**Comparative Analysis of the Moisture Content and Density on Bending Strength of *Azadirachta Indica* and *Siamea* *Senna* in Steam Cold Method.**

**ABSTRACT**

This study investigated the steam and cold bending strength of sapwood and heartwood from two underutilised timber species, *Azadirachta indica* (Neem) and *Senna siamea* (Cassia), to evaluate their viability as alternatives to conventional species such as *Khaya ivorensis* (African Mahogany) in the furniture and joinery industries. The physical characteristics, including moisture content and basic density, were evaluated according to the EN 13183-1 (2002) and ISO 3131 (1975) standards. The bending characteristics were assessed using the form tool method at both cold and steam temperatures. Descriptive statistics revealed significant variability among the species and wood segments. Neem sapwood revealed the highest moisture content at 88.15%, whilst Cassia heartwood displayed the lowest at 47.50%. The density analysis indicated that Cassia heartwood displayed the highest basic density at 898 kg/m³, whereas Neem sapwood registered the lowest at 674.61 kg/m³. Mixed ANOVA demonstrated statistically significant variations in density and moisture content (F=44.073, p<0.05), with pairwise comparisons revealing significant differences among most group pairs, except for the comparison between Neem heartwood and Cassia sapwood. Bending studies demonstrated that Cassia heartwood displayed exceptional performance in both cold and steam bending, achieving up to 85% undamaged samples during steam bending, therefore categorising it in Quality Class I. Neem sapwood exhibited superior performance relative to heartwood in steam bending, classifying it in Quality Class II. A direct correlation between wood density and bending strength was noted, as demonstrated by the elevated density and enhanced bending performance of Cassia heartwood in both cold and steam treatments. The study revealed a favourable correlation between wood density and bending quality. This study advocates for the utilisation of Cassia and Neem as sustainable alternatives to traditionally harvested species, contributing to forest conservation efforts in Ghana.

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

**1. INTRODUCTION**

Wood bending is a time-honoured method that continues to be vital in contemporary joinery and furniture production, especially in the fabrication of window and door frames, glue-laminated beams, door construction, and different furniture elements. Curved components, such as chair legs and rails, can be fabricated by either sawing or bending techniques. Wood bending is regarded as the most economical, efficient, and resource-conserving way for fabricating strong and long-lasting components among the several techniques for shaping curved parts (Ayarkwa et al., 2011). Despite wood's inherent straightness and rigidity, all timber species have a specific ability to be curved to a particular radius (Wiedenhoeft, 2010). The bending process entails concurrent stretching of fibres on the convex side and compression on the concave side of the curve (Syerko et al., 2012).

Wood bending can be executed either cold or through heat and moisture treatments, such as steaming or chemical plasticization with ammonia or urea, when adhesive application is not simultaneous. These treatments markedly enhance the flexibility of wood (Hackenberg et al., 2021). Wood plasticization is generally accomplished by means of atmospheric-pressure steaming, immersion in hot or boiling water, or microwave heating (Luan et al., 2022). These activities weaken the cell walls, permitting adequate compressive deformation to achieve the necessary curvature. Wood in a hot and humid state exhibits enhanced flexibility relative to cold or dry wood (Börcsök and Pásztory, 2021). Steaming softens the inherent wood polymers, making them thermoplastic-like and agreeable to reshape under applied tension and heat. Lee et al. (2018). After being moulded and dried in the correct form, the wood regains its rigidity and strength, thereby permanently preserving the curved shape.

Key elements affecting steam and cold bending procedures comprise specimen dimensions, moisture content, basic density, steaming time, bend radius, and the equipment utilised (Mikšik, et al., 2023). For instance, samples with a thickness of 25 mm necessitate 30–40 minutes of steaming, while thinner samples, around 15 mm, require a reduced duration (Ayarkwa et al., 2011). The ideal moisture concentration for efficient steaming is between 18% and 25%; lower moisture levels require prolonged steaming times to attain sufficient plasticization (Ratnasingam et al., 2022). Plasticised wood can experience compressive deformation of 25–30% along the grain, while tensile extension is limited to 1–2%, highlighting that bending-induced deformation primarily transpires through compression rather than stretching to avert structural failure (Wang, 2020).

The selection of wood species for manufacturing components with mild to moderate curvature is often based on availability and appropriateness. For applications necessitating significant curvature, the wood's inherent bending properties become the principal selection factor (Kuljich et al., 2015). The bending properties differ clearly among species and even among individuals of the same species (Bachmann et al., 2012). Thin veneers can be flexibly manipulated without prior conditioning, while the bending of thicker solid wood requires softening via thermal or chemical processes.

Moisture content significantly influences the mechanical characteristics of wood. The moisture distribution within a tree is dependent upon species, growth conditions, and environmental factors (Tomczak et al., 2021). Logs gathered under comparable conditions may have variations in moisture distribution, even among individuals of the same species (Nilsson et al., 2013). Wood density is a crucial element that affects bending performance, as higher density often correlates with enhanced bending behaviour (Balboni et al., 2021). Density discrepancies are present between sapwood and heartwood and vertical axes of the tree and among growth rings. Heartwood exhibits greater density owing to thicker cell walls and diminished lumen size relative to sapwood (Esteban et al., 2024). In certain coniferous species, heartwood density may surpass that of sapwood by more than 100%, affecting the tree's total density (Sillett et al., 2015; Cherelli et al., 2018). A direct correlation frequently exists between the densities of sapwood and heartwood inside individual trees (Bahmani et al., 2020). Optimal steam bending necessitates defect-free, straight-grained wood to avert failures such as rupture, delamination, or surface checking.

Additional factors influencing bending performance encompass age, growth ring width, cellular architecture, resin concentration, environmental circumstances, and genetic diversity among species (Schneeweiß and Felber, 2013). In contrast to sawn components, bent elements conserve wood, minimise processing waste, and improve strength by maintaining continuous grain orientation, hence supporting sustainable forest management techniques (Ge et al., 2023). Excessive bending can result in mechanical failures identified as cross-grain strain, splintering, or brashness (Ayarkwa, 2000).

In Ghana, few studies have investigated the steam and cold bending properties of sapwood and heartwood. This study aims to assess the bending properties of Neem and Cassia, underutilised timber species from Ghana, to guide their potential use in the furniture and joinery sectors and to aid the Ghana Forestry Commission in promoting sustainable forest resource management to mitigate deforestation and the over-exploitation of primary timber species.

**2. MATERIALS AND METHODS**

Three mature trees, specifically Cassia siamea (Cassia) and Azadirachta indica (Neem), were chosen according to their commercial harvesting diameters, which ranged from 360 mm to 520 mm, measured at a height of 250 mm above ground level. Logs were meticulously delineated to clearly differentiate the heartwood and sapwood segments of each tree. The logs were subsequently treated using a horizontal band saw to yield timber dimensions of 50 mm 200 mm 2400 mm. A total of roughly 48 timber pieces were recovered from the six logs (three from each species). Test specimens were made from these for the evaluation of the various qualities outlined in this study. The specimen's moisture content prior to the cold and steam bending test was 18%, as reported in the research by Ayarkwa et al. (2011). A total of eighty specimens, including both sapwood and heartwood samples, were prepared and evaluated for each property at the Timber Testing Laboratory of the Centre for Scientific and Industrial Research – Forestry Research Institute of Ghana (CSIR-FORIG) in Fumesua, Kumasi, Ghana.

**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 demonstrated in the study by Mitchual et al. (2019). The moisture content (MC) of each item was determined using the subsequent equation: The moisture content of the sample was then calculated 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**

A total of 80 samples of sapwood and heartwood were utilised to ascertain density. Each specimen, measuring 50 mm 50 mm 300 mm, was saturated by immersion in water for 24 hours or through vacuum impregnation to guarantee full swelling, as demonstrated in the research conducted by Dadzie et al. 2018 The complete swelled volume of each specimen was ascertained via the hydrostatic (immersion) method in compliance with the ISO 3131 (1975) standard. The mass of a water-filled container was initially documented. Thereafter, each wood specimen was entirely immersed in the container, and the total mass of the container, water, and submerged specimen was recorded. Archimedes' principle states that the increase in weight, proportional to the weight of the displaced water in grammes, is numerically equal to the amount of water displaced in cubic millimetres (mm³), reflecting the expanded volume of the specimen. Subsequent to volume estimation, all specimens were subjected to oven drying at a temperature of 103 ± 2°C until a consistent weight was achieved, following which their oven-dry masses were recorded.

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.

(1987), Ayarkwa etal. (2000), and Amoah etal. (2012)

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(1987), Ayarkwa etal. (2000), and Amoah etal. (2012

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

Test specimens for cold and steam bending assessments were prepared from clear, straight-grained wood with dimensions of 15 mm × 15 mm × 500 mm, incorporating both sapwood and heartwood sections, as per the methodology outlined by Ayarkwa et al. (2011). This study utilised a form tool for both cold and steam bending testing. The form tool was constructed from a 19 mm thick plywood board, on which 660 mm curvatures were delineated and subsequently cut using a jigsaw to create concave and convex shapes. Each instrument was equipped with a single specimen and securely fastened using sash clamps (Figure 2).

The proportion of unbroken samples was determined for each species, and the most prevalent failure type for each species was documented. Mahogany (*Khaya ivorensis*) and Danta (*Nesogordonia papaverifera*) served as controls due to their prevalent use by furniture producers and joiners, with their bending properties thoroughly recorded by Ayarkwa et al. (2011). The species were subsequently categorised into three recommended quality classes. In Class I, categorised as superior-quality species, over 85 percent of the samples remained intact. In Class II, indicative of high-quality species, 50 to 85 percent of the samples were intact. In Class III, designated as low-quality species, less than 50 percent of the samples remained intact.



**Figure 1 Test** **samples for bending quality tests**.

**Cold Bending Quality**

A total of 160 specimens comprising both sapwood and heartwood of each species were subjected to cold bending tests. The samples were soaked in cold water for a period of 4 hours, after which they were carefully clamped with sash clamps in the form tool designed with a curvature radius of 660 mm (Figures 2). 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 2. Form tool technique for cold and steam bending tests**

**Steam Bending Quality**

A steel barrel was modified and repurposed as a steam chamber. The top of the barrel was severed to form a lid, with the detached cover reattached to the barrel using hinges. Mild steel rods were welded along the inside ring of the barrel at a height of 440 mm from the base to function as a platform for supporting the wood samples. Water was introduced into the chamber to a specified minimum level of 280 mm and heated to a temperature of 100°C. The test specimens were first immersed in water for one hour, then arranged on the platform within the warmed steam chamber in batches and exposed to steaming for 30 minutes. After extraction from the steam chamber with a makeshift wooden clipper, the heated steamed samples were promptly secured with sash clamps in the form tool to a curvature radius of 660 mm while still hot, and subsequently allowed to set in a manner analogous to the cold bending procedure. After bending, the proportion of intact samples was assessed for each species, and the primary failure mode identified for each species was documented.

**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**

The descriptive statistics in Table 1 reveal that Neem sapwood displayed the highest mean moisture content at 88.15, while Cassia heartwood recorded the lowest mean value at 47.50. The mixed analysis of variance results (F = 126.625, P < 0.05), presented in Table 2, indicated a statistically significant variation in moisture content among at least two of the assessed wood types, specifically sapwood and heartwood of the timber species Neem and Cassia. Subsequent analysis through paired comparisons (Table 3) validated the presence of significant differences among each assessed group pair. The mean difference of 15.3% between the sapwood (88.2%) and heartwood (72.9%) of Neem was statistically significant, demonstrating that the sapwood has a higher moisture content than the heartwood. The intrinsic differentiation between heartwood and sapwood in Neem and Cassia is essential for material selection.

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| **Table 1. Descriptive statistics of moisture content (MC) of the timber species**

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| --- | --- | --- | --- | --- | --- | --- |
| Wood species | Wood portion | N | Min % | Max % | Mean % | Std.Dev |
| Neem | SWHW | 2020 | 73.0057.00 | 99.0088.00 | 88.1572.95 | 7.259.04 |
| Cassia | SWHW | 2020 | 49.0038.00 | 71.0057.00 | 60.4047.50 | 6.415.91 |
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|  |  |
| --- | --- |
| Valid N(listwise) |  |

 |  | 20 |  |  |  |  |

Note: N = Number of specimens, SW = Sapwood, HW = Heartwood**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 portion | Mean (J) | MeanDif. (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 |

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

**3.2 Density**

According to the descriptive statistics in Table 4, the sapwood of Neem had the lowest mean density of 674.61 N/mm³, while the heartwood of Cassia demonstrated the highest density at 898.00 N/mm³. The mixed ANOVA analysis results (F=44.073, P<.05) indicated in Table 5 demonstrate a statistically significant difference in density between at least two qualities (sapwood and heartwood) of the timber species (neem and cassia). A pairwise analysis was performed to determine which group pairs exhibited significant differences, revealing significant differences across all pairs except for the comparison between the heartwood of Neem and the sapwood of Cassia (refer to Table 6). The mean difference of -82.129 between the sapwood (674.61 N/mm³) and heartwood (756.7400 N/mm³) of neem is statistically significant, indicating that neem sapwood has a lower density than its heartwood.

The density examination of the two timber species, Neem and Cassia, demonstrated significant differences between their sapwood and heartwood sections, as shown in Table 4. The heartwood of Cassia had the highest mean density of 898.00 kg/m³, while the sapwood of Neem demonstrated the lowest mean density of 674.61 kg/m³. Cassia consistently demonstrated greater density values than Neem in both sapwood and heartwood, indicating that Cassia has enhanced structural integrity and strength relative to Neem. The density disparities between sapwood and heartwood in both species were significant, indicating inherent heterogeneity in wood production processes, including cell wall thickening and the accumulation of extractives in heartwood (Pournou and Pournou 2020; Esteban et al., 2024). The mixed ANOVA results (Table 5) indicated that the density variations among the four groups (Neem sapwood, Neem heartwood, Cassia sapwood, Cassia heartwood) were statistically significant (F=44.073, p<0.05). This suggests that the observed density variations are unbelievable to have happened by accident and represent real differences across the wood kinds and species. The impact size (Partial Eta Squared = 0.846) indicates that the factor "timber property" (sapwood versus heartwood) explained a substantial percentage of the variance in density. The interaction effect between density and timber species was not statistically significant (p=0.644), indicating that the density differences between sapwood and heartwood were uniform across both species.

Pairwise comparisons (Table 6) indicated that most differences in mean density among the wood types were statistically significant at the 0.05 level. The average difference in density between Neem sapwood and heartwood was 82.129 kg/m³ (p 0.005), demonstrating that Neem heartwood is substantially denser than its sapwood. Notable disparities were identified between Neem sapwood and Cassia sapwood (mean difference 66.984 kg/m³, p 0.013) as well as between Neem sapwood and Cassia heartwood (mean difference -223.389 kg/m³, p<0.001). Cassia heartwood had a markedly higher density than all other wood varieties, underscoring its appropriateness for applications necessitating substantial density and strength, including steam bending and load-bearing elements in joinery and furniture manufacturing.

The density difference between Neem heartwood and Cassia sapwood was not statistically significant (p 0.349), indicating a resemblance in these specific sections despite originating from distinct species. According to Balalau et al. (2015), this overlap may have ramifications for applications where moderate density suffices, and cost or availability factors render either wood a viable option. The density result indicates that Cassia, especially its heartwood, possesses superior material properties in comparison to Neem. The variations in density may affect mechanical qualities like bending strength and stiffness, as denser woods typically demonstrate superior performance in these areas. The findings demonstrate that the selection of wood components (sapwood versus heartwood) is essential for optimising materials for certain engineering and bending strengths.

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| **Table 4. Descriptive statistics of the density of the timber species**

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| --- | --- | --- | --- | --- | --- | --- |
| Timber species | Wood portion | N | MimKg/m3 | MaxKg/m3 | MeanKg/m3 | Std. Dev. |
| Neem | SWHW | 2020 | 630.00680.00 | 720.00850.00 | 674.61756.74 | 30.7759.75 |
| Cassia | SWHW | 2020 | 664.17759.00 | 810.00981.00 | 741.59898.00 | 50.1361.92 |
| 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**

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

Regarding cold bending characteristics, the sapwood of both species demonstrated lesser bending quality relative to their respective heartwood. The sapwood of Neem had 30 percent unbroken specimens, but the sapwood of Cassia displayed 50 percent unbroken specimens, as shown in Table 7. This performance can be ascribed to the diminished overall strength and elevated moisture content of the sapwood, which heightens its vulnerability to cracking during the bending process. Wang et al. (2021) assert that wood moisture content substantially diminishes its strength qualities. Moreover, sapwood often displays fewer imperfections, such as fractures, which can undermine the mechanical integrity of wood during bending processes (Rosner et al., 2018). Cassia heartwood exhibited 60 percent intact specimens, whereas Neem heartwood displayed 35 percent intact specimens. These attributes indicate that heartwood is more appropriate to produce furniture and joinery elements necessitating curved shapes. Typically, sapwood exhibits lower cold bending strength relative to heartwood; however, in certain wood species, the disparity in bending performance between sapwood and heartwood is less significant (Bektaş et al., 2020). To improve the flexibility of sapwood and minimise the risk of fracture, it is advisable that the sapwood from both species be immersed for extended periods before bending. According to Bektaş et al. (2020), this promotes the flexibility of sapwood and diminishes breaking, as moisture renders the wood more malleable and amenable to shaping. The predominant failure mode identified during the cold bending of Neem was cross-grain tension, as depicted in Figure 3 (a), while the characteristic failure pattern for Cassia is represented in Figure 3 (b).

Table 7 demonstrates a strong link between wood density and cold bending ability. Cassia, possessing a density of 898 kg/m³, gave 60 percent intact samples, while Neem, with a lesser density of 756 kg/m³, produced merely 35 percent intact samples. The findings align with those of Ayarkwa et al. (2011), who indicated that wood density markedly affects the bending performance of timber, with high-density woods typically demonstrating enhanced bending characteristics relative to low-density species (Pham et al., 2021). This conclusion, however, contradicts the claim by Riesco et al. (2012), who said that a robust association between wood density and bending quality does not exist. Christoforo et al. (2014) also noted that the bending strength of the species increases with higher density. Consequently, the sample density for this investigation may be regarded as sufficient.

**Table 7** **Sapwood and heartwood versus cold bending quality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Wood type | N | No of brokenSpecimens | %Unbrokenspecimens |  Quality classes | Commonfailure 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

  **(a) (b)**

**Figure. 3. Sample cross-grained tensile failure of Nee and Cassia**

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**3.4 Steam Bending Quality**

The results displayed in Table 8 for steam bending characteristics mirrored the trends noted in the cold bending testing. Cassia demonstrated exceptional performance, with 85 percent of its heartwood samples intact. The sapwood of Neem exhibited a bending strength of 50 percent, surpassing the heartwood's 45 percent in steam bending tests. According to Dzurenda et al. (2023), this may be ascribed to the intrinsic flexibility of sapwood's cellular architecture, which is generally more agreeable to deformation under steam conditions than that of heartwood. The characteristics may have jointly enhanced the steam bending performance of Neem sapwood, indicating its appropriateness for furniture and joinery applications necessitating bending and shaping. Figure 4(a) depicts samples of Cassia post-bending, whereas Figure 4(b) presents the similar samples from the Neem wood species.

**Table 8 Sapwood and heartwood versus steam bending quality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | Wood type | N | No of brokenSpecimens | % UnbrokenSpecimens | 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



1. (b)

**Figure 4** **Cassia and Neemwoods after cold and steam bending**

Cassia had exceptional performance in steam bending, as indicated by the high percentage of intact samples, and may thus be categorised within the suggested Class I, signifying outstanding steam bending characteristics. Conversely, Neem was categorised under the suggested Class II, indicating favourable steam bending characteristics. The exceptional steam bending capability of Cassia can be ascribed to its linear wood grain, limited knot occurrence, and smooth texture, all of which promote its flexibility during bending.

Table 8 indicates that a direct correlation exists between wood density and steam bending quality when contrasting very high-density species with medium-density species. For instance, 85 percent of Cassia samples, possessing a density of 898 kg/m³, stayed intact, whereas just 50 percent of Neem samples, with a density of 674.61 kg/m³, remained intact. This discovery aligns with the findings of Ayarkwa et al. (2011), which indicated that wood density strongly affects bending performance, with high-density timbers typically demonstrating improved bending characteristics compared to lower-density species. This conclusion, however, contradicts the claim made by Ratnasingam et al. (2022), who contended that a strong association between wood density and bending quality does not exist.

This study indicates that Neem and Cassia exhibit advantageous steam bending strength, rendering them appropriate for furniture and joinery applications. The steam bending properties of both the sapwood and heartwood of Neem and Cassia are comparable to those of Emire (Terminalia ivorensis), Danta (Nesogordonia papaverifera), Yorke (Broussonatia papyrifera), Mahogany (Khaya spp), Eucalyptus (Eucalyptus tereticornis), Rubberwood (Hevea brasiliensis), Cocoa-wood (Cocos nucifera), and Borassus palm (Borassus aethiopum), as reported by Ayarkwa et al. (2011). These species are well regarded for their appropriateness in furniture manufacturing, joinery, and various wood-based uses.



**Figure 5. Comparison of the steam bending performance of Neem and Cassia with that of nine other wood species.**

**4. CONCLUSION**

The research thoroughly assessed the physical characteristics and flexural properties of sapwood and heartwood from Neem (Azadirachta indica) and Cassia (Cassia siamea) timber species, emphasising its prospective uses in the furniture and joinery sectors. Notable discrepancies were noted in moisture content, basic density, and cold and steam bending performances among the wood species and kinds. Moisture content research indicated a statistically significant variation among timber species and wood sections, with Neem sapwood displaying the highest mean moisture content (88.15%) and Cassia heartwood showing the lowest (47.50%). Elevated moisture levels in sapwood, especially in Neem, resulted in diminished stiffness and heightened vulnerability to failure under cold bending forces. Density studies revealed that Cassia heartwood possessed the highest mean basic density (898 kg/m³), whilst Neem sapwood demonstrated the lowest (674.61 kg/m³). The mixed ANOVA analysis results (F = 44.073, p < 0.05) indicated a significant difference in density across at least two timber qualities. Pairwise comparisons revealed that most density differences among wood types and species were statistically significant at the 0.05 level, except for Neem heartwood and Cassia sapwood. The findings underscore the significant impact of wood species and tissue type on basic density, which is directly associated with the bending behaviour of the materials.

The bending experiments revealed significant differences in the mechanical properties of the wood species when subjected to both cold and steam bending techniques. In cold bending, Cassia heartwood demonstrated the highest percentage of intact samples, whereas Neem sapwood consistently shown inferior bending quality. The cold bending results indicated that the sapwood sections of both species typically exhibited subpar performance, presumably because to their elevated moisture content and diminished density, which compromise their resistance to mechanical deformation. Steam bending yielded findings that favoured Cassia heartwood, which was categorised as Class I due to its exceptional bending properties, attaining 85% unbroken samples when utilising the form tool approach. Conversely, Neem was categorised as Class II, exhibiting satisfactory albeit relatively inferior steam bending strength. A direct correlation between wood density and bending quality was noted, as demonstrated by the elevated density of Cassia heartwood and its enhanced bending performance in both cold and steam treatments. The findings indicate that Cassia and Neem may function as effective substitutes for historically favoured species like Khaya ivorensis and Nesogordonia papaverifera, therefore aiding sustainable wood use and forest conservation initiatives 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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specifically in grammatical precision and language improvement. The AI was employed exclusively to enhance grammatical accuracy and clarity, without modifying the scientific conclusions of the manuscript.

2.

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