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Physical and mechanical properties of rubberwood (*Hevea brasiliensis*) in three rubber-growing zones of Bangladesh

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Abstract

Rubber tree (*Hevea brasiliensis*) is a tropical plant, and rubberwood, as a timber, has great utilization potential. In Bangladesh, despite its large potential, limited research has so far been carried out to investigate the properties of rubberwood in terms of seasoning conditions and growing zones. This study investigated selected physical (density, moisture content, volumetric shrinkage) and mechanical (modulus of elasticity (*MOE*), modulus of rupture (*MOR*), compressive strength, shear strength parallel to the grain, and Janka hardness) properties of rubberwood in green and air-dry (AD) conditions, which were harvested after the latex extraction period ended. In addition, differences between samples collected from four geographic locations (Chattogram, Cox's Bazar, Sylhet, and Tangail) and three different stem heights were considered. Logs from three 32-year-old rubber trees were collected from each of the four sites, totaling 12 sample trees. After felling, the trees were delimbed, and the stems were cut into three logs: bottom (0.5–3.5 m), middle (3.5–6.5 m), and top (6.5–9.5 m). The logs were then band-sawn into planks with an approximate thickness of 5.08 cm. The planks were further reduced to specimen sizes for each test. After air-drying, all specimens reached an equilibrium moisture content of approximately 12%. Stem height and site conditions had a substantial impact on wood density and mechanical characteristics. Wood collected from the bottom logs and in Tangail had considerably higher ($p < 0.05$) densities than those from the upper logs and the other three sites. Within stems, both the green and dry specimens from the bottom logs exhibited 24–32% and 8.6–19% higher mechanical properties, respectively, than those from the upper logs. Air-drying produced noticeable increases in *MOE*, *MOR*, compressive strength, hardness, and shear strength. Wood specimens from Chattogram and Sylhet exhibited, on average, better mechanical properties than those from Cox's Bazar and Tangail. This study offers site-specific data for rubberwood in Bangladesh, emphasizing the combined effects of stem position and site heterogeneity, even though the overall patterns are consistent with accepted wood science concepts. The results highlight the opportunities of rubberwood in the woodworking sector, as this study contributes to the understanding of the variability of rubberwood properties, with useful insights for optimizing raw material selection and utilization of wood sections for specific applications.

Keywords Mechanical properties, Physical properties, Rubberwood, Rubber-growing zone, Wood structure, Wood variation

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Introduction

Rubber tree (*Hevea brasiliensis*), an important cash crop of the Euphorbiaceae family, is distributed across most tropical and subtropical regions of the world [1]. Originating from the Amazon Basin in Brazil, rubber trees first arrived in Asia in 1877 [2], and are nowadays planted in 20 countries, including Bangladesh, Cambodia, China, Indonesia, India, Malaysia, Myanmar, Thailand, the Philippines, and Vietnam [3]. Globally, rubberwood plantations account for an estimated 7.73 million hectares across 17 reporting nations, with 87% of the total being in South and Southeast Asia [4]. Rubber trees are planted mainly for producing natural latex [5, 6]. After diminishing their latex productivity by around 30 years, rubber trees are harvested. Until a few decades ago, most rubber trees were used as a fuel in the processing of rubber, steel industries, tobacco curing, brick kilns, and in locomotive engines [7, 8]. Currently, rubberwood is a popular material for furniture, plywood, veneers, and composite panels (e.g., particleboard, fiberboard) [2, 4, 9, 10]. Nevertheless, low density and poor dimensional stability of wood limit its applicability in the wood product industries [10, 11].

In Bangladesh, the demand for rubberwood has recently increased for furniture industries, mainly due to restrictions on the harvesting of natural timber resources [12]. Since 1962, Bangladesh Forest Industries Development Corporation (BFIDC) has established 18 rubber gardens in three rubber-growing zones: Chattogram, Sylhet, and Madhupur/Tangail, encompassing an area of 15,452.7 hectares [13]. In addition, there are 26,031.99 hectares of private rubber tree plantations established in hilly areas [14]. Altogether, the public and private rubber tree plantations make up a huge potential supply to the furniture industries. The total use of rubberwood in Bangladesh was 3398 m³ in 2024, and most of it was used in the furniture industry [15]. Sawn rubberwood is nowadays utilized in producing chairs, tables, beds, wardrobes, sofa sets, doors, window frames, as well as plywood, hardboard, and solid moldings in Bangladesh. In 2022–2023, Bangladesh produced \$ 7.9 million worth of furniture using only rubberwood [16]. It is important to understand the physical and mechanical properties of rubberwood to identify the applicability of raw materials of different origins in furniture industries [17] and to improve the efficiency of material utilization.

The age of the vascular cambium and radial growth are key factors in regulating the maturation of wood. Juvenile wood, characterized by shorter fibers, lower density, and lower mechanical strength, is produced during the early stages of growth. After a certain age, the cambium gradually begins to produce mature wood with longer fibers, thicker cell walls, higher density, and

improved mechanical properties [18, 19]. The juvenile wood core is concentrated near the pith, running along the height of the tree, while mature wood is formed in the outer growth rings as the tree ages [20, 21]. As the basal stem develops earlier, it contains more mature wood, compared to the upper stem sections, which are mainly dominated by juvenile wood. Consequently, earlier studies reported butt logs with a big variation in average mechanical properties of tropical wood species since they contain both mature and juvenile wood. The basal portion of the mature stem in species such as teak (*Tectona grandis*), garjan (*Dipterocarpus* spp.), and eucalyptus (*Eucalyptus camaldulensis*) is dominated by mature wood, which has higher density, longer fiber length, and superior mechanical qualities [22–24]. This longitudinal variation causes a significant difference in physical and mechanical properties, which is acute when dried and green wood is compared due to differing moisture loss [25, 26]. Majumdar et al. [27] examined the effect of age and vertical position of the stem on the physical and mechanical properties of rubberwood in Bangladesh, but they did not consider the different seasoning conditions. Seasoning (drying) affects the properties of wood species in Bangladesh, with higher modulus of rupture (*MOR*) and modulus of elasticity (*MOE*) in seasoned *Gmelina arborea*, *Swietenia macrophylla*, and *Mangifera indica* than in green wood [28]. In most cases, dried wood is used rather than green wood, therefore comparing the characteristics of green and air-dried wood is critical for quantifying the effects of moisture loss on performance. Such comparisons are useful for understanding drying-induced changes, allow for precise prediction of service behavior (e.g., ability to retain its strength, resist deformation, and dimensional stability under varying moisture conditions), and facilitate the use of suitable design and grading values.

Several studies on the physical and mechanical properties of rubberwood have been carried out in Brazil and Southeast Asia. In Brazil, rubberwood has been suggested for potential use in furniture industries due to its relatively high basic density ($>0.540 \text{ g cm}^{-3}$), low volumetric shrinkage ($<10\%$), and medium to high compression strength parallel to the grain ($>40 \text{ MPa}$) [29, 30]. In India, wood density, *MOE*, *MOR*, and maximum compressive stress of rubberwood were identified as comparable with several other tropical wood species [31]. Physical and mechanical properties of hydrothermally, thermo-hygro-mechanically, and microwave heat-treated rubberwood were studied in Malaysia, Thailand, and Vietnam [6, 32, 33]. Based on these studies, the wood properties vary not only with species but also within the same species, among different geographical locations. However, there is a lack of studies on the

properties of rubberwood in Bangladesh. Chowdhury et al. [34] emphasized the research needs on physical and mechanical properties of lesser-used species like rubber, to diminish the pressure on heavily used species in the wood industries in Bangladesh.

To bridge the existing shortcomings in knowledge, this article investigates selected physical (density, moisture content, volumetric shrinkage) and mechanical (*MOR*, *MOE*, compressive strength, shear strength parallel to the grain, Janka hardness) properties of rubberwood (after the latex extraction period ended) in two seasoning conditions. In addition, differences between samples collected from four different geographical locations and three different stem heights (top, bottom, and middle) are considered, which provides species and region-specific mechanical property data for rubberwood, which is currently lacking in the literature.

Materials and methods

Study areas and site conditions

Four rubber gardens were randomly selected from three major rubber-growing zones (Chattogram, Sylhet, and Madhupur/Tangail) in Bangladesh for this study

(Fig. 1). Two gardens (*Datmara* rubber garden, Chattogram, and *Ramu* rubber garden, Cox's Bazar) were selected from the Chattogram rubber-growing zone, which is characterized by hilly terrain and favorable climatic conditions for rubber plantation. The *Santospur* rubber garden was chosen from the Madhupur/Tangail rubber-growing zone, which is part of the central plateau and exhibits relatively flat topography and loamy soil types. Finally, from the Sylhet rubber-growing zone, the *Shahjibazar* rubber garden was selected, and this is featured by undulating terrain and heavy rainfall, providing distinct growing conditions for rubber trees. The site conditions of the selected rubber gardens are stated in Table 1.

Cox's Bazar experiences an average annual rainfall of 3000–3500 mm and has temperatures ranging from 22–35 °C [35]. The soil is well-drained and mainly composed of sandy loam and loam with low organic content, with average pH levels ranging from 4.5 to 6.5. *Ramu*, Cox's Bazar has been classified as an “exposed coast” due to its intensive interaction with the sea and higher susceptibility to salinity, cyclone risks, and tidal movement [36].

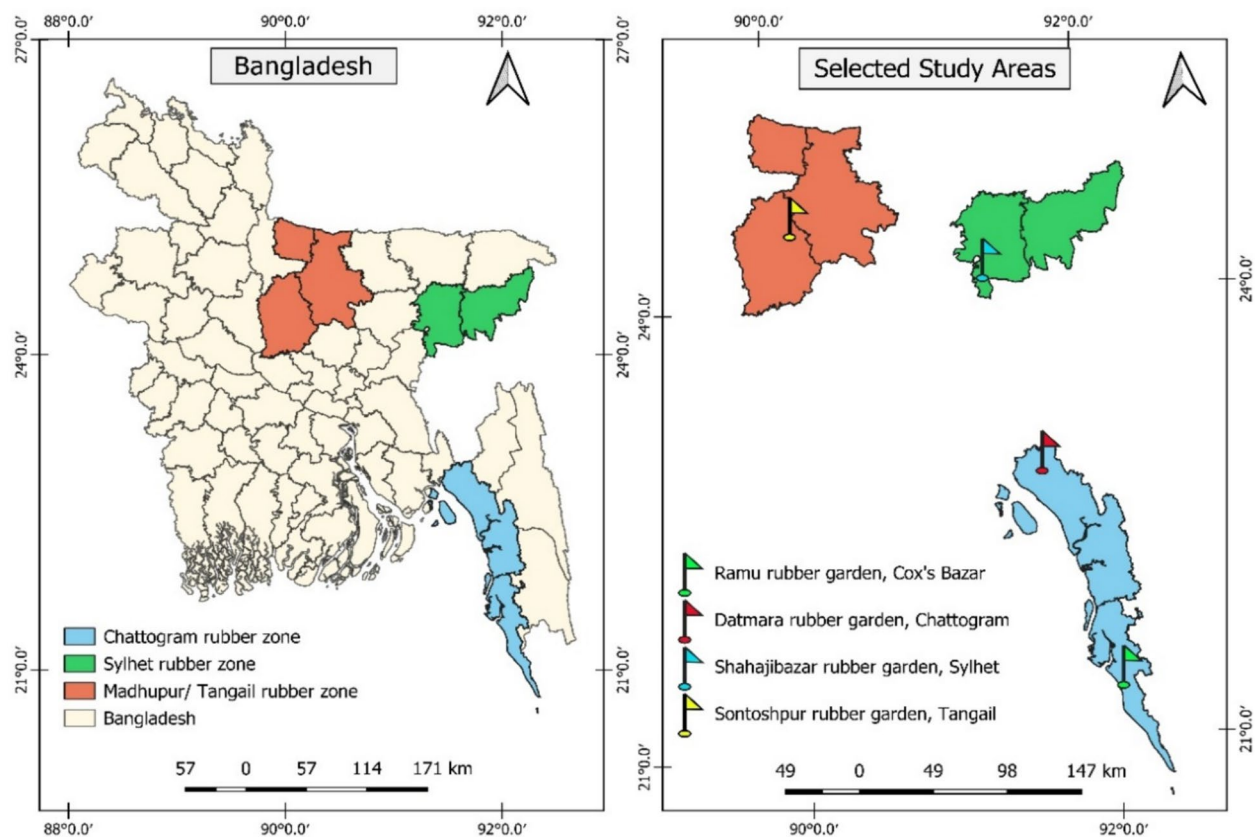


Fig. 1 Spatial distribution of the study sites across Bangladesh

Table 1 Site characteristics of the selected study sites in Bangladesh

	Chattogram	Cox's bazar	Sylhet	Tangail	Source
Geographic features	*AEZ 29 High to low hills with steep to rolling topography	AEZ 29 High to low hills with steep to rolling topography	AEZ 29 High to low hills with steep to rolling topography	AEZ 28 Medium–high land	[39]
Temperature (°C)	22–35	22–35	20–32	20–33	[35]
Rainfall (mm)	3000–4000	3000–3500	3000–5000	1500–2500	[35]
Elevation (m)	62.15	33.39	55.46	20.35	[40]
Soil type	Sandy loam to clay loam	Sandy loam and loam	Sandy loam to clay loam	Silt loams to silty clay loams	

* AEZ agro-ecological zone

Chattogram experiences an average annual temperature of 22–35 °C and annual rainfall of 3,000–4,000 mm, mainly during the monsoon months [35]. In 2017 and 2018, Chattogram experienced average rainfalls of 3661 mm and 2731 mm [37]. The soil is predominantly sandy loam to clay loam, deep and brown soils on low hills, with good drainage on sloping terrain and a moderate amount of organic matter. The pH levels range from 4.5 to 5.5 [38].

The Tangail rubber-growing zone experiences an average annual temperature of 20–33 °C and rainfall of approximately 1500–2500 mm [35]. The soils in this area are predominantly silt loams to silty clay loams on the ridges, and clay in the basins. Organic matter content is medium with a slightly decreasing trend [41]. pH of soils ranges from 3.96 to 5.11, suggesting the presence of very strongly to moderately acidic soils in the region [42].

The Sylhet rubber-growing zone experiences an average annual temperature between 20 °C and 32 °C and annual rainfall of 3000–5000 mm [35]. The soil characteristics are similar to those in the Chattogram rubber-growing zone.

Sample collection and preparation

Logs of three 32-year-old RRIM 600 rubber tree clones were collected from each of the four sites, making 12 sample trees (3 trees × 4 sites = 12) altogether. At each site, trees were first screened based on the straightness of the stem, absence of natural defects, and a minimum circumference of 70 cm at breast height. After the initial screening, three trees were randomly selected from the population of eligible trees. The selected trees were felled at 0.3–0.5 m above the ground and divided into three sections (top, middle, and bottom). The specimens for the bottom, middle, and top sections were collected at heights of 0.5–3.5, 3.5–6.5, and 6.5–9.5 m, respectively, with radii ranging from 11.1–12.7, 9.6–11.1, and 8.0–9.6 cm, respectively. Each log was sawn longitudinally through the pith, and the logs were then band-sawn into planks collected from approximately 4–12.7 cm radial

distance from the pith, depending on height. According to a study on rubberwood conducted in Brazil [43], juvenile wood extends approximately 4–5.5 cm from the pith, beyond which the mature wood zone begins. Therefore, while planks from the middle and bottom sections represent predominantly mature wood, those from the top portion contain a small fraction of late juvenile wood, due to their smaller radius. Sampling positions and plank dimensions were chosen to maximize the representation of mature wood where possible. The planks were cut slightly larger than the final specimen dimensions and were further reduced to the required sizes for each test using a surface planner, in accordance with the ASTM standards. A subset of specimens was tested immediately after the felling to assess their properties under their initial moisture content. The number of specimens tested for each property is presented (Table 2).

To measure the parameters under air-dry conditions, a second group of specimens was cut into nominal dimensions of 5.08 × 5.08 × 76.2 cm and stacked on top of each other in a climate chamber (temperature: 20–25 °C, relative humidity: 60–65%) until they reached constant mass, *i.e.*, equilibrium moisture content (EMC) of approximately 12%.

Data collection

Physical properties

Tests for physical properties included the moisture content (%), basic density (kg m⁻³), and volumetric shrinkage (%) (Eqs. 1–3; Table 3). Oven-drying was used to determine the moisture content. The specimens were dried at a constant temperature of 103 ± 2 °C, in a forced convection oven until they achieved a constant mass [44]. To measure the density, volumes of the green and air-dry specimens were measured using a digital caliper with 0.01 mm precision, and the volume of the oven-dried specimens was measured using the water immersion method after coating the wood blocks with a thin layer of hot paraffin to prevent moisture from entering the wood, taking care to remove it quickly to ensure only a thin

Table 2 Summary of specimens' distribution for the variables studied

Property	Seasoning condition	Sections	No. of specimens examined for one site	No. of specimens examined for four sites	Total no. of specimens examined per property
MC, ρ, VS	Green	Top	6	24	72
		Middle	6	24	
		Bottom	6	24	
	Air-dry	Top	6	24	72
		Middle	6	24	
		Bottom	6	24	
$MOR, MOE, C_{ }, C_{\perp}, S_{ }$ (Radial), $S_{ }$ (Tangential)	Green	Top	5	20	$60 \times 6 = 360$
		Middle	5	20	
		Bottom	5	20	
	Air-dry	Top	5	20	$60 \times 6 = 360$
		Middle	5	20	
		Bottom	5	20	
Janka hardness (Radial, Tangential, End)	Green	Top	6	24	$72 \times 3 = 216$
		Middle	6	24	
		Bottom	6	24	
	Air-dry	Top	6	24	$72 \times 3 = 216$
		Middle	6	24	
		Bottom	6	24	

MC moisture content, ρ density, VS volumetric shrinkage, MOR modulus of rupture, MOE modulus of elasticity, $C_{||}$ compression parallel to the grain, $C_{\perp}$ compression perpendicular to the grain, shear strength parallel to the grain ($S_{||}$, radial), shear strength parallel to the grain ($S_{||}$, tangential), side Janka hardness (radial, tangential), end Janka hardness)

Table 3 List of equations used in the study

No	Equation	Term definitions	Dimensions (cm ³) (R×T×L)	Reference
1	Moisture content, $MC = \frac{(m_M - m_0) \times 100}{m_0}$	m_M = Initial mass, m_0 = Oven-dry mass	$5.08 \times 5.08 \times 2.54$	[44]
2	Density, $\rho_M = \frac{m_M}{V_M}$	m_M = Mass of specimen at moisture content M, V_M = Volume of specimen at moisture content M	$5.08 \times 5.08 \times 2.54$	[44]
3	Volumetric shrinkage, $VS = \frac{V_M - V_0}{V_M} \times 100$	V_M = Volume of specimen at moisture content M, V_0 = Volume of specimen after oven drying	$5.08 \times 5.08 \times 2.54$	[26]
4	Modulus of rupture, $MOR = \frac{3P_{max}l}{2bd^2}$	P_{max} = Maximum force borne by the specimen loaded to failure l = Span of the test specimen b = Breadth of the test specimen d = Depth of the test specimen	$5.08 \times 5.08 \times 76.2$	[46]
5	Modulus of elasticity, $MOE = \frac{Pl^3}{4bd^3\Delta}$	P = Force at the limit of proportionality Δ = Deflection at the limit of proportionality	$5.08 \times 5.08 \times 76.2$	[46]
6	Compression parallel to the grain, $C_{ } = \frac{P_{max}}{A}$	P_{max} = Maximum force borne by specimen loaded to failure A = Area of cross section of the specimen	$5.08 \times 5.08 \times 20.32$	[46]
7	Compression perpendicular to the grain, $C_{\perp} = \frac{P}{A}$	P = Force at the limit of proportionality A = Loaded bearing area of the specimen surface	$5.08 \times 5.08 \times 15.24$	[46]
8	Shear strength (R/T), $\frac{P_{max}}{A}$	P_{max} = Maximum force borne by the specimen loaded to failure A = Area of radial/tangential section of the specimen	$5.08 \times 5.08 \times 6.35$	[47]
9	Side Janka hardness, $\frac{H_r + H_t}{2}$	H_r = Radial Hardness H_t = Tangential Hardness	$5.08 \times 5.08 \times 15.24$	[48]
10	End Janka hardness, Load average		$5.08 \times 5.08 \times 15.24$	[48]

R radial, L longitudinal, T Tangential denote anatomical sections of the wood specimen

coating so that the change in dimensions is negligible [44, 45]. Volumetric shrinkage was evaluated as a percentage of volume change from green to air-dry conditions and from air-dry to oven-dry conditions.

Mechanical properties

We examined the mechanical properties of rubberwood: modulus of rupture (*MOR*, MPa), modulus of elasticity (*MOE*, MPa), compressive strength parallel to the grain ($C_{||}$, MPa), compressive strength perpendicular to the grain ($C_{\perp}$, MPa), shear strength in radial and tangential sections (MPa), and Janka hardness (N). Compressive tests perpendicular to the grain were conducted using a partial-area loading configuration, in which the load was applied through a metal bearing plate 2 inch (5.08 cm) in width placed across the upper surface of the specimen at equal distances from the ends. All tests were performed following the ASTM standards for measuring small, clear wood specimens. The specimen sizes and equations for each parameter are summarized in Table 3.

Data processing and analysis

The mean values from tests were determined in different seasoning conditions, within-stem locations, and sites for all the variables studied. A *t*-test was conducted to identify significant differences between the green and air-dry conditions of wood for each site. One-way analysis of variance (ANOVA) followed by post hoc (Tukey's HSD) was performed to identify whether the mean values of specimens from different within-stem locations (top, middle, bottom) differ from each other. Moreover, one-way ANOVA, followed by posthoc (Tukey's HSD) test was performed to identify pairwise significant differences between the four gardens or sites. The data were analyzed using Microsoft Excel and the Statistical Package for the Social Sciences (SPSS, version 26).

Results

Physical properties

Moisture content, density, and volumetric shrinkage

The moisture content of the green rubberwood specimens ranged from 30.0 to 35.1%. After air-drying, all specimens reached an EMC of approximately 12%. The average densities in green and air-dry conditions were 708.7 and 634.1 kg m⁻³, respectively. The samples across all locations displayed a shrinkage of 4.3–5.0% (Table 4) from air-dry to oven-dry conditions. Irrespective of the seasoning conditions, the density was highest in the samples collected from Tangail and the lowest in the specimens from Cox's Bazar (Fig. 2).

Mechanical properties

Modulus of rupture (*MOR*) and modulus of elasticity (*MOE*)

Expectedly, both *MOR* and *MOE* of rubberwood were significantly ($p \leq 0.05$) higher in air-dry condition than in green condition (Table 5). Regarding the within-stem location, the bottom section showed significantly ($p \leq 0.05$) higher *MOR* and *MOE* compared to the top and middle sections (Table 5).

In terms of the site differences, *MOR* of the specimens collected from Chattogram was significantly higher ($p \leq 0.05$) compared to the specimens collected from Sylhet in green condition and those collected from Cox's Bazar in dry condition (Fig. 3a). The *MOE* of the specimens collected from Chattogram was significantly higher ($p \leq 0.05$) compared to those collected from the other three gardens (Fig. 3b).

Compressive strength and shear strength parallel to the grain

The compressive strength parallel to the grain ($C_{||}$) and shear strength parallel to the grain (both radial and tangential sections) were significantly ($p \leq 0.05$) higher in air-dry specimens than in green specimens

Table 4 Physical properties (standard deviation) of green and air-dry rubberwood collected from four different rubber plantation sites in Bangladesh

Sections of specimens collected	Moisture content (%)		Density (kg m ⁻³)		Volumetric Shrinkage (%)	
	Green	Air-dry	Green	Air-dry	Green to air-dry	Air-dry to oven-dry
Top	35.1 ^{ap} (4.4)	11.8 ^{bp} (1.1)	694.1 ^{aq} (31.0)	628.6 ^{bp} (30.2)	13.8 ^{ap} (3.4)	4.3 ^{bp} (1.1)
Middle	32.3 ^{apq} (4.2)	11.8 ^{bp} (1.4)	702.8 ^{aq} (25.4)	632.6 ^{bp} (32.2)	13.0 ^{ap} (3.1)	5.0 ^{bp} (1.1)
Bottom	30.0 ^{aq} (5.1)	11.7 ^{bp} (1.2)	729.2 ^{ap} (23.2)	641.2 ^{bp} (24.6)	12.0 ^{ap} (2.5)	4.3 ^{bp} (1.3)
Mean	32.5 ^a (6.15)	11.8 ^b (1.2)	708.7 ^a (25.7)	634.1 ^b (33.2)	12.9 ^a (3.3)	4.5 ^b (1.6)

Small letters (*a*, *b*) in the same row and (*p*, *q*, *r*) in the same column indicate significant difference between green and air-dry conditions and among the three sections, respectively, at $p \leq 0.05$

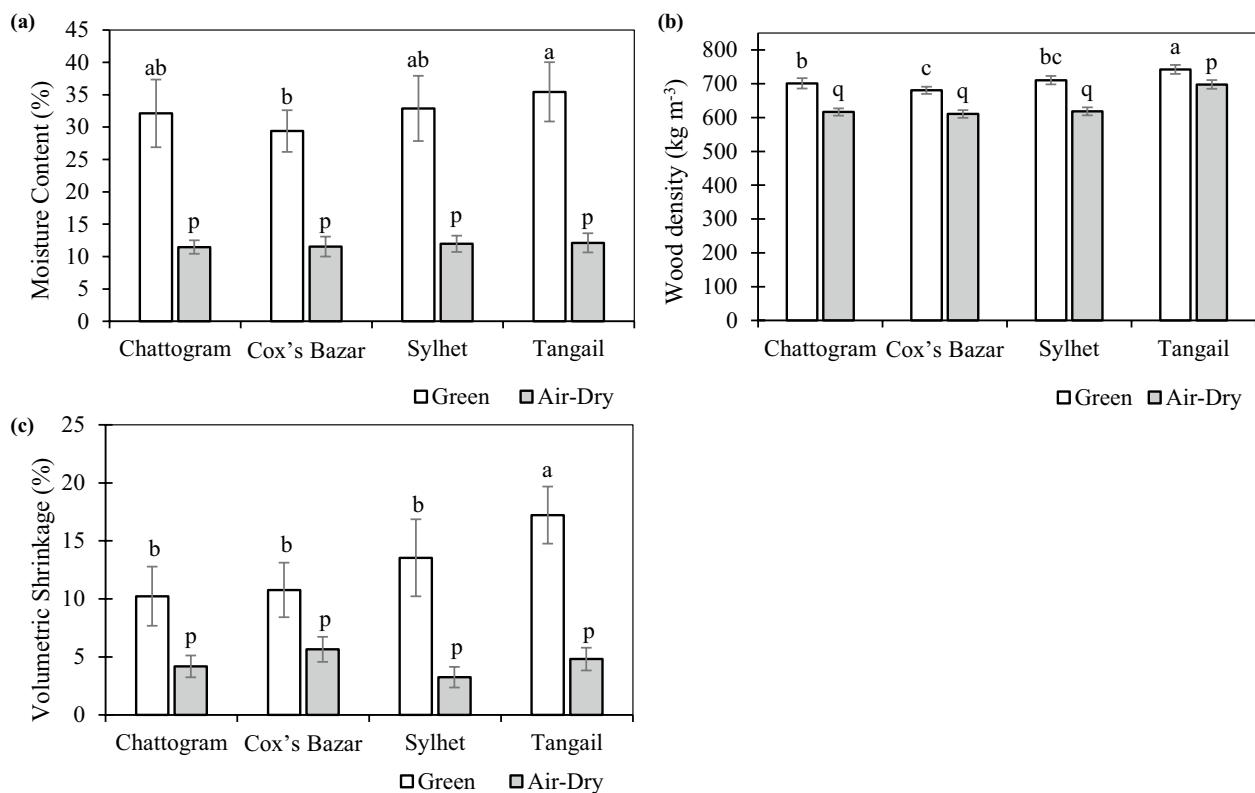


Fig. 2 Mean values of **a** moisture content (%), **b** density (kg m⁻³), and **c** volumetric shrinkage (%) across top, middle, and bottom sections of green and air-dry rubberwood collected from four different sites in Bangladesh. Error bars represent standard deviations (SD). Small letters (a, b, c, d) for green wood and (p, q, r, s) for air-dry wood on the bar indicate statistically significant difference among four sites at $p \leq 0.05$

Table 5 Mean values (standard deviations) of modulus of rupture (MOR, MPa) and modulus of elasticity (MOE, MPa) of the top, middle, and bottom sections of green and air-dry rubberwood collected from four different sites in Bangladesh

Section	MOR		MOE	
	Green	Air-dry	Green	Air-dry
Top	48.0 ^{br} (2.9)	64.6 ^{ar} (1.6)	8585.8 ^{br} (911.3)	10,809.6 ^{aq} (827.9)
Middle	51.6 ^{bq} (4.3)	66.8 ^{aq} (1.1)	9806.4 ^{bq} (1401.2)	11,470.0 ^{aq} (1288.5)
Bottom	57.3 ^{bp} (2.7)	69.2 ^{ap} (1.4)	11,081.8 ^{bp} (933.8)	12,603.0 ^{ap} (1086.9)
Mean	52.3 ^b (2.5)	66.9 ^a (2.3)	9824.7 ^b (1495.5)	11,627.5 ^a (1301.4)

Small letters (a, b) in the same row and (p, q, r) in the same column indicate statistically significant difference between green and air-dry conditions and among the three sections, respectively, at $p \leq 0.05$

(Table 6). Compression strength perpendicular to the grain ($C_{\perp}$) did not differ significantly between the air-dry and green specimens from the top and middle log sections. Specimens from the bottom section showed

significantly ($p \leq 0.05$) higher compressive and shear strength compared to the top and middle sections (Table 6).

Across sites, the $C_{\parallel}$ values of green specimens were higher ($p \leq 0.05$) in the specimens collected from Sylhet than those from the other three sites. In air-dry conditions, the $C_{\parallel}$ of rubberwood collected from Tangail and Cox's Bazar was higher ($p \leq 0.05$) than that collected from the other two sites (Fig. 3c). The $C_{\perp}$ values of air-dried specimens from Sylhet and Chattogram were higher ($p \leq 0.05$) than those from the other two sites. In green conditions, the mean $C_{\perp}$ of specimens collected from Sylhet was higher ($p \leq 0.05$) than that from the other three sites (Fig. 3d). For shear strength parallel to the grain, both radial and tangential sections' shear strength were higher ($p \leq 0.05$ for both) in specimens from Sylhet and Chattogram compared to the specimens from the other two sites (Figs. 3e, f).

Janka hardness

The side and end Janka hardness of air-dry specimens were higher ($p \leq 0.05$) than those of the green ones. The hardness of the bottom specimens was higher ($p \leq 0.05$) than the top and middle specimens (Table 7). Both side

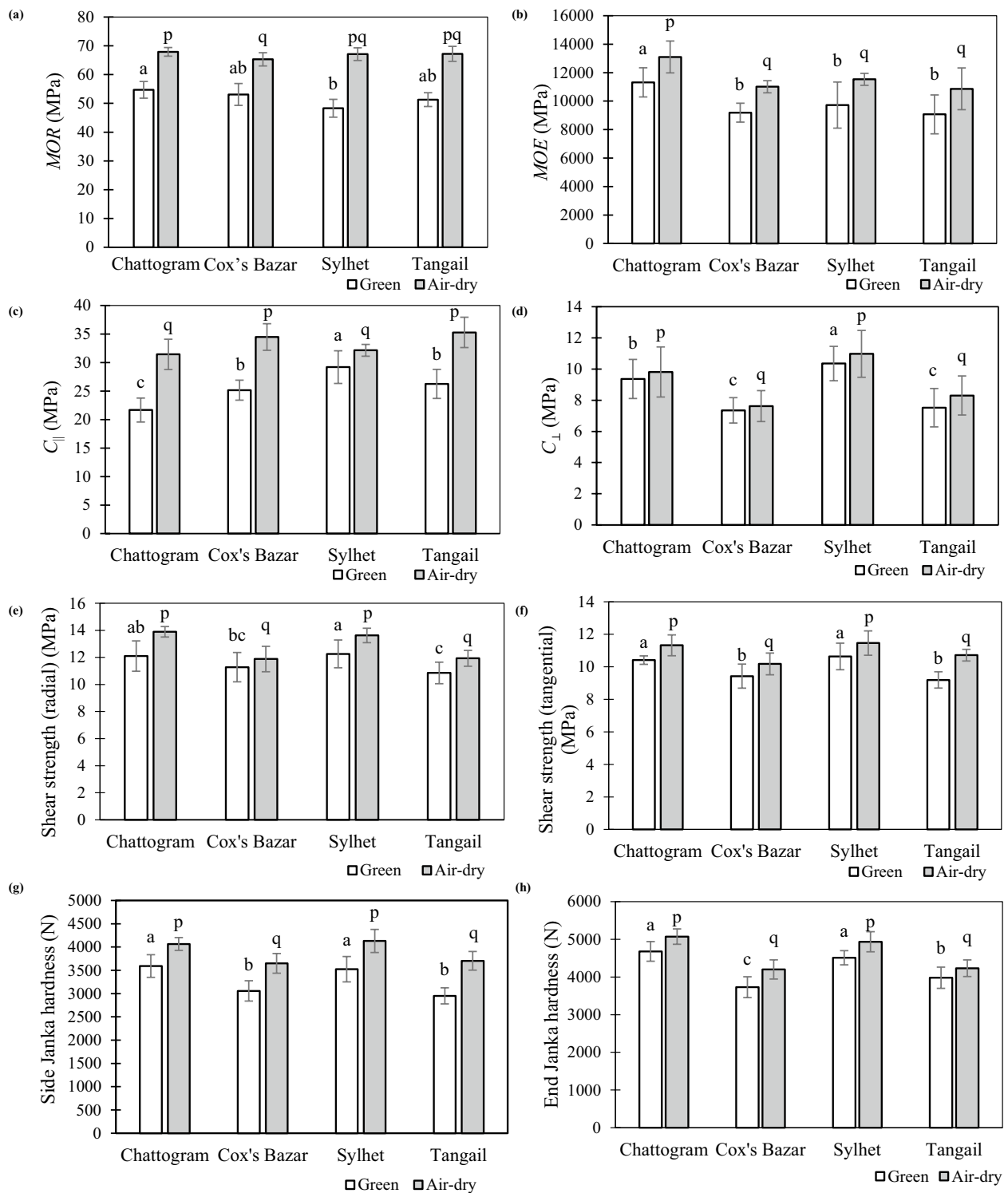


Fig. 3 Mean values of **a** modulus of rupture (MOR, MPa), **b** modulus of elasticity (MOE, MPa), **c** compression strength parallel to the grain ($C_{||}$, MPa), **d** compression strength perpendicular to the grain ($C_{\perp}$, MPa), **e** shear strength parallel to the grain in radial section (MPa), **f** shear strength parallel to the grain in tangential section (MPa), **g** side Janka hardness (N), and **h** end Janka hardness (N) across top, middle, and bottom sections of green and air-dry rubberwood collected from four different sites in Bangladesh. Error bars represent standard deviations (SD). Small letters (a, b, c, d) for green wood and (p, q, r, s) for air-dry wood on the bar indicate statistically significant difference among four sites at $p \leq 0.05$

Table 6 Mean values of compressive strength (MPa) and shear strength parallel to the grain (MPa) with standard deviation (in parentheses) of the top, middle, and bottom sections of rubberwood collected from four different sites in Bangladesh

Section	Compression parallel to grain ($C_{ }$)		Compression perpendicular to grain ($C_{\perp}$)		Shear strength parallel to grain in radial section		Shear strength parallel to grain in tangential section	
	Green	Air-dry	Green	Air-dry	Green	Air-dry	Green	Air-dry
Top	23.4 ^{br} (2.6)	30.0 ^{aq} (2.1)	7.5 ^{aq} (1.3)	7.7 ^{ar} (1.2)	10.5 ^{br} (1.0)	12.4 ^{aq} (1.3)	9.3 ^{bq} (0.9)	10.3 ^{ar} (1.0)
Middle	24.9 ^{bq} (3.4)	33.6 ^{aq} (3.3)	8.6 ^{ap} (1.5)	9.2 ^{aq} (1.4)	11.7 ^{bq} (0.8)	12.8 ^{apq} (0.9)	10.0 ^{bp} (1.1)	10.9 ^{aq} (0.6)
Bottom	28.4 ^{bp} (3.0)	36.3 ^{ap} (2.9)	9.7 ^{bp} (1.4)	10.7 ^{ap} (1.7)	12.7 ^{bp} (0.8)	13.3 ^{ap} (1.0)	10.4 ^{bp} (0.8)	11.5 ^{ap} (0.7)
Mean	25.5 ^b (2.6)	33.3 ^a (3.0)	8.6 ^a (1.7)	9.2 ^a (1.9)	11.6 ^b (1.1)	12.8 ^a (1.5)	9.9 ^b (1.0)	10.9 ^a (1.1)

Small letters (*a, b*) in the same row and (*p, q, r*) in the same column indicate statistically significant difference between green and air-dry conditions and among the three sections, respectively, at $p \leq 0.05$

Table 7 Mean values of side Janka hardness (N) and end Janka hardness (N) (standard deviation in parentheses) of the top, middle, and bottom sections of rubberwood collected across four different sites in Bangladesh

	Side Janka hardness		End Janka hardness	
	Green	Air-dry	Green	Air-dry
Top	3014.0 ^{br} (199.1)	3640.3 ^{ar} (210.6)	3937.5 ^{br} (417.5)	4287.2 ^{ar} (413.6)
Middle	3273.1 ^{bq} (226.9)	3866.0 ^{aq} (252.2)	4236.0 ^{bq} (397.5)	4599.3 ^{aq} (436.7)
Bottom	3555.9 ^{bp} (272.9)	4161.4 ^{ap} (208.0)	4520.7 ^{bp} (363.3)	4949.2 ^{ap} (399.4)
Mean	3281.1 ^b (302.3)	3889.3 ^a (255.5)	4231.4 ^b (435.9)	4611.9 ^a (478.8)

Small letters (*a, b*) in the same row and (*p, q, r*) in the same column indicate statistically significant difference between green and air-dry conditions and among the three sections, respectively, at $p \leq 0.05$

and end hardness of specimens from Chattogram and Sylhet were higher ($p \leq 0.05$) than that of specimens from the two other sites (Fig. 3g).

Discussion

In this study, we analyzed several physical properties (density, moisture content, volumetric shrinkage, *MOR*, *MOE*, compressive strength, shear strength parallel to the grain, Janka hardness) of rubberwood to investigate how they differ between dry and green wood, vertical positions in the stem, and across different regions in Bangladesh.

Wood density, moisture content, and volumetric shrinkage

In all geographical locations, the *MC* of green rubberwood specimens was approximately 3 times higher *MC* than that of air-dry ones. In terms of the within-stem

location, the top section had, on average, 17% higher *MC* than the bottom section. Anatomical variation along the stem may partly account for this difference in *MC*. Several vessel traits show significant variation with height, with the lowest vessel diameter occurring at the base [49], which shows a negative correlation with vessel frequency, suggesting that fewer vessels lead to larger vessel diameters at the top section [50, 51]. Previous studies have associated vessel diameter with higher moisture content, as larger conduits can store and transport greater volumes of water [50, 52]. Furthermore, vessel lumen fraction, defined as the product of vessel size and vessel number, has been found to cause a disproportionate increase in xylem hydraulic conductivity, resulting in greater water volume within the vessels [53]. All of these vessel traits might account for the higher moisture content in the top section. Among the four sites, Tangail showed the highest *MC* in green rubberwood, exceeding that of Cox's Bazar by 21%.

In this study, the mean green density (708.7 kg m^{-3}) was higher than that reported (560 to 650 kg m^{-3}) in several studies on Asian rubberwood [6, 7, 31, 54, 55]. The mean AD density of 634.1 kg m^{-3} is similar to 640 kg m^{-3} of Malaysian rubberwood at 17.2% *MC* [56], but ca. 6–7% lower than in the two different *Hevea* clones reported by Junior et al. [29]. This difference can be attributed to the differences in moisture levels and clones of the rubberwood specimens tested. The average AD density obtained in this study was 7.5% and 11.2% higher than those (590 and 570 kg m^{-3}) of Teak (*Tectona grandis*) and Mahogany (*Swietenia macrophylla*), respectively, in Bangladesh [57, 58]. Moisture content is the key factor in measuring density due to the hygroscopicity of wood [59]. Wood anatomy and, subsequently, its density are also influenced by environmental factors, growth conditions, and

management practices [60], creating considerable differences within and between logs.

Wood shrinkage generally begins at about the fiber saturation point, when most bound water is removed from the cell walls and cavities, and continues until the wood is completely dry [61]. In this study, shrinkage from the green to AD condition was nearly 3 times higher than that observed in the AD to OD (oven-dry) condition, which can be attributable to the larger removal of bound water during the green to AD stage. The average AD shrinkage found in this study (4.5%) is similar to that (3.6–5.8% shrinkage) of Teak and Mahogany found in India and Bangladesh [57, 58, 62, 63], showing similar dimensional stability to these commonly used hardwood species. High-density wood generally shrinks more than low-density wood, as it contains a greater volume of water at the same moisture level [64, 65]. Consistent with this, we found that green wood samples from the Tangail site shrank 1.3–1.7 times more than those collected from Chattogram and Sylhet, despite having statistically similar moisture contents. This can be explained by the difference in agro-ecological zone, soil, rainfall, and elevation of Tangail than the other three sites (Table 1). Tangail's lower annual rainfall (1500–2500 mm) and finer-textured soils (silt loams to silty clay loams) may favor slower growth and higher wood density, resulting in increased shrinkage. These findings emphasize the need to take site circumstances into account when evaluating the dimensional stability of rubberwood for industrial and structural applications.

Mechanical properties

Strength across seasoning conditions and within-stem locations

MOE, bending strength (*MOR*), and compression strength parallel to the grain and perpendicular to grain value of AD rubberwood were, respectively, 18.4, 28, 30.5, and 7% higher compared to the green specimens. Hardness and shear strength of wood were also 9–19% higher in AD conditions than in green conditions. These strength gains are consistent with the well-documented effect of moisture reduction on wood mechanics, since drying strengthens hydrogen bonding between microfibrils and cell wall stiffness [26, 66–68]. Moreover, *MOR* values of AD wood (64.6–69.2 MPa) detected in this study are close to those (62.6–67.8 MPa) reported by Herawati et al. [69] and Majumdar et al. [27] in AD rubberwood in Indonesia and Bangladesh. However, compression strength perpendicular to the grain ($C_{\perp}$) (9.2 MPa) was nearly twice as high (4.6–5.3 MPa) as reported by Majumdar et al. [27]. Both studies determined $C_{\perp}$ using the same ASTM standard under air-dry conditions, suggesting that differences in calculation

procedures are unlikely to explain the discrepancy. The trees used in the present study (32 years old) were of similar age to those examined by Majumdar et al. [27] (30 years old). However, the reference study does not specify the radial position of specimens or the sampling strategy within the stem. Because $C_{\perp}$ is sensitive to density and within-tree variation, differences in specimen characteristics may have contributed to the higher values observed in the present study.

In terms of within-stem height location, the green specimens from the bottom logs had, on average, 24–32% higher mechanical properties than those from the top and middle logs. In AD rubberwood, the respective differences were 8.6–19%, indicating the reduction in vertical variability after drying shows that moisture homogeneity may help to minimize strength gradients throughout the stem. The compressive strength parallel to grain of rubberwood in the bottom Sect. (36.3 MPa) was higher than that (31.1 to 32.6 MPa) reported by Majumdar et al. [27] and Mohd Shukari [56]. The *MOE* of the bottom Sect. (12,603 MPa) was also higher than that (8800–10400 MPa) reported by Riyaphan et al. [55]. Height-related variation in *MOE*, *MOR*, $C_{||}$, and $C_{\perp}$ has been reported in, e.g., rubberwood [27], *Pinus pinaster* [70], and *Pinus patula* [71], highlighting that this pattern of variation is not species-specific but inherent to tree growth.

In this study, the mean *MOR* (66.9 MPa) of rubberwood is approximately 1.5 times less than that of teak from India and Bangladesh (94 and 99 MPa) [57, 62]. The *MOE* (11,627.5 MPa) is similar to that (11,670 MPa) of Indian teak and 9% less than the Bangladeshi (12,846.7 MPa) teak [57, 62]. We also found that rubberwood has 1.1–1.6 times higher *MOE* (7119.6 vs. 9806.7 MPa) and *MOR* (49.7 vs. 61.8 MPa) than mahogany in India and Bangladesh [58, 72]. However, the radial section's shear strength of rubberwood (12.8 MPa) was 35% higher than that of teak (9.5 MPa). Other parameters like compressive strength and hardness are lower in rubberwood than in teak and mahogany [57, 58, 62, 72]. High temperature drying has been found to enhance the mechanical properties of rubberwood more than teak [11, 73]. This suggests that, with higher density and strength properties comparable to those of teak and mahogany, rubberwood can serve as a suitable replacement for these species. Rubberwood's eco-friendly nature, fairly acceptable durability, aesthetic appeal, along with its high machinability and ease of finishing, also contribute to its potential in the furniture industry [74].

Strength across sites

In our study, the mechanical properties of rubberwood collected from Chattogram and Sylhet were found to

be higher than those collected from the other two sites. Related to bending properties, the *MOR* of green specimens collected from Chattogram was 13% higher than that of green specimens from Sylhet. Similarly, the *MOR* of air-dry specimens from Chattogram was 4% higher than the *MOR* of Cox's Bazar's specimens. The *MOE* of rubberwood from Chattogram was 16–25% and 14–21% higher in green and air-dry conditions, respectively, compared to the other three sites. Specimens from Sylhet showed the highest compressive strength among the three sites. For instance, the compression strength parallel to the grain ($C_{||}$) value for green specimens from Sylhet (29.2 MPa) was 10–36% higher than that of specimens from the other three sites. The compression strength perpendicular to the grain ($C_{\perp}$) of specimens from Sylhet (10.4–11.0 MPa) was 38–41% and 32–44% higher for green and air-dry specimens, respectively, than those from Cox's Bazar and Tangail. This may be due to the compact cellular structure of wood samples collected from Sylhet, showing high resistance to compressive loading; however, without direct measurements of anatomical traits or soil and environmental variables, the underlying causes of site-specific variations cannot be conclusively ascertained. In terms of general structural behavior, the limiting factor against radial compressive load is the weakest part of the cellular structure (usually earlywood), whereas the tangential and longitudinal compressive properties depend on the strongest section (usually latewood cell walls).

The radial section's shear strength of wood collected from Chattogram and Sylhet in green (12.1, 12.3 MPa) and AD condition (13.9, 13.6 MPa) was 7.3–13% (green) and 14.2–17.9% (AD) higher than that of specimens from Cox's Bazar and Tangail. A similar trend was observed for shear strength in the tangential section. Related to withstanding the tear and wear, the side Janka hardness of wood collected from Chattogram and Sylhet was 15.2–21.7% (green) and 9.8–13.2% (AD) higher than Cox's Bazar and Tangail. Similarly, the end Janka hardness of specimens collected from Chattogram and Sylhet was 13.3–25.5% (green) and 16.6–20.8% (AD) higher than that of specimens from Cox's Bazar and Tangail. These values of side hardness (38.9 MPa) and end hardness (46.1 MPa) are similar to the findings of Mohd Shukari [56] and Naji et al. [75] for Malaysian rubberwood, growing under similar temperature and rainfall conditions to Sylhet and Chattogram in Bangladesh.

Overall, the specimens from Chattogram and Sylhet rubber gardens demonstrated higher strength values, which may indicate more favorable growth conditions, including moderate soil fertility and adequate moisture availability (see Table 1). Conversely, Cox's Bazar and Tangail exhibited comparatively lower strength values,

which may be associated with differences in soil nutrients, moisture availability, and local environmental stressors. The coastal proximity of Ramu rubber garden in Cox's Bazar may expose the trees to higher salinity, potentially affecting wood density and strength. Salinity negatively impacts soil properties [76], seed germination, crop development, and productivity of rubber trees [77–79]. Latex production and dry matter (shoot and root weight) of the guayule plant have also been reported to decrease as salinity increased [80]. Although these findings support the possibility of salinity-related effects on rubberwood strength, more site-specific research is yet to investigate the level of salinity and associated soil factors directly influencing mechanical properties in coastal rubber plantations.

Despite higher wood density in Tangail, the mechanical properties were not superior, possibly due to intercropping of rubber plantations with pineapple and other crops. The practice of intercropping in rubber plantations may lead to competition for soil nutrients, significantly reducing the growth of diameter at breast height (DBH), height, and crown width of rubber trees compared to a monoculture of rubber trees [81, 82]. Additionally, existing research indicates that the soil nutrient levels of Tangail (Madhupur tract) are below the optimal level [83, 84].

The regional difference observed in this study demonstrates the potential for a regional distribution of rubberwood for specific end uses. Rubberwood from Chattogram and Sylhet may be more suitable for structural components, furniture frames, or load-bearing applications, due to higher strength and stiffness, while those from Tangail and Cox's Bazar can be used in panel products, interior furnishing, engineered wood products, laminated panels, composite boards, or other non-load-bearing purposes. Such an application can improve resource efficiency without further treatments. However, technological advancements in the field of seasoning and chemical treatments have substantial potential to improve the strength of rubberwood procured from Tangail and Cox's Bazar as well. Effective use of rubberwood for manufacturing furniture and other purposes would reduce pressure on traditional timber species, reduce timber imports, and have a positive impact on the environment.

Based on the results, it is obvious that rubberwood has untapped potential in the woodworking sector. However, the variability of rubberwood material properties should be more thoroughly considered in order to realize the full potential of plantation wood. It is also important to investigate the effect of salinity as an environmental stressor on the degradation of rubberwood quality, particularly in the Cox's Bazar region. Melatonin [79] and endophytic

bacteria [78] were found to improve salt stress tolerance in rubber tree seedlings by lowering chlorophyll degradation and H_2O_2 accumulation in leaves. A deeper understanding of the tree-crop interaction in rubber plantations is expected to improve the productivity in the Tangail rubber-growing zone.

Conclusions

The study investigated the variability of the physical and mechanical properties of rubberwood based on seasoning conditions, stem height, and across four sites located in the Chattogram, Sylhet, and Tangail rubber growing zones of Bangladesh. The properties were, as a rule, better in the bottom logs than in the middle and top logs. Furthermore, samples from Chattogram and Sylhet exhibited higher values in *MOE*, *MOR*, compression strength, shear strength, and Janka hardness. *MOE* and *MOR* values of rubberwood were found to be higher than those of, e.g., mahogany from Bangladesh or India. These findings suggest the potential of rubberwood for structural applications.

Rubberwood, being a sustainable resource, possesses promising prospects for its future utilization in Bangladesh's timber industry. The availability of rubberwood logs can be seen as an advantage to the wood industry, particularly with the ongoing enforcement of a ban on logging in natural forests and the resulting shortage of timber. The results of this study contribute to formulating rubberwood management, harvesting, and utilization policies and practices.

Abbreviations

AD	Air-dry
AEZ	Agro-ecological zone
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
BFIDC	Bangladesh Forest Industries Development Corporation
DBH	Diameter at breast height
EMC	Equilibrium moisture content
MC	Moisture content
MOE	Modulus of elasticity
MOR	Modulus of rupture
OD	Oven-dry
SD	Standard deviation
VS	Volumetric shrinkage

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Author contributions

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Data availability

Data will be made available on request.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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