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EFFECT OF COPPER SULFATE IMPREGNATION ON THE PHYSICAL-MECHANICAL PROPERTIES OF SENGON AND COCONUT WOOD

Pengaruh Impregnasi Tembaga Sulfat terhadap Sifat Fisis-Mekanis Kayu Sengon dan Kelapa

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ABSTRACT

This study investigated the effect of copper sulfate ($CuSO_4$) impregnation on the physical and mechanical properties of sengon wood (*Falcataria moluccana*) and coconut wood (*Cocos nucifera*) for green building applications. Wood samples aged 7 years from Samarinda, East Kalimantan, were treated using a vacuum-pressure impregnation method. Physical properties were evaluated through weight percent gain (WPG) and density, while mechanical properties were assessed by modulus of elasticity (MOE) and modulus of rupture (MOR). $CuSO_4$ impregnation significantly increased WPG and density in both species, with coconut wood showing higher absorption in WPG (21.84%) than sengon wood (14.47%) due to its more porous structure. MOE decreased in both species after treatment, with a greater reduction in sengon wood due to its lower density. For MOR, sengon wood showed a slight decrease, whereas coconut wood demonstrated an increase from 587.42 to 663.96 kg/cm², attributed to the interaction between the impregnation solution and its denser fiber structure. $CuSO_4$ impregnation was more effective in enhancing the bending strength of coconut wood, though the stiffness reduction in both species should be considered for sustainable building material applications.

Keywords: Coconut Wood; Copper Sulfate; Impregnation; Physical-Mechanical Properties; Sengon Wood.

ABSTRAK

Penelitian ini mengkaji pengaruh impregnasi dengan tembaga sulfat ($CuSO_4$) terhadap sifat fisik dan mekanik kayu sengon (*Falcataria moluccana*) dan kayu kelapa (*Cocos nucifera*) untuk aplikasi bangunan ramah lingkungan. Sampel kayu berusia 7 tahun yang berasal dari Samarinda, Kalimantan Timur, diolah menggunakan metode impregnasi vakum-tekan. Sifat fisik dievaluasi melalui persen kenaikan berat (WPG) dan kerapatan, sedangkan sifat mekanik dinilai berdasarkan modulus elastisitas (MOE) dan modulus patah (MOR). Impregnasi $CuSO_4$ secara signifikan meningkatkan WPG dan kerapatan pada kedua jenis kayu tersebut, dengan kayu kelapa menunjukkan nilai persen kenaikan berat yang lebih tinggi (21,84%) dibandingkan kayu sengon (14,47%) karena strukturnya yang lebih berpori. MOE menurun pada kedua jenis kayu setelah perlakuan, dengan penurunan yang lebih besar pada kayu sengon karena kerapatannya yang lebih rendah. Untuk MOR, kayu sengon menunjukkan penurunan yang sedikit, sedangkan kayu kelapa menunjukkan peningkatan dari 587,42 kg/cm² menjadi 663,96 kg/cm², yang dikaitkan dengan interaksi antara larutan impregnasi dan struktur seratnya yang lebih padat. Impregnasi $CuSO_4$ lebih efektif dalam meningkatkan kekuatan lentur kayu kelapa, meskipun penurunan kekakuan pada kedua jenis kayu tersebut perlu dipertimbangkan untuk aplikasi bahan bangunan berkelanjutan.

Kata kunci: Impregnasi; Kayu Kelapa; Kayu Sengon; Sifat Fisis-Mekanis; Tembaga Sulfat

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A. INTRODUCTION

The development of the green building concept has encouraged the use of construction materials that are highly durable and derived from renewable resources, thereby having a lower environmental impact than conventional materials (Mahardika *et al.* 2025). Wood, as a readily renewable material, is capable of sequestering carbon throughout its service life and requires relatively less energy to produce than steel or concrete (Patrizi *et al.* 2026). However, the increasing demand for sustainable building materials is not always linear with the availability of high-quality wood, making the use of fast-growing wood species and alternative biomass sources crucial (Ningrum & Yuniawati, 2023).

In Indonesia, sengon wood (*Falcataria moluccana*) and coconut wood (*Cocos nucifera*) are abundant lignocellulosic resources with the potential to support the development of materials for green building. Sengon and coconut trees have rapid growth and high productivity, making them potential raw materials for engineered wood (Fariha *et al.* 2025). Nevertheless, the utilisation of both wood species remains limited due to their mechanical properties being insufficient for applications requiring high strength and stiffness. Sengon wood has low density, resulting in limited mechanical strength (Fadia *et al.* 2023a). Whilst coconut wood exhibits high variability in properties due to its heterogeneous anatomical structure along the stem cross-section (Srivaro *et al.* 2020).

One approach with potential for further development is chemical modification through impregnation. Copper sulphate ($CuSO_4$) is of particular interest because it penetrates wood tissue readily and has long been used as a preservative against fungi and wood-destroying organisms (Ciglian & Reinprecht, 2022). Copper ions deposited within the wood structure may also affect dimensional stability and cell wall interactions, which in turn can influence physical and mechanical properties (Lasota *et al.* 2019). However, research on copper-based treatments has focused mainly on preservation, and where mechanical effects have been examined, studies have centred on temperate softwoods such as radiata pine and Norway spruce (Aguayo *et al.* 2022; Ciglian & Reinprecht, 2022). Reviews of sengon modification list acetylation, furfurylation, thermal modification, and impregnation with other agents (Julian & Fukuda, 2024) and recent sengon impregnation work has used nanoparticle systems (Fadia *et al.* 2023b). Few studies have compared how the same $CuSO_4$ treatment affects species with contrasting structures, such as low-density, relatively homogeneous sengon and heterogeneous coconut wood with a pronounced density gradient across the stem (Arieny & Kuswytasari, 2025; Yadava *et al.* 2026).

Consequently, this study evaluates changes in the density and mechanical properties of sengon and coconut wood following $CuSO_4$ impregnation, with particular attention to how the response differs between the two species. The sustainability contribution of this approach is framed in terms of extended service life and improved performance of fast-growing, underutilised biomass, which can reduce pressure on high-quality timber and delay replacement. $CuSO_4$ is recognized as a copper-based biocidal compound with known ecotoxicity, and copper leaching during service or at end of life is an environmental concern (Atiang' *et al.* 2025; Morais *et al.* 2021). The findings are intended to inform modification strategies that improve the technical value of sengon and coconut wood, thereby making them more suitable for sustainable building material applications within the concept of green building.

B. METHODS

Materials

This study used raw materials from sengon wood (*Falcataria moluccana*) and coconut tree (*Cocos nucifera*) harvested in Samarinda, East Kalimantan, Indonesia, at an age of 7 years. The selected sengon trees were 18 m tall with a diameter of 27 cm (at breast height of 1.3 m), whilst the coconut trees were 13 m tall with a diameter of 24 cm. All trees used had straight trunks and showed no visible defects or signs of attack by destructive organisms. Wood samples were taken from the same longitudinal position in every tree –in this study, the middle section of the log– to obtain uniform material characteristics. The wood was cut into test specimens measuring 2 cm × 2 cm × 30 cm (British Standard, 1957), with 10 specimens of each treatment. The chemicals used were copper (II) sulphate pentahydrate ($CuSO_4.5H_2O$ produced by Merck, Germany, with 99% purity) and distilled water.

Impregnation Process

An impregnation solution of 5.2% (w/v) $CuSO_4$ was prepared by dissolving 572 g of copper (II) sulphate pentahydrate ($CuSO_4.5H_2O$) in 11 L of distilled water at room temperature, corresponding to approximately 52 g/L (≈ 0.21 mol/L, or ≈ 13.2 g Cu/L). The solution was stirred using a magnetic stirrer for 15 minutes to obtain a homogeneous mixture, a clear blue solution, and no visible undissolved crystals. Before the impregnation process began, the wood was first dried at a temperature of 103±2 °C to achieve a constant wood weight, after which the wood was weighed and its dimensions measured. The impregnation process was carried out using the vacuum-pressure method. The wood was arranged and

placed into the impregnation chamber. After the tube was sealed, an initial vacuum of 0.8 kg/cm^2 was applied for 15 minutes, and the solution was introduced into the chamber while the vacuum was maintained. A pressure of 10 kg/cm^2 was then applied for 60 minutes, followed by a final vacuum of 0.8 kg/cm^2 for 15 minutes. The wood specimens were removed and drained of excess solution from the wood. The wood was oven-dried in an oven at 103±2 °C to constant weight, then reweighed and remeasured.

Physical and Mechanical Properties Measurement

The effectiveness of wood impregnation is measured by the increase in weight and density of the wood before and after impregnation. The increase in wood weight is calculated using the weight percent gain (WPG), which is the percentage difference between the weight before (W_0) and after (W_1) impregnation. Density, on the other hand, is the ratio of mass (g) to volume (cm^3) of the wood at a specific moisture content. The following equations are used to calculate the WPG and density values.

$$WPG(\%) = \frac{W_1 - W_0}{W_0} \times 100$$

$$Density\ (g/cm^3) = \frac{mass\ (g)}{volume\ (cm^3)}$$

The mechanical strength testing of wood carried out in this study includes measurements of the modulus of elasticity (MOE) and modulus of rupture (MOR). Wood that has been weighed and measured for its dimensions will be tested using a universal testing machine (UTM). These tests used the one-point loading method (ASTM D143-22, 2022). To obtain the MOE value, the wood sample is loaded to the proportional limit, whilst the MOR value is obtained when the wood sample has fractured. Subsequently, the MOE and MOR values are calculated using the following formulae.

$$MOE\ \ (kg/cm^2) = \frac{L^3.\Delta F}{4.a^3.b.\Delta f}$$

$$MOR\ \ (kg/cm^2) = \frac{3.Fmax.L}{2.a^2.b}$$

where ΔF is the load below the proportional limit, L is the span length, Δf is the deflection caused by load F, Fmax is the maximum load applied to the wood sample, a is the sample thickness, and b is the sample width.

Data Analysis

The research data were analysed using a completely randomised design with IBM SPSS (Statistical Package for Service Solutions) version 25.0. The data were evaluated using analysis of variance (ANOVA) and followed by Duncan's test at a 95% confidence level 95%. The correlation between parameters was evaluated using Pearson's correlation.

C. RESULTS AND DISCUSSION

The success of the $CuSO_4$ impregnation process in the structure of sengon and coconut wood affects their physical and mechanical properties. The physical property parameters that serve as key indicators in this process include moisture content and density. The increase in moisture content and density in sengon and coconut wood following $CuSO_4$ impregnation, compared with untreated wood, is shown in Table 1.

Table 1. Physical properties of the impregnated wood

Species	Treatment	WPG (%)	Density (g/cm3)
Sengon	Untreated	0^a	0.34 ± 0.03^a
	$CuSO_4$-treated	14.47 ± 8.63^b	0.44 ± 0.05^{ab}
Coconut	Untreated	0^a	0.55 ± 0.11^b
	$CuSO_4$-treated	21.84 ± 7.65^b	0.94 ± 0.20^c

Note: ^{a,ab,b,c} Different letters indicate significant differences

Based on Table 1, the results of the analysis of variance confirm that the $CuSO_4$ impregnation treatment had a significant effect on the WPG values of sengon and coconut wood. Untreated wood showed no increase in WPG values for either species, as expected, because no chemical solution was introduced. In contrast, impregnated sengon and coconut wood both gained weight, and coconut wood showed a higher WPG than sengon wood. This difference is likely related to the lower density and more porous anatomical structure of coconut wood. Coconut stems consist of vascular bundles embedded in parenchymatous ground tissue, and the latter is highly permeable and offers more void space for solution uptake (Srivaro *et al.* 2020). Since WPG is defined in relation to oven-dried mass, species with lower density also tend to exhibit higher WPG for the same absorbed solution volume. Standard deviations were high in both species, indicating substantial variation in uptake among the specimens. All specimens were taken from the same longitudinal position, namely the middle of the log, and the same radial zone, which limits, but does not eliminate, within-tree variation. The remaining variability likely reflects natural differences in density and anatomy among trees and among specimens, rather than inconsistency in the treatment, because all specimens were treated together in a single vacuum-pressure cycle under identical conditions.

$CuSO_4$ treatment also had a significant effect on the density of both species. Test results showed that untreated coconut wood had a higher density than sengon wood. This reflects the fundamental differences in the properties of the two materials. Sengon wood has thin cell walls with a high proportion of cellular voids, resulting in low wood density (Mastap *et al.* 2023). On the other hand, coconut wood has dense fibre bundles, creating a very compact wood structure and thus a high density (Wang *et al.* 2023). In addition to the already high initial density of coconut wood, the high density of coconut wood following $CuSO_4$ impregnation treatment also indicates a significant response to the impregnation treatment compared to sengon wood. $CuSO_4$ treatment caused an increase in density in both wood species. This increase is consistent with the WPG values obtained; the higher the absorption of the $CuSO_4$ solution, the greater the increase in mass per unit volume of wood. The preservative that successfully penetrated the cell walls has crystallised, thereby increasing the density of both woods (Pramasari *et al.* 2021).

Evaluation of the mechanical properties of sengon and coconut wood treated with $CuSO_4$ showed that the treatment had different effects on the MOE and MOR values. As shown in Figure 1, coconut wood had a higher MOE value than sengon wood under both treatment conditions. In untreated wood, the MOE value of coconut wood reached 61,726.49 kg/cm², whilst sengon wood was only 42,724.77 kg/cm². This indicates that coconut wood has a higher stiffness than sengon, making it better able to resist elastic deformation when subjected to a load (Kusnindar *et al.* 2018).

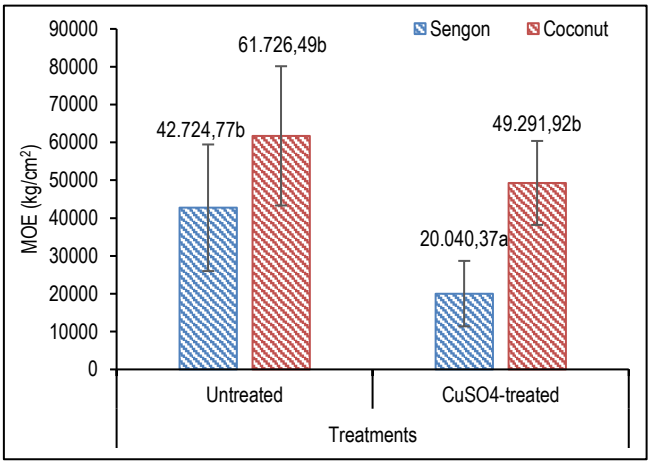
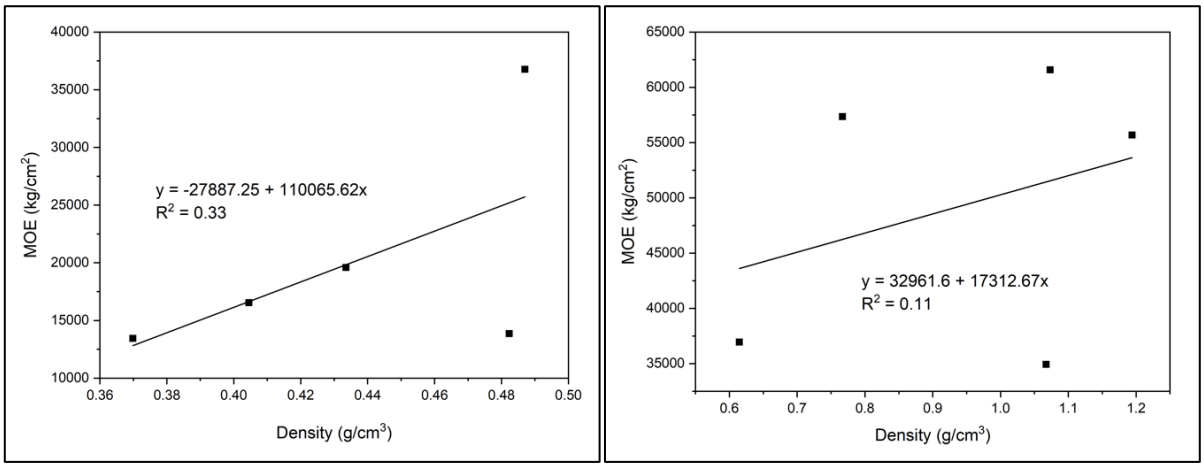


Figure 1. MOE values of sengon and coconut wood after impregnation treatment

Following $CuSO_4$ impregnation, the MOE values of both materials decreased compared to untreated wood. The low extractive content in sengon wood may allow chemicals to be absorbed readily (Mangurai & Munadian, 2024), and the $CuSO_4$ solutions were acidic, so partial hydrolysis of cell wall polymers during impregnation and oven-drying could have reduced stiffness (Gea, 2025). This mechanism was not examined in the present study and remains a hypothesis. Coconut wood still had a higher MOE than sengon wood in both conditions. This is consistent with its higher initial density and fibrous vascular bundles (Herawati *et al.* 2025; Oduor & Githiomi, 2006), which may help it retain stiffness better than the lower-density, more porous sengon wood (Wulandari & Amin, 2022). Notably, MOE of coconut wood increased after treatment while its MOE decreased, indicating that the treatment did not affect strength and stiffness in the same way. This difference should be investigated further, for example by combining mechanical tests with chemical or microstructural analysis.



(a) (b)

Figure 2. Pearson's correlation between density and MOE of (a) sengon and (b) coconut wood

Density was positively related to MOE in both species (Figure 2), indicating that MOE tended to increase with density. The relationship was moderate in sengon wood and weak in coconut wood, so density explained about 33% and 11% of the variation in MOE, respectively. The remaining variation was likely influenced by other factors, such as anatomical characteristics, cell wall thickness, specimen-to-specimen variability, and the distribution of $CuSO^4$ within the wood structure (Lahtehla *et al.* 2014).Because density was measured after treatment and therefore includes deposited copper salt, it may not reflect cell wall substance alone, which could further weaken the relationship. The stronger relationship in sengon is consistent with its more homogeneous structure, whereas the weaker one in coconut wood is consistent with the heterogeneity of its vascular bundle distribution, although this was not tested directly in this study.

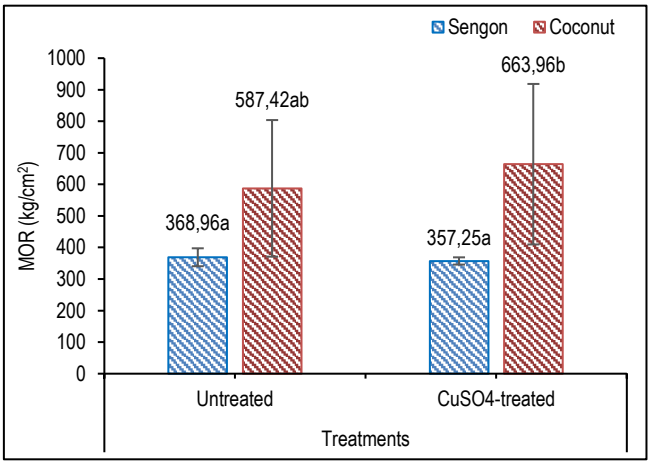
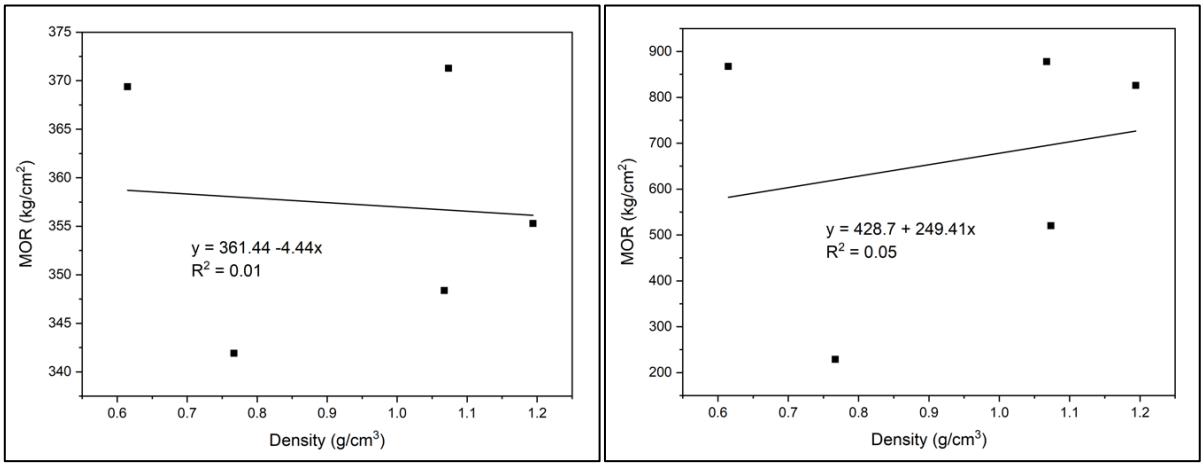


Figure 3. MOR values of sengon and coconut wood following impregnation treatment

Figure 3 shows the results of MOR evaluation of both sengon and coconut wood. The MOR value indicates the maximum bending stress a specimen sustains before failure. Coconut wood had a higher MOR than sengon wood in both conditions. Untreated sengon reached 368.96 kg/cm², whilst coconut wood reached 587.42 kg/cm². After $CuSO_4$ impregnation treatment, the MOR of sengon wood decreased slightly to 357.25 kg/cm². This small decrease indicates that $CuSO_4$ had no effect on improving the bending strength of sengon wood. A similar absence of improvement, or a reduction in some strength properties, has been reported for Norway spruce treated with inorganic preservatives; notably shear strength (Ciglian & Reinprecht, 2022). As chemical changes in the cell wall were not examined, the underlying cause of the slight decrease cannot be conclusively determined. Potential contributing factors include the mild acidity of the $CuSO_4$ solution, in combination with oven-drying at 103±2 °C, which may have induced slight hydrolysis of hemicelluloses, as well as natural variation among specimens. However, these explanations remain hypothetical and require further investigation, for instance, through FTIR analysis or other chemical composition analyses.

In contrast, the MOR of coconut wood increased to 663.96 kg/cm² following $CuSO_4$ treatment. Coconut wood has vascular bundles distributed across the stem, which makes its mechanical properties non-uniform (Hunggurami *et al.* 2014), and part of this difference may therefore reflect natural variation between specimens. The higher WPD of coconut wood (Table 1) shows that more copper salt was deposited in it, and this deposit may have increased density and stiffened

the cell wall and the ground tissue around the bundles, improving stress distribution during bending (Rahayu *et al.* 2024). Initial density also strongly influences MOR through cell wall thickness and lumen diameter (Mańkowski *et al.* 2025). These findings suggest that $CuSO_4$ impregnation does not reduce the bending strength of coconut wood and may increase it, although the mechanism requires confirmation, and the increase should be interpreted with caution given the variability noted above.



(a) (b)

Figure 4. Pearson's correlation between density and MOR of (a) sengon and (b) coconut wood

The relationship between density and MOR is shown in Figure 4. In sengon wood (Figure 4a), the relationship was negligible (R^2 = 0.01, slightly negative slope). In coconut wood (Figure 4b), the relationship was weakly positive (R^2 = 0.05). Density therefore explained about 1% and 5% of variation in MOR, respectively, and neither relationship was statistically significant. This indicates that density had little influence on MOR within the range tested, and that variation in MOR was likely governed by other factors such as anatomical characteristics, cell wall structure, the distribution of $CuSO_4$ within the wood matrix, and specimen-to-specimen variability (Lahtehla *et al.* 2014).One reason for the weak relationship may be that density here was measured after treatment and includes the mass of deposited copper salt, so it no longer reflects only the amount of wood substance carrying the load. Density in the treated groups increased with $CuSO_4$ uptake, which in sengon was not accompanied by an increase in MOR.

These results define the practical value of the treatment. For sengon, $CuSO_4$ impregnation gave no gain in bending strength and a small decrease, so it cannot be recommended where strength improvement is the aim. For coconut wood, bending strength was maintained or increased, but this result needs confirmation with larger samples, given the variability noted above. The potential benefit of CuSO4 therefore lies mainly in biological protection, which was not tested here and is documented in the literature (Ciglian & Reinprecht, 2022). The treated wood may be considered for non-structural of lightly loaded applications in which decay and insect resistance matter more than a gain in strength, such as interior elements and cladding or fencing without ground contact, provided the copper leaching issues discussed above are addressed. The use of treated wood in structural elements, ground-contact applications, or environments near water and food is not recommended without further evaluation of its durability, leaching potential, and long-term mechanical performance.

D. CONCLUSION

This study successfully examined the effect of copper sulphate ($CuSO_4$) impregnation on the physical and mechanical properties of sengon and coconut wood. $CuSO_4$ impregnation treatment significantly increased the WPG and density values in both wood species. However, there was a decrease in the MOE value following $CuSO_4$ impregnation treatment in both wood species. This is because $CuSO_4$ is acidic, which degrades the components of the wood cell walls. In addition, there was a slight decrease in the MOR value of sengon wood, although in coconut wood it actually increased due to the interaction of the impregnation solution with its denser fibres. Analysis of correlation confirmed a weak correlation between wood density and mechanical properties, including MOE and MOR. Overall, $CuSO_4$ impregnation was more effective in increasing the flexural strength of coconut wood compared to sengon wood, although the reduction in stiffness in both species still needs to be considered in its application as a sustainable building material.

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AUTHOR'S DECLARATION

- Conflicts of Interest: None.
- We here by confirm that all the Figures and Tables in the manuscript are ours.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- No potentially identified images or data are present in the manuscript.

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