated clear distinctions in the performance of the wood species under

both cold and steam bending methods. In cold bending, Cassia heartwood achieved the highest

proportion of unbroken samples, while Neem sapwood consistently exhibited lower bending quality. These differences are attributed to the superior density and structural integrity of Cassia heartwood, as well as its lower moisture content compared to Neem sapwood. The cold bending results also revealed that sapwood portions of both species generally performed poorly, likely due to their higher moisture content and lower density, which reduces their resistance to mechanical deformation. Steam bending results similarly favored Cassia heartwood, which was classified into the proposed Class I category with superior bending qualities, achieving 85% unbroken samples when bent using the form tool technique. In contrast, Neem was classified into Class II with good, but comparatively lower, steam bending qualities. Interestingly, Neem sapwood outperformed its heartwood in steam bending, likely due to its more flexible and less lignified cellular structure, as suggested by its lower density and higher moisture content. Across both bending methods, the form tool technique demonstrated superior performance relative to the pegged form technique. The form tool reduced bending time and enhanced sample integrity, likely because its concave surface provided better support to tensile fibres, thus mitigating the development of stress concentrations and mechanical failures. This was evident in both cold and steam bending trials, where form tool bending consistently resulted in higher percentages of unbroken samples and reduced bending times compared to the pegged form. A direct relationship between wood density and bending quality was observed, as evidenced by Cassia heartwood's higher density and superior bending performance in both cold and steam methods.

In conclusion, Cassia heartwood emerges as the most suitable material for both cold and steam

bending applications, offering superior mechanical performance and reliability. Neem sapwood,

while less suited for cold bending, it exhibits good potential for steam bending due to its favorable anatomical properties post-steaming. The study further recommends the form tool technique over the pegged form for industrial bending operations, owing to its greater efficiency and material conservation benefits. These findings suggest that Cassia and Neem can serve as viable alternatives to traditionally preferred species such as Khaya ivorensis, Danta, and Cedrela, thereby contributing to sustainable wood utilization and forest conservation efforts in Ghana.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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