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Variations of Stem and Branch Wood Properties of *Nesogordonia papaverifera* in Ghana

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Abstract: The characteristics of *Nesogordonia papaverifera* stemwood and branchwood were investigated. Within Ghana's middle belt, five mature trees with identical diameter at breast height were chosen. Mechanical characteristics and basic density were determined in accordance with British Standard BS 373 and ASTMD 2395, respectively. The IAWA list of microscopic features for hardwood identification was followed by anatomical features. Basic density, mechanical, and anatomical parameters all had a positive connection (P<0.05). Branchwood had a little higher basic density than stemwood, and heartwood had a slightly higher basic density than sapwood. There were minor changes in MoE, MoR, compression, shear, and hardness between the heartwood and sapwood. The stem and branch, on the other hand, were comparable. Fibre percentages were higher in stemwood than branchwood and in heartwoods than sapwoods anatomically. There were more vessels in the branch than in the stem, and in the sap than in the heart. The branchwood of *N. papaverifera* had medium strength qualities that were comparable to most medium construction species' stemwood and could thus be used in addition to their stemwood. The study has offered information on *N. papaverifera* branchwood that may inspire trust and interest in the use of branchwood as a supplemental material in the manufacture of wood products.

Keywords: Density, Mechanical, Anatomy, Stem/Branchwood, *Nesogordonia papaverifera*, Ghana

1. Introduction

Branch wood qualities are being explored in Ghana as a supplement to stemwood, based on the concept of entire tree harvest. Branchwood is a valuable wood resource with a variety of uses; it accounts for 25-32 % of total wood volume and is a secondary resource with high-value applications such as chaise lounges, wall and floor mosaics, garden arbors, dining stools, beds, garment racks, curtain rods, and many others that have yet to be fully explored [1]. Increasing market demand, both locally and globally, has resulted in overexploitation of most 'traditional' market species, with some becoming endangered (such as *Milicia excelsa, Entandrophragma cylindricum, Khaya ivorensis,* and others) [2]. Manufacturers and producers have little choice but to pay attention to the branchwood of known and lesser-known species that were previously disregarded if they are to stay in business as prices of traditional timber rise and quality and quantity diminish [3]. The quality of branchwood, as well as the quality of lesser-known timber species, has yet to be thoroughly investigated. This type of quality assessment considers a variety of physical, mechanical, and anatomical qualities of wood that are all interconnected. *Nesogordonia papaverifera* branchwood is an example of a lesser-known timber species with a great promise for the future.

The abundance of *N. papaverifera* volume was reported in Ghana's forest reserves and farmlands in a recent forest inventory by International Tropical Timber Organization (ITTO), (2019) [4]. The timber species *N. papaverifera* belongs to the Sterculiaceae family. Other names are danta or aprono (Ghana), bete (Ivory Coast), ofun (Nigeria), and koul (Ivory Coast and Cameroon). The tree grows to be 120 feet tall, with a bole that is clean and straight, buttressed, and up to 60 feet long, and trunk diameters of 2 to 3 feet. The tree is gathered in the wild for use as a medicine and a source of wood materials in the local community. The reddish-brown heartwood is clearly distinguished from the 5-8 cm wide strip of lighter-colored sapwood. The grain is narrowly interlocked, forming a stripe figure, the sheen is medium, there is no distinctive scent or taste, the wood is characterized with dark streaks of scar tissue, and it has a faint greasy feel [5].

Although there is some information on the qualities of *N. papaverifera* in the literature, the properties of the wood in one ecological zone differ from those in another. Despite this, there is a scarcity of information on the wood qualities of *N. papaverifera* in Ghana. The current study focuses on the basic density, mechanical, and anatomical features of *N. papaverifera* from Ghana's semi-deciduous forest zone, as well as the interrelationships between these properties. This could provide added value information to stakeholders in the wood products manufacturing business. This will ensure that the forest tree's branch wood is used as a substitute for the tree's stem wood, promoting sustainable forestry and ensuring that future generations will have forest trees to suit their wants and values. The differences between the characteristics of stem and branchwood were explored. The study also aimed to provide a detailed anatomical description as well as a description of the woods' composition. Manufacturers and producers will be able to determine which sections of the tree can be used in the future to replace regularly used timber species based on the findings of this study.

2. Materials and Methods

2.1. Area of Study

To furnish wood for characterization of the species, five matured trees of *N. papaverifera,* aged 42, were obtained from New Koforidua, in the Ejisu – Juaben Municipality, in the center section of the Ashanti area inside Ghana's middle belt. Trees were collected from the wild (a cocoa farm) in the same location inside the open forest of the area, which lies between Latitudes 1° 15' N and 1° 45' N, and Longitudes 6° 15' W and 7° 00 W. It has a land area of 637.2 Km^2 [6]. The rainfall pattern in the Municipal Assembly is bimodal. The rainy season runs from March through July, with July being the wettest month. The yearly rainfall averages between 1200 and 1500 mm throughout the main season. The minor rainfall season begins in September and ends in November, with an average annual minor rainfall of 900–1120 mm. The months of December through February are typically dry, hot, and dusty. The lowest yearly temperatures in the Municipal area are around 25°C in August and the highest are around 32°C in March. During the rainy season, relative humidity is modest yet rather high. The municipality's geography is mainly undulating, with plains and hills varying in height from 240 to 300 m above sea level [6].

2.2. Research Design and Data Collection

Harvesting was done on trees with identical diameters at breast height. A technical officer from the Juaso District Forestry Commission was the first to identify the trees. Fresh dried leaves and seeds were gathered from the trees and sent to the Forest Research Institute of Ghana's laboratory for confirmation of field identification using the field guide to Ghana's forest trees [7].

The study's trees were chosen based on their availability in farms, a diameter at breast height (dbh) larger than 45 cm, and overall trunk straightness. For *N. papaverifera*, the average diameter of the trees at 1.5 m above ground (dbh) was 64.4 cm. A chainsaw was used to cut down the trees that were chosen. Each species' average clear bole length from the beginning of the first branch and the terminal point of buttresses was measured and recorded. The average length measured 1809 cm. To collect varying diameters of branch wood for the study, the whole lengths of the trees were divided into three equal sections and delimited with permanent makers, and 50 cm from the knot, a branch disc of 1.5 - 2 m was taken from the first and second branches of each tree. This criterion was used to ensure that the branch disc was straight and that no evident tension wood was included. There is a total of 25 branch discs (i.e., 5 branches x 5 trees) varying in diameter from 260 to 560 mm. A total of 15 stem discs (five bottom, five middle, and five top) were used to obtain stemwood samples (tree bole cut 1.5 from the ground). All stem and branch wood samples were transported to Boadu Wood Mill for processing from the countryside. The band saw was used to convert the logs to timber using the quarter sawn procedure. After conversion, all samples were air dried for three months before being conditioned in a Fabi Timbers oven to an average moisture content of 12 ± 3% at the same temperature and relative humidity used to oven dry wood. Both branch and stem boards were re-sawn, stripped, and crosscut to the desired test sample sizes after drying. Clear heart and sap wood samples were scrutinized to confirm that they were free of both natural and man-made defects (i.e. samples free of knots, fuzzy and woolly surfaces which are evidence of reaction wood and any other visible defects).

2.3. Density of Stemwood and Branchwood

American Standards for Testing Materials, (ASTM D 2395), (2008) [8] was used to calculate the basic density. Each strip was sawn into 20 mm × 20 mm sections before being crosscut into 20 mm cubes. For density estimation, a total of 750 stem and branch wood samples were used (i.e. 45 heartwood + 45 sapwood 5 trees for stem and 30 heartwood + 30 sapwood 5 trees for branch). The initial mass of the samples was determined using a VWR Science Education RS232 digital electronic balance (with precision 0.001 g) at the Forestry Research Institute of Ghana laboratory shortly after conversion (W_1). The samples were then immersed in water for 24 hours to determine the swelled volume (V_1) using the immersion method. The increase in mass of water displaced by the submerged wood sample is numerically equivalent to the volume of water displaced, according to the Archimedes principle. The wood samples were then oven-dried at 103± 2°C with occasional weighing until they reached a consistent oven-dry mass (W_0) [8]. The experiment was carried out at a temperature of 20°C. The samples' basic density (BD, kgm^{-3}) was then determined using the following formulae:

$$BD = W_0 / V_s \quad (1)$$

Where W_0 = Oven dried mass [g]
V_s = Swollen volume [cm^3].

2.4. Mechanical Properties of Stemwood and Branchwood

Bending characteristics (Modulus of Rupture (MOR) and Modulus of Elasticity (MOE), Compressive strength parallel to the grain, Shear strength parallel to the grain, and Janka Hardness were all found (Tangential and Radial directions). The specimens were subjected to bending properties testing in accordance with British Standard [9]. The logs were sawn into 25 mm and 55 mm thick boards. Half of the boards were used in the green state for the test, while the other half were air-dried and then conditioned in an oven for the dry sample test. The green test specimens were cut to the dimensions and orientations specified by the British Standard [9] and stored in a climate chamber until the tests were performed. The 'dry' test specimens were air dried and conditioned to a moisture level of 12%. The static bending (modulus of elasticity and modulus of rupture) tests were performed using an 'Instron' Universal Testing Machine with a 3-point loading (i.e. central loading) system. For the central loading test pieces, the 2 cm dimensions standard was employed, i.e. 2 cm x 2 cm x 30 cm specimens (i.e. distance between the points of support of the test pieces was 28 cm). A total of 250 stem samples (125 heartwood + 125 sapwood) and 150 branch wood samples (75 heartwood + 75 sapwood) were collected. The yearly rings for the 2 cm test pieces were oriented parallel to the loading direction. Three different tree parts were used to collect samples (bottom, middle and top).

The machine automatically applied the loads at a rate of 6.5 mm/min. At 0.1 N intervals, the applied load and accompanying deflection were automatically recorded. The test piece was loaded up until it broke. The test pieces were supported at the ends in such a way that they were completely free to bend without being limited by friction. The maximum load at failure and the maximum load at the proportionality limit were also reported. With reference to the outside locations of loading, the deflection of the beam at mid-length was also automatically measured. The test lasted 90 ± 3 seconds.

The elasticity modulus, E, was calculated using the following equation:

$$MOE = \frac{P^1 L^2}{4\Delta \prime A^2} \quad (2)$$

Where,
MOE = Young's modulus of elasticity (N/mm^2)
P^1 = maximum load applied at the limit of proportionality (N)
L = area of cross-section of beam normal to direction of load (mm^2)
Δ^1 = deflection at mid-length at limit of proportionality (mm)
L = span of beam (mm).

Modulus of rupture, R was computed by the equation:

$$R = \frac{3PL}{2bd^2} \quad (3)$$

Where,
R = modulus of rupture (N/mm^2)
P = maximum load applied at the midpoint of the sample (N)
L = span of beam (mm)
b = breadth of test piece (mm)
d = depth of the test piece (mm)

The compression resistance was measured in the longitudinal direction. The sample sizes were trimmed to the standard of 2 cm, i.e. 2 cm x 2 cm x 6 cm. A total of 250 stem samples (125 heartwood + 125 sapwood) and 150 branch wood samples (75 heartwood + 75 sapwood) were collected. The test was performed on an "Instron" Universal Testing Machine with a compression test fixture. The experiment was carried out in accordance with British Standards 373 [9]. The load was applied to the test component at a rate of 3.1 x 10-6 mm/min as the loading plates neared each other. The maximum load at failure was measured after the test component was loaded at a rate of 6.5 mm/min. Before the test, the rectangular test pieces were checked to confirm that they were smooth, parallel, and normal to the axis. The plates on which the test piece was placed were parallel to each other throughout the duration of the test. The test lasted 90 ± 3 seconds.

The compressive strength at maximum load was computed as follows:

$$C = \frac{p}{A} \quad (4)$$

Where:
C = compressive strength at maximum load (N/mm^2)
P = maximum load (N)
A = cross sectional area of sample (mm^2)

The parallel to grain shear strength test was carried out in line with British Standards 373 [9]. The sample sizes were 5cm x 5cm x 5cm, as per the specification. A total of 250 stem samples (125 heartwood + 125 sapwood) and 80 branch wood samples (40 heartwood + 40 sapwood) were collected. The test was performed on an "Instron" Universal Testing Machine with a shear test fixture. The load was applied at a constant rate of 0.635 mm/min crosshead movement. Shearing was place in a longitudinal direction. The test piece was subjected to a load until it broke. The load at which the failure occurred was automatically recorded. The test lasted 90 ± 3 seconds.

Shear strength parallel to the grain (V) was calculated as follows:

$$V = \frac{p}{A} \quad (5)$$

Where V = shear (N/mm^2)
P = maximum load (N)
A = area in shear (mm^2)

The hardness (Janka Indention Test) was performed according to the British Standards 373 [9]. The hardness test specimen was 5 cm x 5 cm x 15 cm in size and was sliced radially and tangentially. A total of 250 stem samples (125 heartwood + 125 sapwood) and 80 branchwood samples (40 heartwood + 40 sapwood) were collected. The test was conducted using an "Instron" Universal Testing Machine with a hardness test fixture. The fixture consists of a steel rod with a steel ball measuring 11.3 ± 2.5 mm in diameter at one end. The hemispherical end of the steel bar (steel ball) penetrates the test piece when a weight is applied. The load required to push the hemispherical end of the steel ball into the test piece to a depth of 5.6 mm is automatically recorded as the failure load.

2.5. Anatomical Features of Stemwood and Branchwood

For both stem and branch woods anatomical determination, a total of eighty 20 mm cubes were employed (i.e., eight, 20 mm heartwood cubes and eight, 20 mm sapwood cubes from five trees). Before sectioning with a sliding microtome, samples were softened by soaking in water for 21 days, followed by soaking in a 1:1 combination of ethanol and glycerol for 28 days. Using a sliding microtome, thin sections of 25 µm thickness were cut from the samples' transverse surfaces. The sections were initially cleaned in distilled water before being dyed for about 10 minutes in a 1 percent safranin in 50 % ethanol solution. After that, the sections were rewashed in distilled water and dehydrated for 6 minutes in escalating ethanol concentrations of 30, 50, 70, 80, 90, and 100 %. After that, they were submerged in xylene to eliminate any remaining water. After that, the pieces were firmly mounted in Canada balsam, and the slides were dried in a 60°C oven for 24 hours. Two matchstick-sized specimens were taken from each of the anatomical subsamples for the maceration process. These sizes of matchsticks were placed in separate labeled containers and immersed in a 1:1 mixture of glacial acetic acid and hydrogen peroxide (6%). The specimens in the solution were incubated in a 60°C oven until they were completely macerated. For fibre length measurements, macerated cells were temporarily placed in glycerol. Using a light microscope (Micromaster Premier) and a digital camera, photomicrographs of the slices and macerated slides were shot independently at 40 magnification. All anatomical tissue measurements were done manually on photomicrographs using Image J software. A total of 250 photomicrographs with image sizes of 682 × 512 pixels were employed for both stem and branch woods. The straight-line approach in Image Java was used to manually determine fibre lengths and vessel sizes.

The characterization and description of wood anatomical properties were done in accordance with IAWA committee standards for hardwoods International Association of Wood Anatomist (IAWA), (1989) [10]. From a tangential section, the three primary tissue proportions (fibres, vessels, and parenchyma -axial and ray) were determined. Each image was rotated at a 45° angle. To determine the grid, a rectangular dot-grid scale of 35 points was picked from the innermost portion of each slide. Each dot was examined thoroughly to establish the type of tissue it represented, and the process was repeated five times. From each slide, the proportions of fibre, vascular, and parenchyma cells were calculated. The number of points covering any tissue was counted at each location and expressed as a percentage of the total number of points using the formula by International Association of Wood Anatomist (IAWA), (1989) [10]:

$$Percentage\ of\ tissue = \frac{Number\ of\ points\ covering\ the\ tissue}{Total\ number\ of\ points\ on\ grid} \times 100 \quad (6)$$

2.6. Data Analyses

The data was numerically summarized using descriptive statistics. A regression model was used to assess the relationships between characteristics at various heights. The mean and standard deviation are used to represent the findings of the various parameters determined in order to identify the relationship between the stemwood and branchwood. The statistical significance of each pair of means, as well as variance in quantitative mechanical parameters and anatomical properties, were tested using the Single Factor Turkey Multiple Comparison Test. The Tukey HSD post-hoc tests were used to determine which of the two treatment pairs were substantially different.

3. Results and Discussion

3.1. Basic Density

The basic density of branchwood (721 kgm^{-3}) was just somewhat greater than that of stemwood (712 kgm^{-3}), with no statistically significant difference (Table 1). The basic density of *N. papaverifera* rose throughout the tree height from the bottom to the top and branch. With increased density, the rupture modulus increases. This is in line with Dadzie, P. K., Amoah, M., and Ebanyenle, E., Frimpong-Mensah, K., (2018) [2] previous conclusion that wood strength is proportional to wood density. The heartwood had greater (729 kgm^{-3}) and statistically significant basic density values than their sapwood (700 kgm^{-3}) counterparts in terms of radial variation (Table 1). The discrepancies could be attributed to the heartwood's higher extractive deposits than the sapwood, as well as the xylem maturation process. According to Dadzie, P. K., Amoah, M., and Ebanyenle, E., Frimpong-Mensah, K., (2018) [2] when wood transforms from sapwood to heartwood, its density normally increases. Similarly, the stem-heart (728 kgm^{-3}) had a greater basic density than the stem-sap (698 kgm^{-3}), and the branch-heart (730 kgm^{-3}) had a higher basic density than the branch-sap (712 kgm^{-3}). Deposition of extractives such as phenols and quinines are the most common cause of density change.

3.2. Mechanical Variations

In stemwood and branchwood, as well as heartwood and sapwood of *N. papaverifera*, the variation of modulus of elasticity (MOE) and modulus of rupture (MOR), compressive strength, shear strength, parallel and radial and tangential hardness strength is reported in Table 1. With respect to MOE, the mean stemwood of both heart and sap wood is 12489.63 (232.38) N/mm^2 and its branchwood counterpart is 12902.80 (133.04) N/mm^2. In parenthesis, you'll see the standard deviations. The sapwood 12588.46 (271.08) N/mm^2 and heartwood 12803.97 (285.39) N/mm^2 of *N. papaverifera* exhibited a minor difference in the parameter when it came to the effect of the species' tissues on MOE. Modulus of Elasticity in the stem-heart 12785 N/mm^2 was greater than its counterpart in the stem-sap 12194 N/mm^2, while MOE in the branch-heart 12823 N/mm^2 was higher than its branch-sap 12982 N/mm^2 counterpart. The stemwood of *N. papaverifera* had a modulus of rupture (MOR) of 121.92 (1.92) N/mm^2 while the branchwood had a MOR of 122.28 (2.18) N/mm^2 (Table 1). The total sapwood 119.06 (1.88) N/mm^2 and the heartwood 125.14 (2.24) N/mm^2 showed a similar pattern, with minimal changes in MOR. MOR was higher in the stem-heart 123 N/mm^2 than in the stem-sap 121 N/mm^2 counterpart, and in the branch-heart 128 N/mm^2 than in the branch-sap 117 N/mm^2 counterpart. This supports prior claims that strength qualities improve when moisture content decreases [11]. According to Timber Export Development Board (1994) [12], the Modulus of rupture (MOR) of a small clear specimen at 12 % MC is rated very low if it is less than 50 N/mm^2, low if it is between 50 and 85 N/mm^2, medium if it is between 85 and 120 N/mm^2, high and very high if it is between 120 and 175 N/mm^2, and very high if it is over 175 N/mm^2. In this investigation, the mean modulus of rupture for *N. papaverifera* at 12 % moisture content was classified high to very high (117.02 – 127.59 N/mm^2) in all five trees. When it came to axial variation, the bending strength was consistent: it grew steadily from the base to the top of the tree. The basic density data obtained during the study were identical to this outcome. The strength of wood is related to its density, according to Aguma, Q., & Ogunsanyo, O. Y., (2019) [13]. Most heavy construction species, such as *Sterculia rhinopetala* (wawabima) (127 N/mm^2), *Celtis mildbraedii* (essa) (104 N/mm^2), and *Piptadeniastrum africanum* (dahoma) (109 N/mm^2) and Amaoh, M., & Inyong, S. (2019) [14], have lower modulus of rupture mean values than *N. papaverifera.*

The stemwood of *N. papaverifera* had a compressive strength of 54.00 (0.54) N/mm^2, but the branchwood had a compressive value of 52.28 (0.72) N/mm^2, indicating a 2.2 percent drop (Table 1). In terms of radial variation, the sapwood, with a mean compressive strength of 54.15 (0.71) N/mm^2, and the heartwood, with a mean compressive strength of 52.13 (0.54) N/mm^2, both showed a similar pattern, with only minor changes. Similarly, stem-heart 53 N/mm^2 compressive strength was higher than stem-sap 55 N/mm^2 counterparts, and branch-heart 52 N/mm^2 compressive strength was higher than branch-sap 53 N/mm^2 counterparts. The compressive strength of *N. papaverifera*, which is 53.14 N/mm^2, is comparable to that of most heavy building timbers, such as *Milicia excelsa* (odum) with 52 N/mm^2, *Celtis mildbraedii* (essa) with 50 N/mm^2, and *Albizia iatandza* (albizia) with 51 N/mm^2 [14].

The mature stage for most trees begins around the age of 40 years, according to Brunner, M., K. Frimpong-Mensah, Kankam C. K., Zurcher E., & Wurthrich, K. (2007) [15]. Because the trees in this study were harvested at age 42, they may have had a higher compressive strength because they had already reached maturity. Shorter vessel members were seen in *N. papaverifera*, which could be due to its great resistance to compression. Some anatomical parameters evaluated, such as fibre length, width, double wall thickness, and vessel diameter, may be a contributing cause to the high strength values for *N. papaverifera* trees. The mean shear strength parallel to the grain of *N. papaverifera* stemwood and branchwood was close at 16.30 (0.16) N/mm^2 and 16.54 (0.60) N/mm^2, with the branchwood results only marginally higher than the stemwood increase of 1.47 %. The shear strength of the sapwood (16.04 (0.58) N/mm^2 and the heartwood (16.80 (0.18) N/mm^2 showed a similar pattern, with only minor changes. Similarly, stem-heart 16.36 N/mm^2 shear strength was higher than stem-sap 16.24 N/mm^2 shear strength, while branch-heart 17.24 N/mm^2 shear strength was higher than branch-sap 16.10 N/mm^2 shear strength. Amaoh, M., & Inyong, S. (2019) [14] showed that the strength of heartwood is slightly stronger to resist failure than sapwood for radial change of shear strength parallel to grain. This statement is in support of the study's findings. However, the sapwood portions are statistically inferior to the heartwood portions. Shear strength values obtained for *N. papaverifera* trees compare favourably to those obtained for most heavy construction species, including odum (*Milicia exelsa*) 14.10 N/mm^2, denya (*Cyclidiscus gabunensis*) 11.10 N/mm^2, dahoma (*Piptadeniastrum africanum*) 17.60 N/mm^2, asanfena (*Aningeria altissima*) 9.50 N/mm^2, sonkyi According to Makoto K. Noboru, N & Shinichiro, N., (2018) [17], anatomical factors such as broad rays or early wood – latewood variation can have a significant impact on shear strength.

The stemwood (heart and sap) and its branchwood counterpart of *N. papaverifera* have comparable mean radial and tangential hardness (Table 1). The average radial hardness of stemwood and branchwood was 8.57 N/mm^2 (0.28) and 8.92 N/mm^2 respectively (0.21). In compared to the stemwood of *N. papaverifera*, the branchwood result was higher, increasing by 4.08%. A similar pattern was seen in radial variation, with radial hardness of 9.15 (0.22) N/mm^2 in the sapwood and 8.34 (0.27) N/mm^2 in the heartwood. The branchwood result of 10.29 (0.37) N/mm^2 was higher than the result of 9.04 (0.29) N/mm^2 for tangential hardness. There was no significant difference in radial variation between the sapwood 9.90 (0.30) N/mm^2 and the heartwood 9.43 (0.36) N/mm^2. The average hardness of the axial positions (Bottom, Middle, and Top) varied dramatically along the bole, with the strength decreasing from the bottom to the top. These findings clearly show that different portions of the same tree have different resistance to indentation. In comparison to *Milicia exelsa* 14.10 N/mm^2, *Cyclidiscus gabunensis* 11.10 N/mm^2, and *Aningeria altissima*) 9.50 N/mm^2, *N. papaverifera* had a comparatively strong resistance to indentation for both stem and branch sections.

Table 1. *Mean air dry density and mechanical properties of Nesogordonia papaverifera stemwood and branchwood, heartwood, and sapwood.*

Property	Species component		Species radial variation	
	Stemwood	**Branchwood**	**Heartwood**	**Sapwood**
Air dry density (kgm^{-3})	712*	721*	728	700
Modulus of Elasticity (MPa)	12489.63	12902.80	12803.97	12588.46
Modulus of Rupture (MPa)	121.92	122.28	125.14	119.06
Compression parallel to grain (MPa)	54.00*	52.28*	52.13*	54.15*
Shear parallel to grain (MPa)	16.30	16.54	16.80	16.04
Radial hardness (N/mm^2)	8.57	8.92	8.34	9.15
Tangential hardness (N/mm^2)	9.04	10.29	9.43	9.90

~Mean with asterisks superscript on a row indicates significant differences between the sapwood-heartwood and stem-branch wood.

3.3. Anatomical Variations

The anatomical structure of *N. papaverifera* is depicted in Figure 1, and the cell diameters and proportions of tissues in axial and radial directions are summarized in Table 2. *N. papaverifera* exhibited general hardwood characteristics, such as the primary hardwood cell types (fibres, vessels, rays and axial parenchyma). The wood has obvious growth ring borders and is diffuse-porous.

Fibres, Fibres made up roughly 42% of the cross-sectional area of the wood. They are coarse, angled in transverse section and not aligned in radial rows, thin-to-thick-walled, 1567 µm (1253-1626 µm) long, 21 µm (18-24 µm) wide, with a lumen diameter of 12 µm (09-13.5 µm), and 9 µm (4-10 µm) double wall thickness. Septate and non-septate fibers exist. Pits are abundant, restricted to the radial walls, and bordered in a variety of ways from simple to minute.

Vessels, the arteries are single and in short radial multiples of 2-3, occasionally blocked by tyloses and brownish-black deposits (Figures 1a-b). They have an approximately round to oval shape with alternate intervessel pits. It features simple perforated plates and vessel-ray pits with defined borders across the ray cell, which are comparable in size and shape to intervessel pits. Vessels cover 20% of the ring's surface area and have an average lumen diameter of 49 µm (42-50 µm). Prismatic crystals were also found in the examined species' stemwood and branchwood.

Parenchyma, with 3-4 cells per parenchyma strand, axial parenchyma is diffuse-in-aggregates and sparse paratracheal storied rays, arteries, and fibres. It has procumbent body ray cells with mainly one row upright and square marginal cells (Figure 1). The parenchyma makes about 18% of the tissues.

Lemmens, R. H. M. J. (2007) [18] observed that silica bodies are present in the rays of *A. robusta,* while tyloses obstructed certain capillaries in *T. ivorensis* in a similar investigation. During use, tyloses and crystals discovered in this study have varied effects on wood species. The crystals in *N. papaverifera* exhibited a significant blunting effect on the saws and cutting instruments used to prepare the samples. The number and frequency of tyloses contribute to a reduction in wood's permeability to fluid flow, which limits moisture uptake and makes it resistant to pulping liquor and preservatives [19]. According to Dietsch, P., Franke, B., Gamper, A., & Winter, S. (2015) [20], their presence has an impact on water circulation in live trees. As a result, Sitsofe Kang-Milung (2016) [21] found that *A. Robusta* is extremely permeable to preservative treatments, whereas *T. ivorensis* is very resistant due to the presence of tyloses in its capillaries.

The presence of tyloses occluded in some *N. papaverifera* vessels increases its durability, which may be advantageous as Sitsofe Kang-Milung (2016) [21] found that tyloses boost the wood's durability. As a result, they help trees defend themselves by preventing infections from moving along vessels and allowing toxic extractives to collect without being diluted by the transpiration stream.

3.4. Fiber Specifications

In this investigation, stemwood fibres (1567 µm) were found to be longer than branchwood fibres (1383 µm) in all *N. papaverifera* plants. The influence of growth promotion chemicals near to the tip [22] could be ascribed to shorter fibres in the branch.

The stemwood of *N. papaverifera* (21.50 µm) has a larger fibre diameter than the branchwood (20.50 µm). Inconsistencies in auxin contents in the apical meristem during growth could explain the wider heartwood (21.50 µm) than sapwood (20.50 µm) fibres at both stem and branch of *N. papaverifera*. Larson, P. R. (1960), in Gartner, B. L. (1995) [23] stated that high auxin content in the apical meristem causes large diameter cells to be produced; anything that reduces apical activity causes small diameter cells to be produced, so decreased fibre diameter and fibre lumen diameter along the branches could be the result of reduced apical activity.

In all *N. papaverifera* species, fibre lumen was wider in stemwood (12.00 µm) than branchwood (11.50 µm). The branches' fibre lumina were generally smaller than the stems. Branchwood cells have a smaller diameter and lumina than their stemwood counterparts, according to Samariha, A., & Kasmani, J. E., (2011) [24]. Most of the stem sections have wider lumen widths than the branch, which may result in less cell wall materials and, most likely, less density than the branch's narrower ones. Again, the heartwood segment (12.50 μm) of both stem and branch had a bigger lumen than the sapwood portion. (11.50 μm.)

In *N. papaverifera*, the fibre double wall thickness was larger in stems (9.00 μm) divisions than branchwood (8.50 μm) divisions. In both species, the heartwoods had a larger fibre double wall thickness (9.00 μm) than the sapwood (8.50 μm). Dawkins, H. C, and Philip, M. S., (2020) [1] noticed a decrease in double wall thickness with height between stems and branches in the current investigation. The basic pattern for fibre wall thickness, according to them, is a decrease from the base to the summit of the tree. *Tectona grandis* and *Plantanus occidentalis* showed comparable trends, according to Kiaei, M. (2011) [25]. Furthermore, as shown by Samariha, A., & Kasmani, J. E., (2011) [24] and Longui, E. L., De Brito, R. A., Garcia Silva, D., Romeiro, I. L., De Lima, S. Monteiro, B. F. Antonio, C., & De Melo, G. (2012). [26] for *Ailanthus altissima* and *Eriotheca gracilipes*, fibres from various axial positions of the branchwood showed lower double wall thicknesses than stemwood fibres.

Sapwoods (50.00 μm) had a larger vessel lumen than heartwoods (47.50 μm) for *N. papaverifera*. In stems and branches, sapwood vessels are wider than heartwood vessels, comparable to what Sitsofe Kang-Milung (2016) [21] described about vessel lumina increasing in size from inner to outer wood. The branchwood was wider (49.50 μm) than the stemwood (48.50 μm). *N. papaverifera* stemwood vessels displayed wider lumina than branchwood vessels, which was confirmed. This explains why Gurau, L., Cionca, M, Mansfield-Williams H. & Sawyer G., Octavi, (2010) [27] found smaller vessel lumina in the branches than in the stems of maple wood.

3.5. Tissue Percentages

In *N. papaverifera*, fibre percentages were higher in the stemwood (44.50%) than the branchwood (40.00%), and in heartwoods (49.00%) than sapwoods (35.50%). The current axial and radial trends are consistent with a research by [21], which found that fibre percentage decreases from the pith outward and as tree height increases. Hardwood branches have less fibers than those from the stem, according to Luizon, C. D. L. & Gasson, P. (2012) [28]. This means that fibre content is higher at the bottom than at the top, and heartwood fibres are stronger than sapwood fibres. According to Bhat, K. M., Priya, P. B., & Rugmini, P. (2001) [29], there are no substantial changes in tissue proportions between branchwood and stemwood.

Furthermore, both the stem and branch woods of *N. papaverifera* showed a 42.1 % fibre proportion. The fibre content of *N. papaverifera* would be categorized as medium according to Frimpong-Mensah, K. Boadu, K. B., & Antwi-Boasiako, C., (2017) [30] (41-60 %). The number of vessels in a tree increases with height, according to Luizon, C. D. L. & Gasson, P. (2012) [28]. Furthermore, Emerhi, E. A. (2012) [31] discovered that the percentage of vessels rose from the pith to the bark of trees, meaning that the sapwood has more vessels than the heartwood. For *N. papaverifera,* this was the case. The stemwood (21.50 %) of *N. papaverifera* had more vessels than the branchwood (20.30 %) while sapwood (25.5 %) had more vessels than the heartwood (16.00 %). As a result, increased stemwood vessels may reduce density and some strength qualities.

In general, branchwood parenchyma (40.00%) was higher than stemwood parenchyma (34.51%), and there was a substantial difference between axial and ray parenchyma in all of the species studied. In this investigation, axial parenchyma was shown to be higher than ray parenchyma. Table 2 shows that the heartwood had a higher percentage of ray parenchyma than the sapwood. The axial parenchyma results showed a similar pattern. Similar to what Gurau, L., Cionca, M, Mansfield-Williams H. & Sawyer G., Octavi, (2010) [27] found, the branch has a higher proportion of parenchyma cells than the stem wood.

The presence of more parenchyma cells in the branches of *N. papaverifera* than in the stems supports the findings of Dawkins, H. C, and Philip, M. S., (2020) [1]. In *N. papaverifera*, however, the stem recorded a higher percentage than the branch in axial parenchyma.

Table 2. *Mean anatomical characteristics of stemwood and branchwood, heartwood and sapwood of Nesogordonia papaverifera.*

Property	Species component		Species radial variation	
	Stemwood	**Branchwood**	**Heartwood**	**Sapwood**
Tissue proportion (%)				
Parenchyma	17.50*	20.50*	20.50*	17.50*
Vessel	21.50	20.30	16.00*	25.50*
Ray parenchyma	14.00*	24.50*	20.00*	18.50*
Axial parenchyma	20.51*	15.50*	20.80*	15.50*
Fibre	44.50*	40.00*	49.00*	35.50*
Fibres (μm)				
Length	1567*	1383*	1475	1475
Width	21.50	20.50	21.50	20.50
Lumen diameter	12.00	11.50	12.50	11.00
Wall thickness	9.00	8.50	9.00	8.50
Vessels				
Lumen diameter (μm)	48.50	49.50	47.50*	50.50*
Number of vessels per mm^3	149.50*	155.00*	147*	157*

~Mean with asterisks superscript on a row indicates significant differences between the sapwood-heartwood and stem-branch wood.

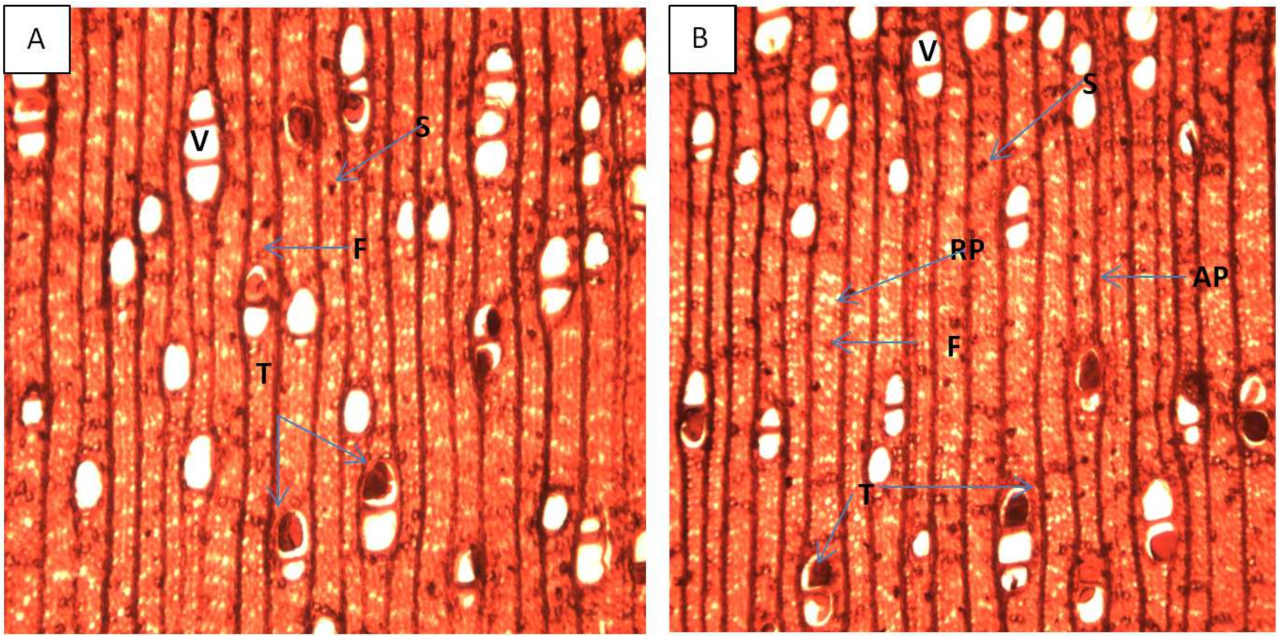

Figure 1. *Sample from N. papaverifera stem (a) and branch (b) showing V (vessel), F (fibre), AP (axial parenchyma), RP (ray parenchyma), T (tyloses), S (silica body).*

The determination and classification of the branch and stem of *N. papaverifera* wood for structural applications is novel in this work. This will aid the wood industry in the modification of wood products and manufacturing processes, as well as the formulation of safety values and design functions of species that will aid in the preservation of our decreasing forest. The findings of this study have offered information on *N. papaverifera* branch and stem wood, which may inspire confidence and encourage interest in using branchwood as a supplemental material for wood product manufacture in and outside of Ghana.

Tree diversity can be found both within and between trees, as well as between growing stands. Environmental factors such as soil, climatic conditions, and other physiological effects are also key sources of variation in wood anatomical structure, which affects the physical and mechanical qualities of the wood [32], Nonetheless, for economic reasons, the samples utilized in this study were gathered in such a way that each species was taken from stem and branch wood parts. As a result, the samples do not cover all possible variability ranges. The number of trees included in the study was again limited to five. This study's shortcomings are as follows.

3.6. Correlation Between Density, Mechanical and Anatomical Properties, of N. papaverifera

Correlation analysis was used to discover and analyse the observed relationships between pairs of variables evaluated. Anatomical features, basic density, mechanical parameters determined (modulus of elasticity, modulus of rupture, compression and shear parallel to grain, and hardness), and correlation analysis demonstrated a substantial link (fibres, vessels and parenchyma). For other hardwood species, the association between basic density and mechanical qualities determined is comparable to that found by Desch, H. E. & Dinwoodie, J. M. (2016) [33].

Basic density was also shown to be connected to some of the anatomical features evaluated. For example, density and fibre length, percentage vessel, vessel lumen diameter, and ray parenchyma all showed a positive association. Anatomical traits were found to have a favourable relationship with basic density and mechanical qualities. Fibre length, vessel lumen diameter, and ray parenchyma, for example, all had positive correlations with density and mechanical qualities. Because numerous parenchyma cells correlate positively with greater mechanical fragility, lowering the mechanical resistance of wood [28], a higher parenchyma percentage would have a negative impact on the strength qualities of the branch rather than the stem. Physical, mechanical, and anatomical qualities of wood are connected to one another, with axial and radial variations as well as positive interrelationships.

4. Conclusion

The goal of this study was to characterize and compare the basic density, mechanical, and anatomical properties of *N. papaverifera* stemwood and branchwood from Ghana to the properties of most high-medium construction species used in the wood industry, as well as the interrelationships between these properties. The following conclusions were drawn based on the findings of this study:

1. Basic density proved to be an accurate predictor of mechanical and anatomical features. The density of the branchwood was slightly higher than that of the stemwood. From the bottom to the top, the parameter was observed to grow.
2. The stemwood and branchwood of *N. papaverifera*

were equivalent. Again, for axial variation, the species' bending strength rose as the tree height grew from the base to the top.

3. The branchwood of *N. papaverifera* exhibited medium strength properties, which compare favorably to stemwood of most medium construction species, such as ofram (*Terminalia superba*), iroko (*Chlorophora spp*), emeri (*Terminalia ivorensis*), and dahoma *(Piptadeniastrum africanum*), and could thus be used in addition to stemwood.
4. When compared to the majority of medium construction species listed above, the branchwood of *N. papaverifera* has a good potential for intensive industrial usage; its qualities are suited for different applications in the wood industry.

Declaration of Interest Statement

There are no conflicts of interest declared by the authors.

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