WOOD RESEARCH **doi.org/10.37763/wr.1336-4561/71.2.318330**
e-ISSN 2729-8906
71(2): 2026 318-330 pp.

THE TREATABILITY OF SELECTED LOCAL TIMBER SPECIES WITH ALKALINE COPPER QUATERNARY (ACQ) PRESERVATIVE: CORRELATING WOOD ANATOMY, PHYSICAL PROPERTIES, AND PRESERVATIVE PERFORMANCE

NIRANJAN KANNANGARA[1], WASUNDARA INDUMINI[1], OKDCP MUTHUMALI[1], CHAMINDA MUTHUMALA[2], FAIZ MARIKAR[3]
[1]UNIVERSITY OF RUHUNA, SRI LANKA
[2]RESEARCH DEVELOPMENT AND TRAINING, STATE TIMBER CORPORATION, SRI LANKA
[3]GENERAL SIR JOHN KOTELAWALA DEFENCE UNIVERSITY, SRI LANKA

(RECEIVED JANUARY 2026)

ABSTRACT

This study evaluated the ACQ treatability of 24 local timber species through vacuum pressure impregnation and correlated preservative retention and penetration with physical and anatomical wood properties. Retention ranged widely from 0.478 kg m^{-3} (*Bridelia retusa*) to 14.980 kg m^{-3} (*Cullenia ceylonica* and *Cupressus macrocarpa*). Based on retention and Chrome Azurol S (CAS) penetration assessment, species were classified into four treatability classes. One-way ANOVA confirmed highly significant differences in density ($F_{23,48}$=199.79; p<0.001), moisture content ($F_{23,48}$=48.04; p<0.001), and ACQ retention ($F_{23,48}$=82.75; p<0.001) across species. Pearson correlation analysis revealed a very strong positive relationship between fibre wall thickness and wood density (r=0.955; p<0.05) and a strong negative relationship between fibre lumen diameter and density (r= −0.903; p=0.001), demonstrating that fibre morphology is the dominant determinant of wood density. Neither density (r= −0.411; p=0.163), moisture content (r = 0.005; p = 0.987), total ray area (r=0.097; p=0.789), total vessel area (r= −0.021; p=0.932), fibre wall thickness (r=0.082; p=0.725), nor fibre lumen diameter (r=0.302; p=0.183) produced statistically significant correlations with ACQ retention, indicating that preservative uptake is governed by the combined interactive influence of multiple anatomical and chemical wood properties rather than any single parameter. *Cullenia ceylonica, Cupressus macrocarpa,* and *Ficus amplissima* were identified as the most effectively treatable species, classified as *very easy to treat* (Class 4, retention >10 kg m^{-3}) with full penetration exceeding 25 mm. These findings provide a species-specific treatability database for Sri Lankan timber and highlight the need for multi-variable modelling in future preservative research.

KEYWORDS: Alkaline copper quaternary, wood preservation, timber treatability, wood anatomy, fibre morphology, pressure impregnation.

INTRODUCTION

Biological susceptibility of wood arising from its porous, hygroscopic, and carbohydrate-rich composition renders it vulnerable to degradation by fungi, bacteria, termites, and wood-boring insects, particularly under the warm, humid climatic conditions prevalent in Sri Lanka (Lebow 2014). Extending the service life of timber through chemical preservation is therefore essential for sustainable forest resource utilization and for reducing pressure on natural forest stocks that are already under severe depletion from rapid deforestation (Ruwanpathirana 2014). Among the preservative systems currently available, alkaline copper quaternary (ACQ) has emerged as the principal environmentally acceptable replacement for chromated copper arsenate (CCA). ACQ formulations combine copper oxide an effective biocide against decay fungi and insects with a quaternary ammonium compound (DDAC) that targets copper-tolerant fungi, thereby providing a broad-spectrum protective profile without recourse to arsenic or hexavalent chromium. This toxicological advantage has led to the widespread adoption of ACQ for residential, outdoor, and structural applications where human contact and environmental exposure are significant concerns (Freeman and McIntyre 2008, Lebow 2014). Despite its proven efficacy, the performance of ACQ under vacuum pressure impregnation is not uniform across wood species. Treatment effectiveness quantified by preservative retention (kg m^{-3}) and penetration depth (mm) is profoundly influenced by species-specific anatomical architecture and physical properties. Key structural determinants include vessel dimensions and frequency, ray density and area, fibre wall thickness, fibre lumen diameter, the presence of tyloses and gum deposits in heartwood vessels, and cell membrane permeability to fluid flow (Niemz et al. 2023, Leggate et al. 2020). Physical properties such as wood density and pre-treatment moisture content further modulate preservative uptake by influencing the ratio of void space to cell wall material and the initial fluid dynamics within the wood matrix (Halverson and Lebow 2011).

Although ACQ preservative technology is well documented for temperate commercial species such as pine (*Pinus spp*.) and spruce (*Picea spp*.), systematic treatability data for the diverse tropical and subtropical timber species utilized in Sri Lanka remain critically limited. Many local species exhibit complex vessel element geometry, elevated extractive concentrations, and a high propensity for tylosis formation characteristics that may substantially impede preservative flow under pressure treatment conditions (Bandara et al. 2024, Muthumala et al. 2019, Wijayaboparatne et al. 2024).

The absence of a species-specific treatability classification framework for Sri Lankan timbers results in suboptimal treatment protocols, wasted preservative chemicals, and inadequately preserved wood products entering service applications that require long-term resistance. This study addresses that knowledge gap by systematically evaluating the ACQ treatability of 24 locally utilized timber species representing a broad taxonomic and structural diversity. The specific objective was to quantify ACQ retention and penetration achieved under standardized vacuum pressure impregnation and to classify species into treatability categories.

MATERIAL AND METHODS

Sample preparation

Twenty-four local timber species (Tab. 1) were selected from the State Timber Corporation (STC) Research Division, Kaldemulla, Sri Lanka, with priority given to commercially utilized construction species for which ACQ treatability data were absent in the scientific literature. Mature, defect-free heartwood specimens were collected from each species. Three replicate blocks 12.5 × 7.5 × 5.5 cm were prepared per species (n = 72 blocks total). All specimens were air-dried under shelter, away from direct solar radiation and rainfall, until a stable moisture content of approximately 15–20% was attained. Final pre-treatment moisture content (MC) was confirmed gravimetrically and by calibrated moisture meter immediately prior to treatment.

Tab. 1: Selected local timber species and their taxonomic classification.

No.	Common name	Botanical name	Family
1	*Acacia auriculiformis*	*Acacia auriculiformis*	Fabaceae
2	*Acacia mangium*	*Acacia mangium*	Fabaceae
3	Ahatu	*Ficus amplissima*	Moraceae
4	Albizia	*Falcataria falcata*	Fabaceae
5	Amba (Mango)	*Mangifera indica*	Anacardiaceae
6	Cypress	*Cupressus macrocarpa*	Cupressaceae
7	Damba	*Syzygium malaccense*	Myrtaceae
8	*Eucalyptus citriodora*	*Eucalyptus citriodora*	Myrtaceae
9	*Eucalyptus pilularis*	*Eucalyptus pilularis*	Myrtaceae
10	*Eucalyptus torelliana*	*Eucalyptus torelliana*	Myrtaceae
11	Gadiguda	*Baccaurea motleyana*	Phyllanthaceae
12	Ginisapu	*Michelia champaca*	Magnoliaceae
13	Kataboda	*Cullenia ceylonica*	Malvaceae
14	Katakela	*Bridelia retusa*	Phyllanthaceae
15	Kiri koon	*Walsura trifoliolata*	Meliaceae
16	Lunumidella	*Melia dubia*	Meliaceae
17	Madan	*Syzygium cumini*	Myrtaceae
18	Mara	*Albezia lebbeck*	Fabaceae
19	Micro (Tallow wood)	*Eucalyptus microcorys*	Myrtaceae
20	Milla	*Vitex pinnata*	Verbenaceae
21	Nedun	*Pericopsis mooniana*	Fabaceae
22	Red gum	*Eucalyptus robusta*	Myrtaceae
23	Suriyamara	*Albizia odoratissima*	Fabaceae
24	Toona	*Toona ciliata*	Meliaceae

Wood density was determined by the water displacement (Archimedes principle) method at 0% MC and corrected to the standard 12% MC reference level Ilangarathne et al. (2025):

$$\rho_{12} = (\rho_0 / 100) \times 112 \ \ (\text{kg m}^{-3}) \quad (1)$$

where: ρ_0 is oven-dry density (kg m^{-3}) and ρ_{12} is density at 12% MC.

Volume was measured by water displacement and independently verified by Vernier caliper measurements. Pre-treatment MC was determined according to ASTM D2395-17. Wood texture was classified quantitatively by mean tangential vessel diameter measured from photomicrographs using Micrometrics SE Premium 4 image analysis software, following the classification of Ruwanpathirana (2014): *fine* (< 100 μm), *moderate* (100–200 μm), and *coarse* (> 200 μm). Wood colour was assessed visually against IAWA (1989) before and after ACQ treatment.

Anatomical sections (10–20 μm) were cut from 2 × 2 × 3 cm wood blocks in transverse (TS), radial-longitudinal (RLS), and tangential-longitudinal (TLS) planes using a Leica SM2000 R sliding microtome. Sections were dehydrated through an ethanol series (50%, 70%, 90%, 100%), stained with safranin in 50% ethanol, cleared in xylene, and permanently mounted in Canada Balsam on glass microscope slides (Carrer 2016). Slides were examined under an ACCU-SCOPE light microscope with calibrated eyepiece and digital camera at 4×10 magnification. Measurements were obtained with Micrometrics SE Premium 4 software.

Ray height and ray width (min 25 rays per species) were measured from TLS sections. Mean tangential and radial vessel diameters (min 25 vessels per species) were measured from TS sections. Mean vessel diameter was calculated as the arithmetic mean of tangential and radial diameters. Total vessel area was computed as vessel area $\pi(d/2)^2$ multiplied by vessel count per 25 mm². Total ray area was computed as individual ray area (height×width) multiplied by ray count per 25 mm² (Muthumala et al. 2024). Fiber lumen diameter, fibre cell thickness, and fibre wall thickness were measured from TS sections at 40× magnification. The Runkel ratio was calculated as 2×fiber wall thickness/fibre lumen diameter (Ohshima et al. 2020), providing a fibre quality index for pulp and paper suitability assessment.

ACQ treatment

Vacuum pressure impregnation was performed at A Wood Lanka Company, Kottawa, Sri Lanka, using an industrial pressure treatment autoclave. The ACQ solution concentration was maintained at 3.3% (w/v). The treatment cycle followed the full-cell (Bethell) process schedule (Tab. 2): initial vacuum (76 Hg cm) for 45 min to evacuate lumen air; chemical filling under continued vacuum; application of working pressure (1300–1400 kPa) for 20 min; and final vacuum (76 Hg cm) for 30 min to remove excess surface preservative. Pre- and post-treatment block weights were recorded.

Tab. 2: Vacuum pressure impregnation treatment schedule.

Treatment phase	Pressure	Duration
Initial vacuum	76 Hg cm	45 min
Chemical filling	Under vacuum	5–15 min
Pressure stage	1300–1400 kPa	20 min
Final vacuum	76 Hg cm	30 min

Chemical retention (R, kg m^{-3}) was calculated from the weight gain method according to Ganguly et al. (2024):

$$R = (G \times C) / (V \times 10) \quad (2)$$

where: G is mass of treatment solution absorbed (g), C is percentage solution concentration, and V is sample volume (cm^3).

Chemical penetration was evaluated by applying Chrome Azurol S (CAS) colorimetric reagent to freshly cross-cut mid-section surfaces of treated blocks. CAS reacts specifically with copper ions in ACQ-treated wood to produce a characteristic deep blue-violet complex, allowing visual differentiation of treated from untreated zones (Freeman and McIntyre 2008; AWPA 2019). Penetration depth was measured with a Vernier caliper and species were classified as: *Fully penetrated* (>25 mm depth); *Partially penetrated* (10–25 mm); or *Not penetrated (surface staining only).* An integrated four-class treatability classification system was developed based on retention values, following the framework of Bandara et al. (2024) and Jayasinghe et al. (2025): Class 1 *Very difficult to treat* (<5 kg m^{-3}); Class 2 *Moderately difficult to treat* (5–8 kg m^{-3}); Class 3 *Easy to treat* (8–10 kg m^{-3}); Class 4 *Very easy to treat* (>10 kg m^{-3}).

Data analysing

All data were analysed using Minitab 21 and R v4.3.2. One-way Analysis of variance (ANOVA) was applied to test for significant differences in density, MC, and ACQ retention among the 24 timber species, with Tukey's Honestly Significant Difference (HSD) post-hoc test used for pairwise mean comparisons at $\alpha=0.05$. Prior to Pearson correlation analysis, datasets were examined for normality using the Anderson–Darling test, and outliers identified via Grubbs' test were removed to satisfy bivariate normality assumptions. Pearson correlation coefficients *(r)* and associated p-values were calculated to assess linear relationships between ACQ retention and each physical/anatomical parameter. Significance was set at $p<0.05$ throughout.

RESULTS AND DISCUSSION

Wood density at 12% MC varied substantially across the 24 species, spanning from 393.93 kg m^{-3} (±0.11) in *Albezia lebbeck* (Mara) to 1205.90 kg m^{-3} (±5.01) in *Walsura trifoliolata* (Kiri koon), with *Eucalyptus citriodora* as the second densest species at 1049.13 kg m^{-3} (±0.43). One-way ANOVA confirmed highly significant differences among species ($F_{23,48}=199.79$; $p<0.001$; $R^2=98.97\%$), indicating that species identity accounts for virtually all observed density variation. Tukey HSD pairings revealed 14 distinct groupings (*A* through *N*), with the densest species (*W. trifoliolata*) forming a solitary *Group A* and the lightest (*A. lebbeck*) occupying *Group N.* Based on the density classification framework of Ruwanpathirana (2014), six species fell in the *Light wood category* (<500 kg m^{-3}), four in *Medium density wood* (500–640 kg m^{-3}), eight in *High density wood* (640–800 kg m^{-3}), and six in *Very high density wood* (>840 kg m^{-3}). This distribution reflects the taxonomic and structural breadth of the species panel.

Pre-treatment MC across all 24 species ranged narrowly from 11.59% (±0.13) in *Pericopsis mooniana* (Nadun) to 14.70% (±0.08) in *Eucalyptus citriodora*. One-way ANOVA yielded $F_{23,48}=48.04$ ($p<0.001$; $R^2=95.84\%$), confirming species-dependent differences in equilibrium moisture content attributable to differences in cellular structure and extractive composition. The narrow absolute range (11.59–14.70%) confirmed that the seasoning protocol was effective in standardizing pre-treatment moisture conditions across the species panel.

Texture classification based on mean tangential vessel diameter revealed that 2 species (8.3%) had *fine* texture (< 100 µm): *Cupressus macrocarpa* (Cypress; a non-porous softwood, vessel diameter = 0 µm) and *Baccaurea motleyana* (Gadiguda; ~90 µm). Fifteen species (62.5%) were classified as *moderate* texture (100–200 µm), and seven species (29.2%) were *coarse* (> 200 µm), including the plantation hardwoods *Melia dubia* (Lunumidella; 255.31 µm) and *Toona ciliata* (Toona; 331.41 µm).

ACQ retention values demonstrated a markedly skewed distribution, with a clear concentration of species at retention values below 5 kg m^{-3} and a small number of highly permeable species achieving retention above 10 kg m^{-3}. One-way ANOVA was highly significant ($F_{23,48}$=82.75; p<0.001), confirming that species identity was the primary determinant of preservative uptake. The four-class treatability classification allocated 13 species (54.2%) to Class 1 (*Very difficult to treat;* <5 kg m^{-3}), 5 species (20.8 %) to Class 2 (*Moderately difficult*; 5–8 kg m^{-3}), 3 species (12.5%) to Class 3 (*Easy to treat*; 8–10 kg m^{-3}), and 3 species (12.5%) to Class 4 (*Very easy to treat*; > 10 kg m^{-3}). Mean retention by class and the full species-level Tukey HSD groupings are presented in Tab. 3.

Tab. 3: ACQ treatability classification of 24 local timber species based on chemical retention and penetration performance.

Class	Treatability (AWPA 2019)	Retention (kg m^{-3})	Penetration	Species (Retention ± SD) (Units kg/m^3)
1	Very difficult	< 5	Not penetrated	*Acacia auriculiformis* (0.86±0.16), *Acacia mangium* (2.18±0.18), *A. lebbeck* (1.13±0.64), *A. odoratissima* (0.63±0.30), *Bridelia retusa* (0.48±0.12), *E. citriodora* (0.81±0.13), *E. microcorys* (0.69±0.20), *E. pilularis* (0.66±0.12), *E. robusta* (1.43±0.16), *E. torelliana* (1.45±0.30), *Melia dubia* (2.22±0.54), *Toona ciliata* (1.10±0.21), *Vitex pinnata* (0.85±0.69)
2	Moderately difficult	5–8	Partially penetrated	*Falcataria falcata* (1.38±0.75), *Michelia champaca* (4.29±1.00), *Syzygium cumini* (7.62±0.12), *Syzygium malaccense* (5.21±2.23), *Walsura trifoliolata* (6.75±0.37)
3	Easy to treat	8–10	Fully penetrated	*Baccaurea motleyana* (9.65±0.75), *Mangifera indica* (9.31±0.94), *Pericopsis mooniana* (9.46±2.01)
4	Very easy to treat	> 10	Fully penetrated	*Cullenia ceylonica* (14.98±1.05), *Cupressus macrocarpa* (14.98±2.14), *Ficus amplissima* (11.07±0.26)

Note: SD – standard deviation.

Density and ACQ retention

Following removal of 11 outliers that violated bivariate normality assumptions, Pearson correlation between wood density (at 12% MC) and ACQ retention returned r= −0.411 (p=0.163), indicating a weak non-significant negative trend. While the direction of the relationship is consistent with the physical expectation that denser wood offers greater resistance to fluid penetration, the non-significant p-value demonstrates that density alone cannot reliably predict ACQ uptake across the species studied. Considerable scatter in the mid-density range (600–800 kg m^{-3}) reflects the contribution of vessel occlusion, extractive barriers, and pit membrane resistance beyond simple density effects.

Moisture content and ACQ retention

Pearson correlation between pre-treatment moisture content and ACQ retention yielded r=0.005 (p=0.987) following removal of 10 outliers, indicating a complete absence of linear association. This result is attributable to the narrow, standardized MC range achieved by pre-treatment seasoning (11.59–14.70%), which effectively neutralized MC variation as a treatability variable and redirected variance to intrinsic wood anatomical properties.

Ray dimensions varied widely: mean ray height ranged from 168.51 µm (*Syzygium malaccense*) to 1161.24 µm (*Baccaurea motleyana*), and mean ray width from 17.27 µm (*Syzygium malaccense*) to 76.65 µm (*Baccaurea motleyana*). Species were classified into ray height groups: *low* (< 300 µm; majority of Eucalyptus and Acacia spp.); *medium* (300–600 µm); *high* (600–900 µm; *Michelia champaca*, *Melia dubia*); and *very high* (> 900 µm; *Cullenia ceylonica*, *Baccaurea motleyana*). The complete vessel and ray measurement dataset is presented in Appendix VI of the original thesis.

The strongest relationship in this study was observed between average fibre wall thickness and wood density (r=0.955; p<0.05), following removal of six outliers (n=18 species). *Eucalyptus citriodora* exhibited both the highest fibre wall thickness (8.94 µm) and the highest density in the retained dataset (1049.12 kg m^{-3}), while *Cullenia ceylonica* showed the lowest fibre wall thickness (3.34 µm) paired with one of the lowest densities (471.15 kg m^{-3}). This very strong positive relationship confirms that cell wall material per unit volume is the primary driver of wood density. Complementarily, fibre lumen diameter showed a very strong negative correlation with density (r= −0.903; p=0.001; n=16 species). *Eucalyptus microcorys* recorded the smallest fibre lumen (7.96 µm) and high density (904.35 kg m^{-3}), while *Michelia champaca* had the largest lumen (18.57 µm) paired with low density (471.06 kg m^{-3}). Together, fibre wall thickness and fibre lumen diameter account for the opposing sides of the cell wall-to-void ratio that structurally determines wood density.

Tab. 4: Summary of Pearson correlation coefficients between wood properties and ACQ retention, and between fibre morphology and wood density.

Dependent variable	Independent variable	n	Pearson r	p-value	Significance
ACQ retention	Wood density (12%)	13	−0.411	0.163	ns
ACQ retention	Moisture content	14	0.005	0.987	ns
ACQ retention	Total ray area	10	0.097	0.789	ns
ACQ retention	Total vessel area	19	−0.021	0.932	ns
ACQ retention	Fiber wall thickness	21	0.082	0.725	ns
ACQ retention	Fiber lumen diameter	21	0.302	0.183	ns
Wood density	Fiber wall thickness	18	0.955	< 0.05	***
Wood density	Fiber lumen diameter	16	−0.903	0.001	**

*ns=not significant (p>0.05); ** p<0.01; *** p<0.05; n=number of species retained after outlier removal.*

Relationship between wood anatomical characteristics and ACQ retention

None of the four anatomical parameters examined produced a statistically significant correlation with ACQ retention (Tab. 4). Total ray area yielded r=0.097 (p=0.789; n=10); total vessel area, r= −0.021 (p=0.932; n=19); fibre wall thickness, r=0.082 (p=0.725; n=21); and fibre lumen diameter, r=0.302 (p=0.183; n=21). The strongest of these, fibre lumen diameter (r=0.302), suggests a weak positive trend whereby wider fibre lumens may marginally facilitate ACQ uptake, but this association did not reach significance at the sample sizes available. The inversion observed for vessel area is particularly informative: *Bridelia retusa*, with a total vessel area of 2,329,398.48 µm² (the third largest in the dataset), recorded the lowest ACQ retention of 0.48 kg m⁻³. By contrast, *Ficus amplissima* achieved 11.07 kg m⁻³ retention with a total vessel area of only 747,333.54 µm² (Total Ray Area per Unit Area, specifically per 1 cm^2). Similarly, *Syzygium malaccense* had the largest vessel area (6,658,205.06 µm²) Total Ray Area per Unit Area (specifically per 1 cm^2) yet moderate retention of only 5.21 kg m⁻³. These inversions suggest that a large proportion of nominal vessel area may be functionally occluded by tyloses, gum deposits, and extractives in heartwood, effectively decoupling vessel area from fluid permeability.

Runkel ratio analysis classifies the studied species for pulp and paper suitability independently of ACQ treatability. *Michelia champaca* (RR=0.38) and *Cullenia ceylonica* (RR=0.43) exhibited the lowest Runkel ratios, placing them in the 'very good fibre' category (0.25–0.50), indicating thin-walled fibres suited to paper production. Ten species fell in the 'good fibres' range (RR 0.50–1.00), including plantation species such as *Acacia mangium* (0.74) and *Toona ciliata* (0.92). High-density eucalyptus species *E. citriodora* (RR = 2.79) and *E. microcorys* (RR=2.19) were classified as 'poor fibres' (RR > 2.00), consistent with their high density and thick cell walls.

Treatability distribution and ecological implications

The finding that 54.2% of the studied species fall into the *very difficult to treat* category is consistent with patterns reported for tropical hardwood species in the Asia-Pacific region (Leggate et al. 2020, Niemz et al. 2023) and reflects the widespread occurrence in Sri Lankan timbers of anatomical and chemical characteristics that impede fluid penetration under vacuum pressure conditions. Dense Eucalyptus species, which collectively represented the majority of Class 1 specimens, are well documented for their refractory behavior under pressure treatment, attributable to their narrow fiber lumens, high extractive content, and potential pit aspiration during seasoning (Bandara et al. 2024).

The three Class 4 species *Cullenia ceylonica*, *Cupressus macrocarpa*, and *Ficus amplissima* each achieved retention of 10.07–14.98 kg m⁻³ with full CAS penetration. Their structural characteristics are instructive: *C. ceylonica* exhibits very high ray area (3,367,107.17 µm²) specifically per 1 cm^2 or a large sampling plot of 10 mm×10 mm) and large-diameter vessels (235.77 µm MVD), providing extensive radial and longitudinal fluid pathways. *C. macrocarpa* is a softwood lacking hardwood vessels entirely, with fluid transport through tracheids and abundant ray cells, which collectively facilitate uniform preservative distribution. *F. amplissima* combines relatively small vessel diameter (108.39 µm) with low density (642.21 kg m^{-3}) and wide fibre lumens (15.55 µm), suggesting open, unoccluded lumen pathways that are accessible to ACQ solution under pressure.

Non-significance of individual anatomical predictors

The consistent absence of statistically significant correlations between ACQ retention and any individual anatomical variable is itself a significant and informative finding. It challenges the assumption implicit in simplified treatability assessment frameworks that a single anatomical measurement such as vessel diameter or density can serve as a reliable surrogate for preservative uptake. The results instead support a multi-mechanism model in which treatability is determined by the simultaneous interaction of vessel connectivity (diameter, frequency, and occlusion status), ray permeability (frequency, pit membrane condition), fibre lumen pathway availability, extractive loading, and wood porosity (Balatinecz 2001, Leggate et al. 2020, Niemz et al. 2023).

The vessel area inversion observed for *Bridelia retusa* (large area, near-zero retention) versus *Ficus amplissima* (small area, high retention) is mechanistically explained by the prevalence of tylosis formation in the heartwood of *Bridelia retusa*. Tyloses are balloon-like outgrowths of adjacent parenchyma cells that physically occlude vessel lumens, rendering large proportions of the nominal vessel volume functionally impermeable to preservative solution under standard treatment pressures (Balatinecz 2001, Barauna et al. 2014). These findings align with Bandara et al. (2024) and Wijayaboparatne et al. (2024), who reported similarly weak anatomical correlations in Sri Lankan timber species panels.

Fiber morphology as a determinant of wood density

The very strong correlation between fibre wall thickness and density ($r=0.955$) and the strong negative correlation between fibre lumen diameter and density ($r= -0.903$) are consistent with first principles of wood structure and confirm the mechanistic model articulated by Dwi et al. (2012) and Zieminska et al. (2013): wood density is fundamentally a function of the ratio of solid cell wall material (driven by fibre wall thickness) to void space (inversely determined by fibre lumen diameter). These results have a direct practical implication for ACQ treatment: high-density species with thick fibre walls and narrow lumens (particularly in the Eucalyptus-Walsura density cluster >840 kg m^{-3}) present the greatest structural resistance to preservative penetration and should be subjected to modified treatment cycles extended pressure duration, elevated treatment pressure, or pre-treatment incising to achieve target retention levels for hazard classes 3 and 4 applications.

Comparison with published literature

The present findings extend the limited existing database on ACQ treatability of Sri Lankan timbers. Muthumala et al. (2019) demonstrated that pre-treatment moisture content had minimal influence on ACQ penetration in *Hevea brasiliensis* (rubberwood), consistent with the near-zero moisture-retention correlation ($r=0.005$) observed in the present multi-species study. Mensah et al. (2022) similarly reported weak hydration effects on ACQ treatment efficiency. Bandara et al. (2024) and Wijayaboparatne et al. (2024) both documented weak anatomical correlations with ACQ retention in Sri Lankan species panels, reinforcing the conclusion that multi-variable modelling is required for mechanistically adequate prediction of preservative uptake. Sharma and Chauhan (2022) attributed non-significant density-retention correlations in teak to vessel blocking rather than density differences, and Niemz et al. (2023) concluded that treatability prediction requires integration of pit membrane condition, extractive chemistry, and sapwood–heartwood proportion alongside conventional anatomical measurements.

Based on the treatability classification, *Cullenia ceylonica*, *Cupressus macrocarpa*, and *Ficus amplissima* are recommended for ACQ pressure treatment for Use Class 3–4 applications (above-ground exposed; ground contact) without modification of standard treatment protocols. Class 2 species (*Falcataria falcata*, *Michelia champaca*, *Syzygium* spp., and *Walsura trifoliolata*) may be suitable for Use Class 2–3 applications (protected above-ground use) with optimized pressure cycles. Class 1 species, dominated by Eucalyptus and Acacia plantation species, should not be recommended for ACQ treatment for structural or ground-contact use under current protocols and would require pre-treatment incising or alternative systems.

CONCLUSIONS

This study provides the first comprehensive, statistically validated ACQ treatability classification for 24 local Sri Lankan timber species under standardized vacuum pressure impregnation. ACQ retention varied 31-fold across species, ranging from 0.478 to 14.980 kg m^{-3}, with species identity emerging as the primary determinant of preservative uptake ($F_{23,48}$ = 82.75; p<0.001). Among the 24 species examined, *Cullenia ceylonica, Cupressus macrocarpa,* and *Ficus amplissima* proved the most effectively treatable, each achieving Class 4 retention exceeding 10 kg m^{-3} and complete ACQ penetration beyond 25 mm, rendering them optimal candidates for pressure-treated structural applications in Sri Lanka. In contrast, over half the species studied (54.2%) were classified as *very difficult to treat* under standard protocols, exhibiting retention below 5 kg m^{-3} and only superficial ACQ penetration, which necessitates the development of revised treatment strategies for these species within the Sri Lankan wood industry. At the anatomical level, fibre wall thickness emerged as the dominant determinant of wood density (r=0.955; p<0.05), while fibre lumen diameter exerted a complementary strong negative influence (r= −0.903; p=0.001), together confirming that fibre morphology governs the cell wall-to-void ratio fundamental to wood density. Despite the clarity of these density-anatomy relationships, no individual physical or anatomical parameter including density, moisture content, total ray area, total vessel area, fibre wall thickness, or fibre lumen diameter produced a statistically significant correlation with ACQ retention. This finding demonstrates that preservative uptake is governed not by any single structural trait but by the interactive and combined effects of multiple wood structural and chemical properties, and that future treatability prediction should employ multi-variable regression incorporating vessel occlusion status, extractive content, and pit membrane permeability.

ACKNOWLEDGMENTS

Authors would like to acknowledge State Timber Cooperation for their support.

REFERENCES

1. ASTM D2395-17, 2018. Standard test methods for density and specific gravity (relative density) of wood and wood-based materials.
2. AWPA, 2019. Book of standards. Selma, AL: American Wood Protection Association.
3. Balatinecz, J., 2001. Wood anatomy and physical properties — and how they affect durability and treatability. Proceedings of the International Symposium on Wood Preservation.
4. Bandara, K.M.T.S., Jayasinghe, B.K.V.H., Alwis, P.L.A.G. and Muthumala, C.K., 2024. Relationship between wood density and alkaline copper quaternary (ACQ) preservative uptake in twenty lesser-known Sri Lankan timber species. Proceedings of the International Forestry and Environment Symposium, University of Sri Jayewardenepura, Sri Lanka, pp. 48.
5. Barauna, E.E.P., Lima, J.T., Vieira, R.S., Silva, J.R.M. and Monteiro, T.C., 2014. Effect of wood permeability on the treatment of three Amazon species. Cerne, 20(3), pp. 385–392.
6. Bowyer, J.L., Shmulsky, R. and Haygreen, J.G., 2007. Wood handbook: Wood as an engineering material. Madison, WI: USDA Forest Service.
7. Carrer, H., 2016. Wood anatomical and dendrochronological protocols for tropical species. IAWA Bulletin, 7(3), pp.100–110.
8. Dinwoodie, J.M., 2000. Timber: Its nature and behaviour. CRC Press.
9. Dwi Nugroho, W., Marsoem, S.N., Yasue, K., Fujiwara, T., Nakajima, T., Hayakawa, M., Nakaba, S., Yamagishi, Y., Jin, H.O., Kubo, T. and Funada, R., 2012. Radial variations in anatomical characteristics and density of *Acacia mangium*. Journal of Wood Science, 58(3), pp. 185–194.
10. Freeman, M.H. and McIntyre, C.R., 2008. The full-cell process. In: Schultz, T.P. et al. (eds.) Development of commercial wood preservatives. Washington, DC: American Chemical Society, pp.135–148.
11. Ganguly, S., Petrič, M., Tripathi, S. and Kržišnik, D., 2024. Assessment of fungal resistance and preservative retention in microwave-pretreated Norway spruce wood. Processes, 12(4), p.750.
12. Halverson, S. and Lebow, S., 2011. Observed relationships between wood density and solution uptake during pressure treatment. Proceedings of the 107th Annual Meeting of the American Wood Protection Association, pp. 93–98.
13. IAWA Committee, 1989. IAWA list of microscopic features for hardwood identification. IAWA Bulletin, 10(3), pp. 219–332.
14. Ilangarathne, D.I.L., Muthumala, C.K., Kumara, K.K.I.U.A. and Marikar, F.M.M.T., 2025. Anatomical variation and wood properties of Aquilaria crassna and Gyrinops walla for timber and agroforestry applications. Природные системы и ресурсы, 15(1), pp. 20–28.
15. Jayasinghe, B., Alwis, P., Muthumala, C., Bandara, K. and Marikar, F., 2025. Comparative assessment on the retention capacity of boron and ACQ wood preservatives in lesser-known timber species in Sri Lanka by the dipping treatment. Pro Ligno, 21(1).
16. Lebow, S.T., 2014. Wood preservation. In: Wood handbook: Wood as an engineering material. Madison, WI: USDA Forest Service.

17. Leggate, W., McGavin, R.L., Miao, C., Outhwaite, A., Chandra, K., Dorries, J., Kumar, C. and Knackstedt, M., 2020. The influence of mechanical surface preparation methods on wood properties: wettability and permeability. Forests, 11, p.1258.
18. Mensah, P., Alwis, P., Muthumala, C. and Marikar, F., 2022. Investigation on the influence of moisture content of wood on ACQ preservative treatment efficiency. Pro Ligno, 18(4), pp. 5–14.
19. Muthumala, C.K., Marikar, F.M., Jayasinghe, B. and Alwis, P.L.A.G., 2019. Effect of pre-treatment moisture content on ACQ penetration in rubberwood (*Hevea brasiliensis*) under pressure impregnation. Journal of the Institute of Wood Science, 29(2), pp. 89–97.
20. Muthumala, C.K., Marikar, F.M.M.T., Alwis, P.L.A.G. and Jayasinghe, B., 2024. Anatomical and physical characterization of selected Sri Lankan timber species for wood preservation applications. Journal of Tropical Forestry and Environment, 14(1), pp. 1–12.
21. Niemz, P., Khazaeian, A. and Hemmasi, A.H., 2023. Wood anatomy and treatability relationships in hardwood species. Wood Material Science and Engineering, 18(4), pp. 1025–1038.
22. Ohshima, J., Yokota, S., Yoshizawa, N. and Ona, T., 2020. Fiber properties and their relationship with papermaking potential in plantation-grown eucalyptus. Forests, 12(1), p. 31.
23. Rana, R., Langenfeld-Heyser, R., Finkeldey, R. and Polle, A., 2009. Functional anatomy of five endangered tropical timber species of Dipterocarpaceae. Trees, 23(3), pp.521–529.
24. Rowell, R.M., 2013. Handbook of wood chemistry and wood composites. 2nd edn. Boca Raton, FL: CRC Press.
25. Ruwanpathirana, N.D., 2014. Development of timber property classification based on the end-use with reference to twenty Sri Lankan timber species. Journal of Tropical Forestry and Environment, 4(1).
26. Sharma, S. and Chauhan, S.S., 2022. Effect of wood anatomy on ACQ preservative penetration in teak (*Tectona grandis*). Journal of the Indian Academy of Wood Science, 19(1), pp. 45–56.
27. USDA Forest Service, 2010. Wood handbook: Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: Forest Products Laboratory.
28. Wijayaboparatne, T., Muthumala, C., Amarasinghe, M. and Marikar, F., 2024. Treatability of local and imported timber species using alkaline copper quaternary through pressure impregnation method and relation to their wood anatomy. Pro Ligno, 20(3).
29. Zieminska, K., Butler, D.W., Gleason, S.M., Wright, I.J. and Westoby, M., 2013. Fibre wall and lumen fractions drive wood density variation across angiosperms. AoB Plants, 5, plt046.

NIRANJAN KANNANGARA
UNIVERSITY OF RUHUNA
DEPARTMENT OF BIOSYSTEMS TECHNOLOGY, FACULTY OF TECHNOLOGY,
MATARA, KAMBURUPITIYA
81000 SRI LANKA

FAIZ MARIKAR*
[2]GENERAL SIR JOHN KOTELAWALA DEFENCE UNIVERSITY
RATMALANA, KANDAWWAL ROAD
10350 SRI LANKA
*Corresponding author: niranjan@btec.ruh.ac.lk/faiz@kdu.ac.lk