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Comprehensive Analysis of Physical, Mechanical, Wettability, Shear, and Bonding Performance Properties of Rubberwood Various Trunk Diameters and Radial Positions Bonded with Various Adhesives for Sustainable Engineered Timber Construction: Bibliometric and Experimental Insights toward the Sustainable Development Goals (SDGs)

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ABSTRACT

This study presents a comprehensive analysis of the physical, mechanical, wettability, shear, and bonding performance properties of rubberwood within and between trunks of various diameters bonded with different adhesives for sustainable engineered timber construction. Rubberwood samples from trunks of different sizes were tested for density, modulus of rupture, modulus of elasticity, compressive strength, shear strength, and wettability. Polyvinyl acetate (PVAc) and polyurethane (PUR) adhesives were applied under varying clamping pressures to evaluate bonding strength and wood failure behavior. The results revealed minimal variation in physical and mechanical properties across radial positions and trunk diameters, while PVAc achieved slightly higher bonding efficiency. Wettability remained stable across zones and surfaces. A bibliometric analysis highlighted increasing global interest in rubberwood and bio-based materials for sustainable construction, emphasizing its relevance to the Sustainable Development Goals (SDGs) and its potential as a renewable material for green innovation.

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1. INTRODUCTION

The rubber tree is one of the most important economic crops available worldwide, especially in tropical regions. In Thailand, the plantation area of the rubber tree is approximately 4 million hectares, which represents around 25% of the global plantation area (see http://forestinfo.forest.go.th/). Rubber trees are primarily cultivated for latex production. However, after approximately 25–30 years, their latex yield declines to an uneconomical level, prompting replantation. The trunks of rubber trees are then transported to rubberwood industries for lumber production. Approximately 3 million cubic meters of rubberwood lumber are produced in Thailand each year, and nearly 90% of this production is exported for furniture manufacturing.

Over the past five years, Thai rubberwood industries have sought new opportunities beyond furniture production, such as utilizing rubberwood as a construction material. Recently, rubberwood has been increasingly used to manufacture engineered wood products, particularly glued laminated timber (glulam) and cross-laminated timber (CLT) (Nadir & Nagarajan 2014; Srivaro *et al.,* 2021; Adnan *et al.,* 2021; Hadi *et al.,* 2021; Srivaro *et al.,* 2022). Both products have demonstrated superior mechanical performance compared to conventional softwood-based materials. Consequently, the development of engineered timber from rubberwood has become a focal point of Thailand's wood industry, supporting commercialization and sustainable utilization of this resource.

To manufacture high-performance engineered wood, understanding the fundamental physical, mechanical, and bonding characteristics of the raw material is crucial. Rubberwood, a hardwood species, is an orthotropic material at the macroscopic level. At the microscopic scale, variations in wood cell structure are observed radially and vertically along the trunk (Onakpoma *et al.,* 2023). These anatomical differences can influence the mechanical performance and bonding behavior of the wood. Several studies have explored rubberwood's fundamental properties and bonding characteristics (Sulaiman *et al.,* 2009; Sik *et al.,* 2009; Naji *et al.,* 2014; Phumichai *et al.,* 2015; Riyaphan *et al.,* 2015; Srivaro *et al.,* 2021; Srivaro *et al.,* 2022); however, a comprehensive evaluation of how property variations occur within a trunk, between different trunk sizes, and how this influence bonding performance is still lacking. This knowledge gap limits the standardization and efficient use of rubberwood in structural applications.

In recent years, the global research landscape has shown increasing interest in sustainable and renewable materials for construction. A bibliometric mapping of Scopus-indexed publications from 2015 to 2025 indicates a strong upward trend in studies focusing on engineered timber, bio-based composites, and rubberwood utilization. These studies are often aligned with the United Nations (UN) Sustainable Development Goals (SDGs) (i.e., SDG 9: Industry, Innovation, and Infrastructure; SDG 12: Responsible Consumption and Production), reflecting a shift toward resource-efficient and environmentally responsible construction materials. Within this trend, rubberwood emerges as a promising renewable resource within the circular bioeconomy, supporting green innovation in tropical regions.

This study investigated the physical and mechanical properties of rubberwood and its bonding performance concerning the position within trunks of different diameters. The effects of sawing pattern, adhesive type, and clamping pressure were also examined to determine their influence on bonding strength. In addition, a bibliometric approach was adopted to contextualize the experimental findings within global research trends on sustainable engineered timber development. Detailed analysis in this study is presented in **Table 1**.

Table 1. Overview of the Analyses Conducted in This Study.

No.	Type of Analysis	Focus Parameters / Variables	Method / Standard	Key Findings
1	**Physical Analysis**	Density (kg/m³)	ISO 13061-3	Density was consistent within and between trunks of various diameters.
2	**Mechanical Analysis**	Modulus of Rupture (MOR), Modulus of Elasticity (MOE), Compressive Strength, Shear Strength	ISO 13061-8, ISO 13061-17	Mechanical properties showed negligible variation across radial positions and trunk sizes.
3	**Wettability Analysis**	Contact Angle on Radial–Longitudinal and Tangential–Longitudinal Surfaces	Sessile Drop Method using Contact Angle Goniometer	Wettability was slightly higher on radial surfaces but remained stable across zones.
4	**Bonding Performance Analysis**	Block Shear Strength, Wood Failure Ratio	ASTM D905, One-Way ANOVA	PVAc showed slightly higher bonding efficiency than PUR under all pressures and directions.
5	**Adhesive Comparison Analysis**	PVAc vs. PUR Adhesives, Clamping Pressure (1 MPa and 3 MPa), Bonding Direction	Hydraulic Pressing Method	Adhesive type and clamping pressure had no significant influence on bonding strength.
6	**Bibliometric Analysis**	Publication trends, keyword networks, and thematic clusters related to rubberwood and sustainable construction	Scopus Database, VOSviewer, Biblioshiny	Global research shows increasing attention to rubberwood as a sustainable material aligned with the SDGs.

The novelty of this study lies in the integration of bibliometric analysis and experimental testing to establish a comprehensive understanding of rubberwood's potential for sustainable engineered timber construction. Unlike previous works that examined only mechanical or adhesive characteristics independently, this research systematically correlates intra-trunk property variations with bonding performance under controlled manufacturing conditions and connects these results with international publication trends. This dual-perspective methodology provides new evidence for material uniformity and reliability, forming the basis for simplified property grading and industrial optimization.

The impact of this study extends to both scientific and practical domains. Scientifically, it contributes to the broader understanding of rubberwood as a sustainable raw material for structural timber systems. Practically, it supports the development of standardized guidelines for rubberwood-based engineered timber, enhancing efficiency and reducing production costs. Furthermore, by aligning its outcomes with SDG 9 and SDG 12, this research promotes sustainable innovation, responsible material utilization, and the advancement of eco-efficient construction practices at both national and global levels.

2. METHODS

2.1. Bibliometric analysis

A bibliometric analysis was conducted to identify global research trends related to rubberwood and engineered timber. Data were retrieved from the Scopus database using keywords such as "rubberwood", updated in October 2025. The collected records were analyzed, providing insights into the evolving research focus on sustainable wood utilization and its alignment with SDGs. Detailed information about bibliometrics is explained elsewhere (Al Husaeni & Nandiyanto, 2022).

2.2. Preparation of rubberwood raw material and property test

Four rubberwood logs with diameters of 19 cm, 21 cm, 23 cm, and 25 cm from 30-year-old rubber trees were randomly selected from a local rubberwood factory for this work. Rubberwood lumber with dimensions of 24 mm (radial) × 80 mm (tangential) × 1000 mm (longitudinal) or 24 mm (tangential) × 80 mm (radial) × 1000 mm (longitudinal) (**Figure 1**) was cut from the cross-sections of the rubberwood logs using a bandsaw. The position of each lumber with respect to the pith was recorded. The lumber was dried at dry-bulb and wet-bulb temperatures of 65 °C and 45 °C, respectively, to a final moisture content of 12% using a laboratory drying kiln at the Center of Excellence in Wood and Biomaterials, Walailak University. Next, the lumber was kept in a conditioning room with the temperature and relative humidity at 20 °C and 65%, respectively, for about 3 weeks.

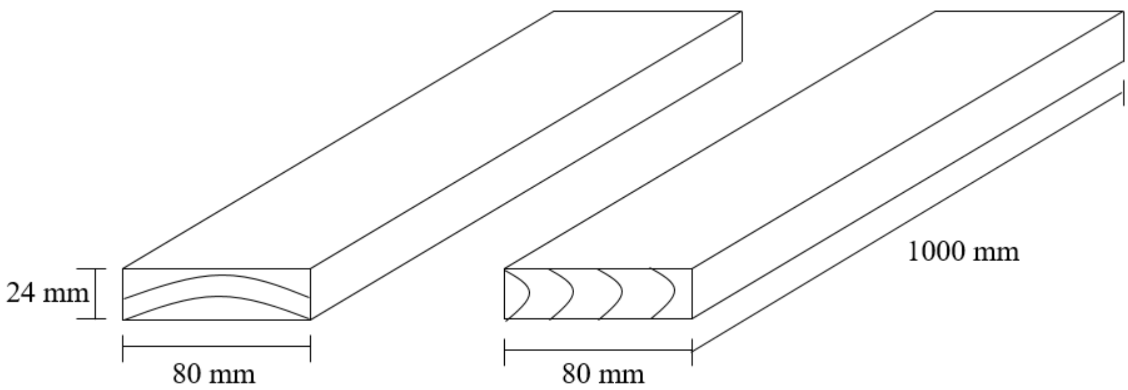

Figure 1. Rubberwood lumber is processed from rubberwood logs.

The fundamental properties of rubberwood raw material were then measured, including its density, modulus of rupture, modulus of elasticity, and compressive and shear strength parallel to the grain properties of rubberwood. The density and shear strength parallel to the grain (either on tangential–longitudinal or radial–longitudinal planes) were measured using specimens with the dimensions of 20 mm (radial) × 20 mm (tangential) × 20 mm (longitudinal). The bending properties (modulus of rupture (MOR) and modulus of elasticity (MOE)) and compressive strength parallel to the grain were measured using specimens with the dimensions of 20 mm (radial) × 20 mm (tangential) × 300 mm (longitudinal) and 20 mm (radial) × 20 mm (tangential) × 60 mm (longitudinal), respectively (**Figure 2**). The span length-to-thickness ratio of 14 was kept constant during the bending test, and the specimen was loaded either in the tangential or radial direction. A mechanical property test was conducted following the guidelines provided in ISO 13061-3, ISO 13061-8, and ISO 13061-17 using a universal testing machine. In total, 24, 36, 25, and 42 test specimens were used for measuring the density, shear strength parallel to the grain, compressive strength parallel to the grain, and bending properties, respectively, which were randomly selected from the processed logs.

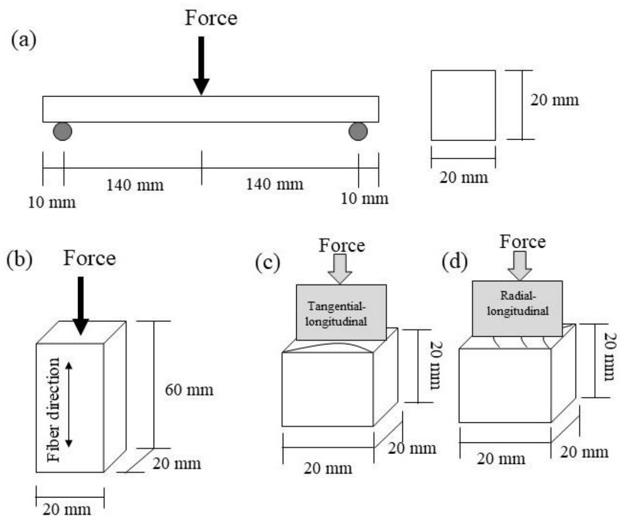

Figure 2. Schematic of the test specimen for (a) three-point bending test, (b) compression parallel to the grain test, (c) shear strength on the tangential–longitudinal plane, and (d) shear strength on the radial–longitudinal plane.

2.3. Wettability test

Two specimen groups from the inner and outer zones of the cross-section were selected to evaluate the wettability of rubberwood (see **Figure 3**). The contact angle of a drop of water was measured on both the tangential–longitudinal (**Figure 3a**) and radial–longitudinal surfaces (**Figure 3b**) of a rubberwood specimen with dimensions of 20 mm ×20 mm × 20 mm using the sessile drop technique with a goniometer (Drop Master, DM300). Distilled water was dropped on the rubberwood surface using a 6μl sessile drop. After 5 seconds of dropping, the contact angle was recorded. Ten samples were used for each condition.

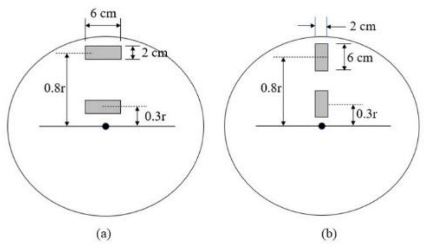

Figure 3. Cutting of rubberwood specimens for wettability and bonding performance study.

2.4. Block shear test

The bonding performance of rubberwood was evaluated using a block shear test. Wood specimens with dimensions of 20 mm (radial) × 50 mm (tangential) × 200 mm (longitudinal) or 20 mm (tangential) × 50 mm (radial) × 200 mm (longitudinal) from the inner and outer zone of the cross-section were cut from the log as shown in **Figure 4**. These specimens were dried to a final moisture content of 12% using a laboratory kiln. The samples were kept in a conditioning room at a temperature and relative humidity of 20 °C and 65%, respectively, for about 3 weeks before the test. The sample was then cut and sanded with 100-grit sandpaper to obtain a specimen with dimensions of 16 mm (radial) × 50 mm (tangential) × 200 mm (longitudinal) or 16 mm (tangential) × 50 mm (radial) × 200 mm (longitudinal). Two wood samples of the same grain orientation were then bonded either with polyvinyl acetate or one-component polyurethane with a spreading rate of 250 g/m^{2,} and the assembly was then coldpressed at pressures of 1 and 3 MPa using a hydraulic press with pressing spaces of 50 cm by 50 cm. A block shear test specimen was then prepared. In order to determine the block shear strength, the test specimen was loaded using the universal testing machine (Lloyd, UK) until fracture. During the test, a crosshead speed of 5 mm/min was used as recommended in ASTM D 905. The maximum load (Pmax) was taken to calculate the block shear strength (BS) using Equation 1

$$BS = \frac{P_{max}}{A} \tag{1}$$

where A is the bonded area.

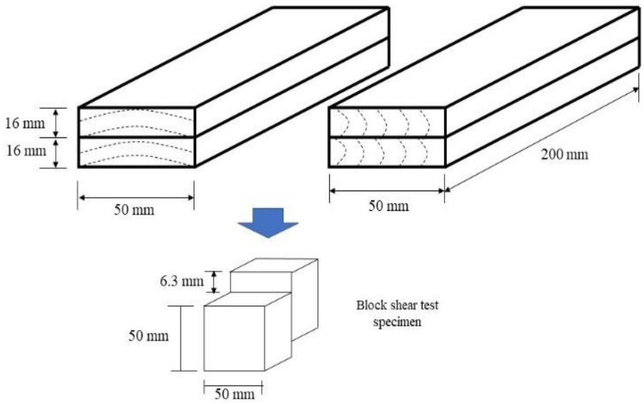

Figure 4. Preparation of specimen for block shear test.

3. RESULTS AND DISCUSSION

3.1. Bibliometric analysis

The bibliometric analysis of Scopus-indexed publications using the keyword *rubberwood* from 1972 to 2025 (see **Figure 5**) reveals a total of 702 documents, indicating a steady and accelerating growth in research output over the past five decades. Early studies appeared sporadically before 1990, followed by a gradual rise after 2000. A significant surge occurred after 2015, marking rubberwood as a growing topic of scientific and industrial interest. The number of publications increased from only 19 papers in 2017 to over 50 in 2020 and 2025, reflecting heightened attention to rubberwood's role in sustainable materials, bio-based manufacturing, and engineered timber construction aligned with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production).

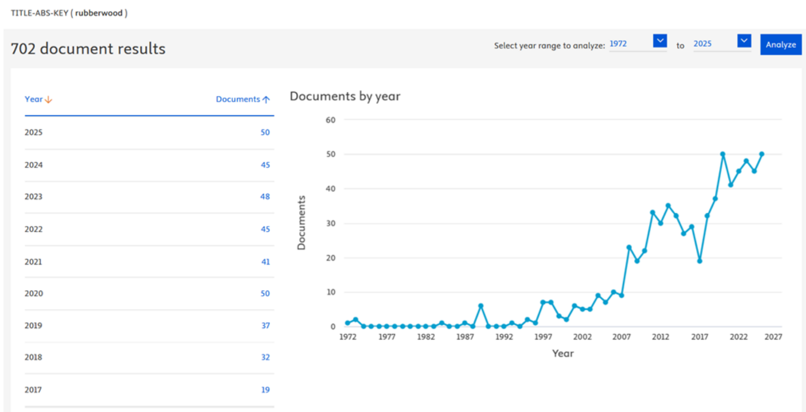

Figure 5. Bibliometric Scopus database using the keyword "rubberwood" taken in October 2025.

3.2. Fundamental properties of rubberwood raw material

Figure 6 plots the density of the rubberwood specimen against the relative distance from the pith (the position of the wood sample with respect to the pith divided by the radius of the cross-section). The density tended to slightly increase from the inner to the outer regions of the cross-section for all trunks. In addition, at a given relative radius, the densities of rubberwood obtained from all rubberwood logs appeared to be roughly identical. A linear equation was then used to fit the experimental data, and the R^2 value (0.0091) was relatively low, indicating that all values were roughly similar regardless of the trunk size and position within the trunk. The average density was found to be 692±21 kg/m^3.

The distributions of the shear strength parallel to the grain, modulus of rupture, modulus of elasticity, and compressive strength parallel to the grain along the cross-section are shown in **Figures 7-10**. Loading directions did not affect the bending properties or shear strength parallel to the grain (see **Figures 7-9**). The examined mechanical properties of rubberwood from the outer regions of the cross-section seemed to be slightly higher than those of the inner region. This might be due to the different fiber lengths along the cross-section; it is longer in the periphery zone (Onakpoma *et al.,* 2023). At a given relative radius, the mechanical properties of rubberwood obtained from various sizes of logs seemed to be identical, as observed for density. A linear equation was used to fit the experimental data, and the R^2 values were relatively low, ranging from 0.000003 to 0.2212. This indicates that all the examined mechanical properties of rubberwood were roughly similar throughout the cross-section, regardless of the trunk size and position within the trunk, which corresponds well with the density trend (see **Figure 6**). The average values of all mechanical properties were then determined, which are shown in **Table 2**.

In comparing other softwood species commonly used in structural applications, the density of rubberwood was approximately 1.5 times higher than that of Black spruce (He *et al.,* 2020), indicating that rubberwood has lower porosity than Black spruce. As porosity is an important parameter determining the bonding performance of wood material, the bonding performance of rubberwood might be difficult. From a mechanical property performance perspective, however, rubberwood showed comparable or higher performance (see **Table 2**).

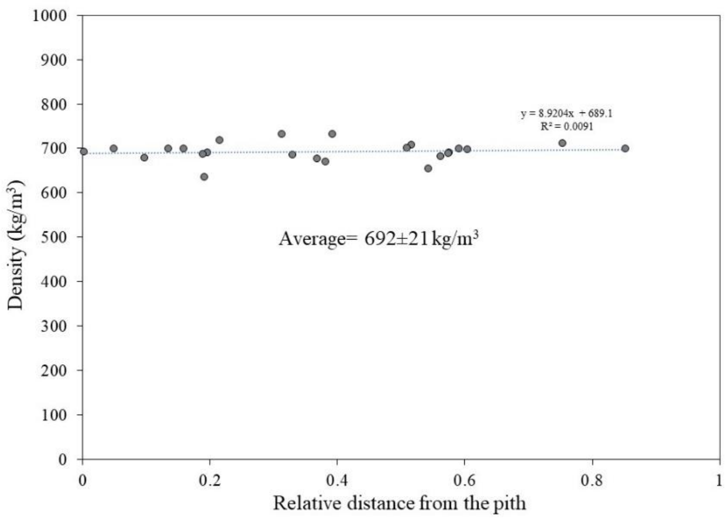

Figure 6. Density of rubberwood specimen at various positions along the cross-section relative to the distance from the pith (Relative distance from the pith = position of wood sample with respect to the pith divided by the radius of the cross-section).

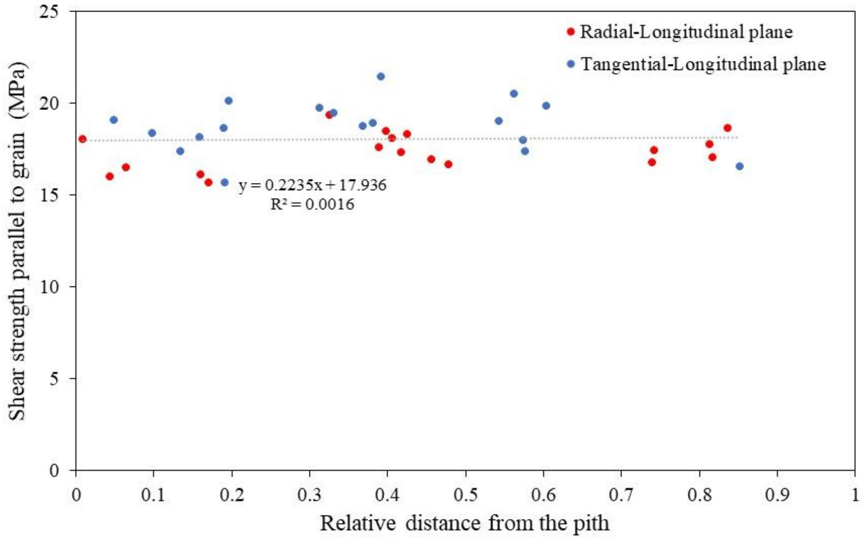

Figure 7. Shear strength parallel to the grain plotted against the relative distance from the pith (Relative distance from the pith = position of wood sample with respect to the pith divided by the radius of the cross-section).

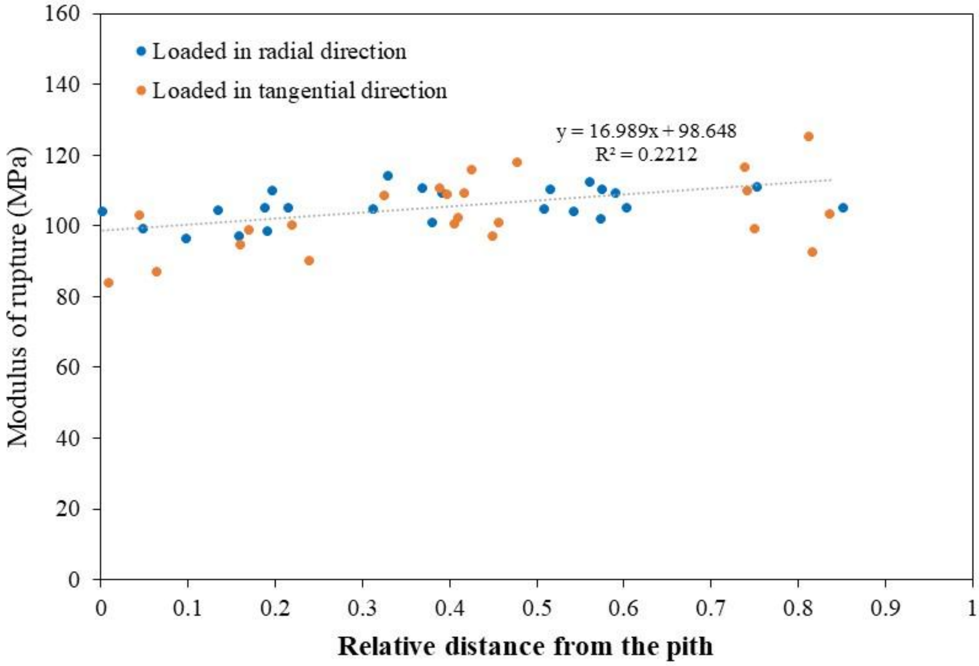

Figure 8. Modulus of rupture plotted against the relative distance from the pith (Relative distance from the pith = position of wood sample with respect to the pith divided by the radius of the cross-section).

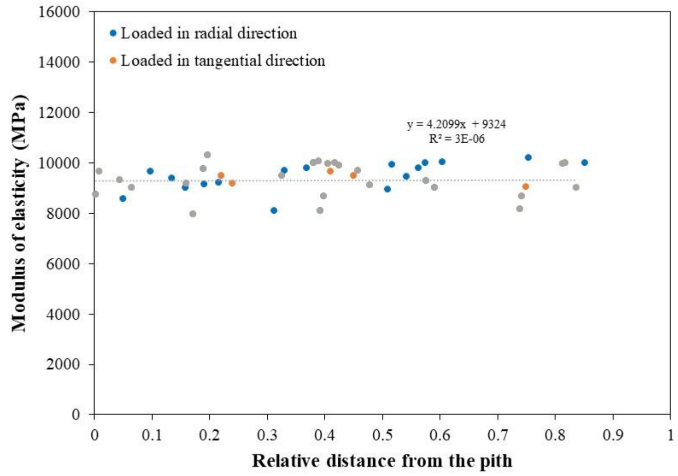

Figure 9. Modulus of rupture plotted against the relative distance from the pith (Relative distance from the pith = position of wood sample with respect to the pith divided by the radius of the cross-section).

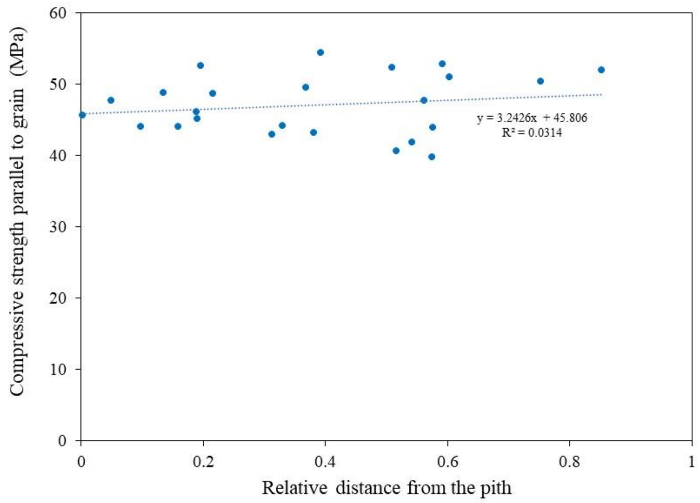

Figure 10. Compressive strength parallel to grain plotted against the relative distance from the pith (Relative distance from the pith = position of wood sample with respect to the pith divided by the radius of the cross-section).

Table 2. Properties of rubberwood compared with those of Black spruce.

Properties	Rubberwood	Black Spruce (He *et al.,* 2020)
Density (kg/m^3)	692 ± 21	470*
Modulus of rupture (MPa)	105 ± 5	74
Modulus of elasticity (MPa)	9,423 ± 621	11,100
Compressive strength parallel to grain (MPa)	47 ± 4	41.1
Shear strength parallel to grain (MPa)	18.0 ± 1.4	8.5

3.3. Wettability

Figure 11 shows the contact angle of the rubberwood raw material taken from the inner and outer regions of the cross-section on the radial–longitudinal and tangential–longitudinal planes. The contact angles on both surfaces were slightly different; the value on the radial–

longitudinal plane seemed to be slightly higher. One of the possible reasons is that ray cells aligned in the radial direction might have helped the penetration of water on the tangential–longitudinal surface, causing the lower contact angle on this plane. In addition, the position of the wood specimen appeared to slightly affect the contact angle. The contact angle taken from the outer zone seemed to be slightly higher.

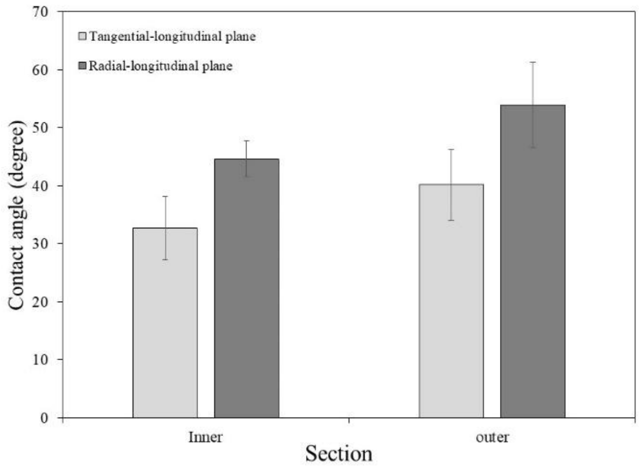

Figure 11. Contact angles on tangential–longitudinal and radial–longitudinal planes of rubberwood raw material taken from inner and outer regions of cross-section.

3.4. Block shear strength

Figures 12 and 13 show the block shear strength of rubberwood bonded with one-component polyurethane and polyvinyl acetate, respectively, at two different clamping pressures. One-way ANOVA at a 0.05 level of significance was used to determine the statistical difference between the mean values of the block shear strength. Clamping pressure, the position of the wood sample, and the bonding plane did not significantly affect the block shear strength for both types of adhesives. Note that a higher wettability of rubberwood on the tangential–longitudinal plane did not help improve the block shear strength.

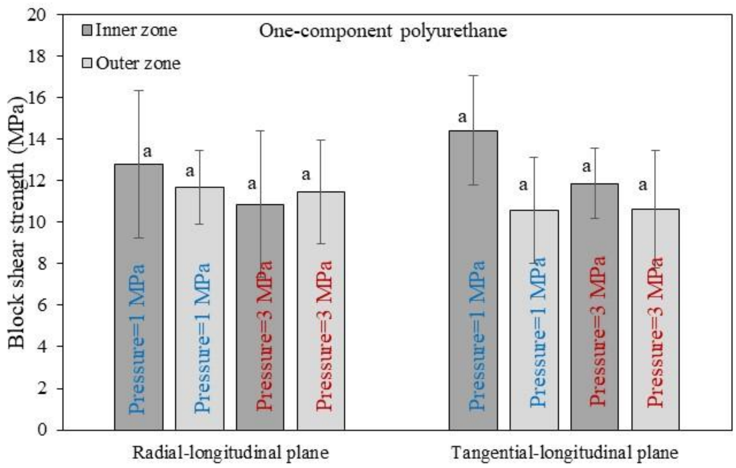

Figure 12. Block shear strength of rubberwood bonded with one-component polyurethane. The same letter indicates that the mean values were not statistically different based on one-way ANOVA at the 0.05 level of significance.

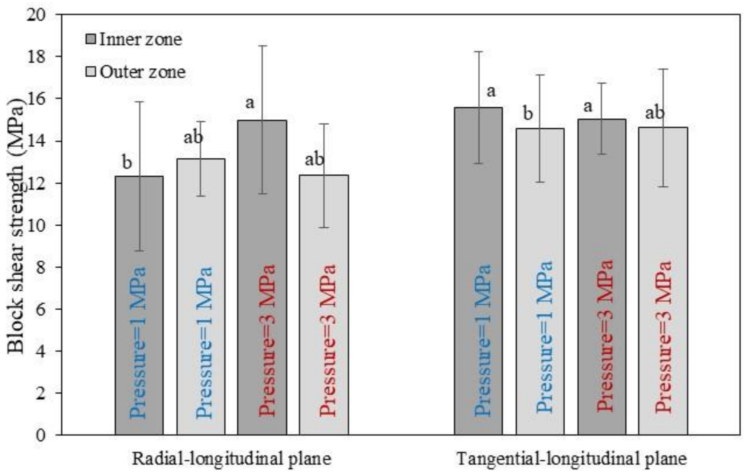

Figure 13. Block shear strength of rubberwood bonded with polyvinyl acetate. The same letter indicates that the mean values were not statistically different based on one-way ANOVA at the 0.05 level of significance.

To compare the block shear strength between the two types of adhesives, the average block shear strength of all conditions for each adhesive type was determined and plotted on the same graph, as shown in **Figure 14**. The block shear strength of the specimen manufactured from polyvinyl acetate seemed to be slightly higher. An examination of the shear plane surface of the specimen after the block shear test revealed that approximately 75% of wood specimens bonded with polyvinyl acetate failed due to wood failure, but the others failed mainly due to poor adhesive bonding (see **Figure 15**). Moreover, approximately 50% of wood samples bonded with one-component polyurethane failed mainly due to poor adhesive bonding (see **Figure 15**). In addition, the obtained block shear strengths, which ranged from 10.6 to 15.6 MPa, were slightly lower than that of rubberwood's shear strength parallel to the grain, as shown in **Table 2** (~18 MPa). Generally, if the wood surface is perfectly bonded, the block shear strength should be nearly that parallel to the grain of the original rubberwood, as wood failure is expected. The bonding surface is not perfectly bonded, as confirmed by the shear plane area shown in **Figure 15**.

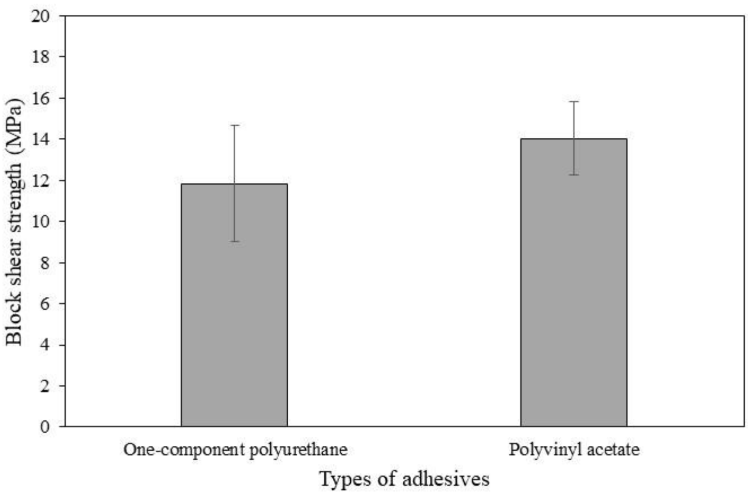

Figure 14. Comparison of the average block shear strength of rubberwood bonded with one-component polyurethane and polyvinyl acetate adhesives.

Figure 15. Surface area of specimen after block shear test: (a) bonded with polyvinyl acetate and (b) bonded with one-component polyurethane.

In comparing other wood species, the obtained block shear strength of rubberwood was approximately 3.9 times higher than that of hem fir (Wang *et al.,* 2018), which was bonded with either one-component polyurethane or emulsion polymer isocyanate (the block shear strength ranged from 2.68 to 3.89 MPa). This might be due to the higher shear strength of rubberwood.

3.5. Relevance to the SDGs

The outcomes of this study directly contribute to advancing the SDGs, particularly SDG 9: Industry, Innovation, and Infrastructure and SDG 12: Responsible Consumption and Production. From an experimental perspective, the demonstrated uniformity in rubberwood's physical and mechanical properties supports efficient material grading and consistent manufacturing performance for engineered timber products. Such stability enables industries to reduce waste, optimize resource utilization, and improve production efficiency in structural applications.

The bibliometric analysis (**Figure 5**) further highlights the increasing global research focus on sustainable construction materials and bio-based innovations. This trend underscores the growing recognition of rubberwood as a renewable raw material that can replace non-renewable and high-emission resources in the construction sector. The combination of empirical findings and bibliometric insights thus positions rubberwood as a key contributor to the circular bioeconomy and low-carbon development strategies. By promoting the integration of scientific innovation with sustainable manufacturing practices, this research reinforces the link between academic evidence and global sustainability frameworks, aligning Thailand's wood-based industry with the long-term goals of SDG 9 and SDG 12.

4. CONCLUSION

This study integrated experimental evaluation and bibliometric analysis to examine the variation in physical and mechanical properties of rubberwood for sustainable engineered timber construction. Experimental findings revealed that property variations within and between trunks of different diameters were negligible, confirming the uniformity and reliability of rubberwood for structural applications. The bonding performance was also consistent across adhesives and clamping pressures. Bibliometric mapping demonstrated a growing global interest in rubberwood research, particularly in sustainable construction and bio-based materials. These combined insights emphasize rubberwood's potential as a renewable resource that supports industrial innovation and responsible material utilization in alignment with SDG 9 and SDG 12.

5. ACKNOWLEDGMENT

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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