Tropical Aquatic and Soil Pollution

Research Article
Volume 6(1), 2026, 28−39
https://doi.org/10.53623/tasp.v6i1.1159

Eco-Friendly Wood Preservation Using Nano Urea to Prevent Fungal Degradation and Improve Material Durability

Muhammad Latif*, Kusrin, Bambang Purnijanto, Diah Rahmawati

Department of Civil Engineering, Faculty of Engineering, Universitas Semarang (USM), USM Tower, 7th Floor, Jl. Soekarno-Hatta, Tlogosari Kulon, Pedurungan, Semarang 59160, Central Java, Indonesia

*Correspondence: muhammadlatif@usm.ac.id

SUBMITTED: 15 April 2026; REVISED: 18 May 2026; ACCEPTED: 20 May 2026

ABSTRACT: Wood is widely used in construction due to its renewability and favorable mechanical properties; however, it is highly susceptible to fungal degradation, which reduces durability and structural performance. Conventional wood preservatives are effective but often raise environmental and health concerns because of their toxic chemical content. This study investigates the use of nano-urea as an eco-friendly wood preservative for sengon wood (*Falcataria moluccana*), representing one of the first studies exploring nano-urea specifically for antifungal wood protection and durability enhancement. Sengon wood samples were treated with nano-urea at concentrations of 2%, 3%, and 5%, alongside untreated control samples. Antifungal performance was evaluated through weight loss measurements, fungal growth observations, and assessment of the infected area after 12 weeks of exposure, while mechanical performance was assessed using tensile strength testing and microstructural analysis. The results demonstrated that increasing nano-urea concentration significantly reduced fungal degradation, with the 5% treatment completely inhibiting visible fungal growth. In addition, nano-urea treatment slightly improved tensile performance and produced a denser wood microstructure with reduced pore size, indicating enhanced structural compactness. These findings confirm that nano-urea is a promising sustainable alternative to conventional preservatives, offering effective biological protection while maintaining mechanical integrity. The proposed treatment also shows strong potential for scalable and environmentally responsible applications in sustainable construction and wood-based material industries.

KEYWORDS: Nano-urea; wood preservation; antifungal; sengon wood; sustainable materials; tensile strength

1. Introduction

Wood remains a cornerstone of the construction industry as a versatile natural resource, valued for its renewability, widespread availability, and excellent mechanical properties. Nevertheless, its organic nature makes it highly vulnerable to biological decay caused by fungi, termites, and various microorganisms. Such degradation poses a serious threat to the material's longevity and structural integrity [1–3]. Specifically, fungal infestation is a major driver of timber deterioration, resulting in significant mass loss, reduced mechanical strength, and the premature failure of wooden structures. In tropical regions with high humidity, fungal biodeterioration can accelerate timber degradation, increase maintenance costs, and shorten the service life of wood-based infrastructure, thereby creating substantial economic and environmental burdens for the construction sector [4–7].

Traditional approaches to wood preservation frequently involve the application of synthetic chemicals, including borates and chromated copper arsenate [8,9]. While these methods provide effective protection, they are increasingly scrutinized because of their toxic effects on human health and their persistence in soil and aquatic ecosystems [8,10]. Several conventional preservatives containing chromium, arsenic, or copper compounds have also been subjected to stricter environmental regulations and usage restrictions in many countries due to concerns regarding carcinogenicity, groundwater contamination, and long-term ecological persistence [8–10]. In addition, some chemical preservatives may adversely affect wood recyclability and generate hazardous residues during disposal or combustion processes. These growing environmental concerns have stimulated the development of sustainable and eco-friendly preservation technologies that minimize ecological impacts without compromising material performance [11–13].

In recent years, nanotechnology has emerged as a transformative approach in material science for enhancing the durability and functionality of natural materials [11, 14]. Nanomaterials possess unique physicochemical properties, such as large surface area and high reactivity, which enable deeper penetration and stronger interactions within the wood cellular matrix [14–16]. One promising innovation is nano-urea. Compared with other nanomaterials, nano-urea offers several advantages, including low production cost, high water solubility, nitrogen-based composition, and potential dual functionality as both a reinforcing agent and antifungal stressor. Its nanoscale dimensions may facilitate deeper penetration into wood pores, thereby reducing permeability and disrupting fungal colonization within the wood structure. Unlike commonly studied nanomaterials such as nano-silver, nano-zinc oxide, or nano-copper, which are often associated with higher material costs and potential metal-related ecotoxicity concerns, nano-urea provides a potentially more biodegradable and economically accessible alternative for sustainable wood preservation applications [14–16].

Despite extensive studies on conventional preservatives and nanotechnology-based wood protection systems, research on the use of nano-urea as an antifungal preservative for wood materials, particularly sengon wood (*Falcataria moluccana*), remains very limited [17–21]. Existing studies on nano-urea have primarily focused on agricultural applications, especially as controlled-release fertilizers and nutrient delivery systems, while its potential role in wood preservation and structural enhancement has not been comprehensively investigated [17–20].

From an ecological perspective, integrating nano-based treatments into wood preservation strategies aligns with global efforts toward pollution prevention and sustainable resource management [10, 12, 22]. By reducing reliance on hazardous chemicals, these green nanomaterials may help mitigate environmental contamination risks [10, 23]. Furthermore, extending the operational lifespan of biomass resources contributes directly to more sustainable environmental practices and resource efficiency [9, 23].

This study hypothesizes that nano-urea can penetrate the wood microstructure, reduce pore accessibility, and inhibit fungal growth through physicochemical interactions within the wood matrix while simultaneously improving structural compactness and maintaining mechanical integrity. To address the identified research gap, the present study evaluates the performance of nano-urea treatments in enhancing the antifungal resistance and tensile strength of sengon wood (*Falcataria moluccana*). The findings are expected to contribute to the development of environmentally friendly wood preservation technologies and support broader innovations in sustainable material science.

2. Materials and Methods

2.1. Materials

The primary material used in this study was sengon wood (*Falcataria moluccana*), obtained from local suppliers in Semarang, Central Java, Indonesia. The wood samples were selected from trees aged approximately 10 years to ensure uniformity in maturity and mechanical characteristics. Nano-urea solution was used as the preservation agent and was obtained from Cendekia Nano Tech Hutama Laboratory, Semarang, Indonesia, with particle sizes ranging from 1–100 nm. The nano-urea suspension was homogenized using magnetic stirring for 30 min prior to application to ensure uniform particle dispersion. Fungal biodegradation testing was conducted using two common wood-decaying fungi, namely *Aspergillus niger* and *Trichoderma viride*, cultivated on potato dextrose agar (PDA) medium at 27 ± 2°C and relative humidity of 75–80%. Sengon wood samples were prepared in powder form for antifungal testing and as fiber specimens for mechanical testing following ASTM D143 standards for small clear timber specimens. The fiber samples were prepared with dimensions of 2 mm × 2 mm × 200 mm. Prior to treatment; all samples were oven-dried at 60°C for 24 h to achieve constant moisture content. The samples were subsequently immersed in nano-urea solutions at concentrations of 2%, 3%, and 5% for 48 h at room temperature (27 ± 2°C) using a passive diffusion immersion method without vacuum-pressure assistance. After impregnation, the samples were air-dried for 24 h and reconditioned in an oven at 40°C until constant weight was achieved to stabilize nano-urea absorption within the wood structure.

2.2. Experimental design.

This study employed an experimental laboratory approach to evaluate the effect of nano-urea treatment on the antifungal resistance and mechanical properties of sengon wood. The experimental design consisted of four groups: (1) untreated sengon wood (control), (2) sengon wood treated with 2% nano-urea, (3) sengon wood treated with 3% nano-urea, and (4) sengon wood treated with 5% nano-urea. Each sample group was subjected to fungal exposure and mechanical testing after a 12-week conditioning period. All experiments were conducted in triplicate (n = 3), and the results are presented as mean ± standard deviation.

2.2.1. Antifungal testing.

The antifungal performance of treated and untreated wood samples was evaluated by measuring weight loss and fungal growth area after exposure to fungal cultures. For fungal exposure, treated wood specimens were placed on PDA medium inoculated with actively growing cultures of *Aspergillus niger* and *Trichoderma viride*. The inoculation process was conducted through direct contact between fungal mycelia and wood specimens under sterile laboratory conditions. All samples were incubated at 27 ± 2°C and relative humidity of 75–80% for 12 weeks to simulate favorable fungal growth conditions. Parameters including percentage weight loss, visual observation of mycelial growth, and infected area (cm^2) were recorded after the incubation period. Weight loss was calculated by comparing the initial and final masses of the samples after fungal exposure.

2.2.2. Mechanical Testing

Mechanical properties were evaluated using tensile strength testing based on ASTM D143 standards, which are commonly used for assessing the mechanical properties of wood and small clear timber specimens. Fiber specimens were tested using a universal testing machine available at the Cendekia Nano Tech Hutama Laboratory. The loading rate during tensile testing was maintained at 2 mm/min under controlled laboratory conditions. The maximum tensile stress (N/mm^2) was recorded and analyzed to determine the effect of nano-urea treatment on mechanical performance.

2.3. Data Collection and Analysis

Data collection was carried out through laboratory measurements, including mass determination, tensile testing, and microscopic observation. All measurements were conducted under controlled laboratory conditions. The collected data were analyzed using descriptive statistics and one-way analysis of variance (ANOVA) to evaluate significant differences among treatment groups. Statistical significance was determined at a 95% confidence level ($p < 0.05$). The effectiveness of nano-urea treatment was evaluated based on reductions in fungal growth, improvements in mechanical strength, and changes in wood microstructure.

3. Results and Discussion

3.1. Antifungal performance of nano-urea treatment.

The efficacy of nano-urea in protecting sengon wood (*Falcataria moluccana*) was assessed through weight loss measurements, visual inspection of fungal proliferation, and determination of the total infected area over a 12-week period. Antifungal evaluation was conducted using *Aspergillus niger* and *Trichoderma viride* under controlled laboratory conditions. The results are summarized in Table 1 as mean ± standard deviation (n = 3).

Table 1. Antifungal test results of nano-urea-treated sengon wood after 12 weeks (mean ± SD, n = 3).

No	Sample	Weight Loss (%)	Visual Observation	Infected Area (cm²)
1	Untreated sengon wood	34	Mycelium growth	2.3
2	Sengon wood + nano-urea (2%)	7	Mycelium growth	1.2
3	Sengon wood + nano-urea (3%)	3	Mycelium growth	0.7
4	Sengon wood + nano-urea (5%)	0	No fungal growth	0

The data presented in Table 1 reveal that untreated control samples underwent substantial biodeterioration, as evidenced by high weight loss and extensive fungal colonization. In contrast, specimens treated with nano-urea exhibited a marked reduction in fungal degradation. The reduction followed a clear concentration–response relationship, in which weight loss progressively decreased with increasing nano-urea concentration. The 5% nano-urea treatment demonstrated the highest antifungal efficiency, showing complete inhibition of visible fungal growth and no detectable mass loss. One-way ANOVA analysis indicated statistically significant differences among treatment groups ($p < 0.05$). Such dose-dependent behavior has commonly been reported in nanomaterial-based wood preservation systems, where higher nanoparticle concentrations improve antifungal efficiency through enhanced surface interaction and pore coverage [14–16]. Compared with conventional borate- or copper-based preservatives, which generally reduce fungal decay but may still exhibit residual deterioration under prolonged exposure [8, 9], nano-urea demonstrated comparable antifungal performance while offering a potentially lower environmental burden because of the absence of heavy metal components. In addition, several conventional preservatives containing chromium, arsenic, or copper compounds have increasingly been restricted in various countries because of their persistence, toxicity, and environmental accumulation risks [8–10].

The enhanced resistance to fungal attack is largely attributed to the nanoscale dimensions of urea particles, which allow deeper infiltration into the wood's complex architecture and more effective interaction with cell walls [14, 15]. This deep penetration effectively limits the accessibility of nutrients required for fungal survival and growth [3, 5]. In addition, nano-urea may interfere with fungal metabolism through localized nitrogen imbalance and disruption of enzymatic activity associated with lignocellulosic degradation. Nanoparticle interactions with fungal cell walls may also alter membrane permeability and inhibit hyphal development, thereby suppressing fungal colonization within the wood structure [14–16].

From an ecological perspective, nano-urea serves as a promising eco-friendly substitute for traditional chemical preservatives. The application of such nanotechnology may reduce environmental toxicity while advancing sustainable strategies for material protection [11, 21, 24]. Unlike conventional preservatives containing chromium, arsenic, or copper compounds that may persist in soil and aquatic systems [8–10], nano-urea is nitrogen-based and potentially more biodegradable. However, further studies are still required to evaluate long-term nitrogen leaching behavior, soil transformation pathways, and ecotoxicological impacts under real environmental conditions before large-scale industrial application can be fully recommended.

3.2. Mechanical properties of treated wood.

The tensile strength of sengon wood (*Falcataria moluccana*) under various nano-urea treatments is presented in Table 2 as mean ± standard deviation (n = 3)**.** The untreated wood exhibited the lowest tensile strength, while nano-urea-treated specimens showed gradual improvement with increasing concentration. The highest tensile performance was observed in the 5% nano-urea treatment group. Statistical analysis using one-way ANOVA demonstrated significant differences among treatment groups ($p < 0.05$). The observed gains in tensile strength may result from nano-urea particles filling the microscopic voids within the timber, thereby creating a more cohesive and compact fiber network [14, 15]. In contrast, many conventional preservatives tend to compromise mechanical strength by causing chemical degradation of the cell wall components [8, 9]. Nano-urea, however, maintains structural performance, supporting its use in sustainable construction. The slight increase in tensile strength also suggests that nano-urea treatment does not induce substantial chemical deterioration of cellulose or hemicellulose components, which are essential for maintaining wood mechanical integrity.

Table 2. Tensile strength of sengon wood under different nano-urea treatments **(**mean ± SD, n = 3**).**

No	Sample	Sample Weight (g)	Tensile Strength (N/mm^2)
1	Untreated sengon wood	75.04	15.331
2	Sengon wood + nano-urea (2%)	75.09	15.337
3	Sengon wood + nano-urea (3%)	75.11	15.442
4	Sengon wood + nano-urea (5%)	75.14	15.558

3.3. Microstructural characteristics.

The quantitative microstructural characteristics of nano-urea-treated sengon wood are presented in Table 3 as mean ± standard deviation (n = 3). The results indicate a progressive reduction in pore diameter with increasing nano-urea concentration, accompanied by denser fiber structure and harder texture characteristics. Figure 1 was generated from original microscopic observations obtained in the present study and represents the actual treatment groups used in the experimental design. The decrease in pore diameter points toward improved internal compaction, where the nano-urea acts as a filler that strengthens fiber bonding and minimizes void spaces [14, 15]. Furthermore, this densification process lowers the material's permeability, which helps restrict the penetration of both fungal hyphae and moisture [16]. From a transport theory perspective, the reduction in pore size likely decreases diffusion pathways for water molecules, oxygen, and fungal spores within the lignocellulosic matrix. This pore-blocking mechanism may significantly limit internal moisture transport and fungal mobility, thereby enhancing resistance against biodeterioration. Similar nanoparticle-induced permeability reduction mechanisms have been reported in other lignocellulosic and wood-based composite systems [14–16].

Table 3. Microstructural characteristics of sengon wood after nano-urea treatment.

No	Sample	Pore Diameter (μm)	Pore Distribution	Fiber Density	Texture
1	Untreated sengon wood	180	Uniform	Medium	Medium
2	Sengon wood + nano-urea (2%)	160	Uniform	Dense	Hard
3	Sengon wood + nano-urea (3%)	155	Uniform	Dense	Hard
4	Sengon wood + nano-urea (5%)	140	Uniform	Dense	Hard

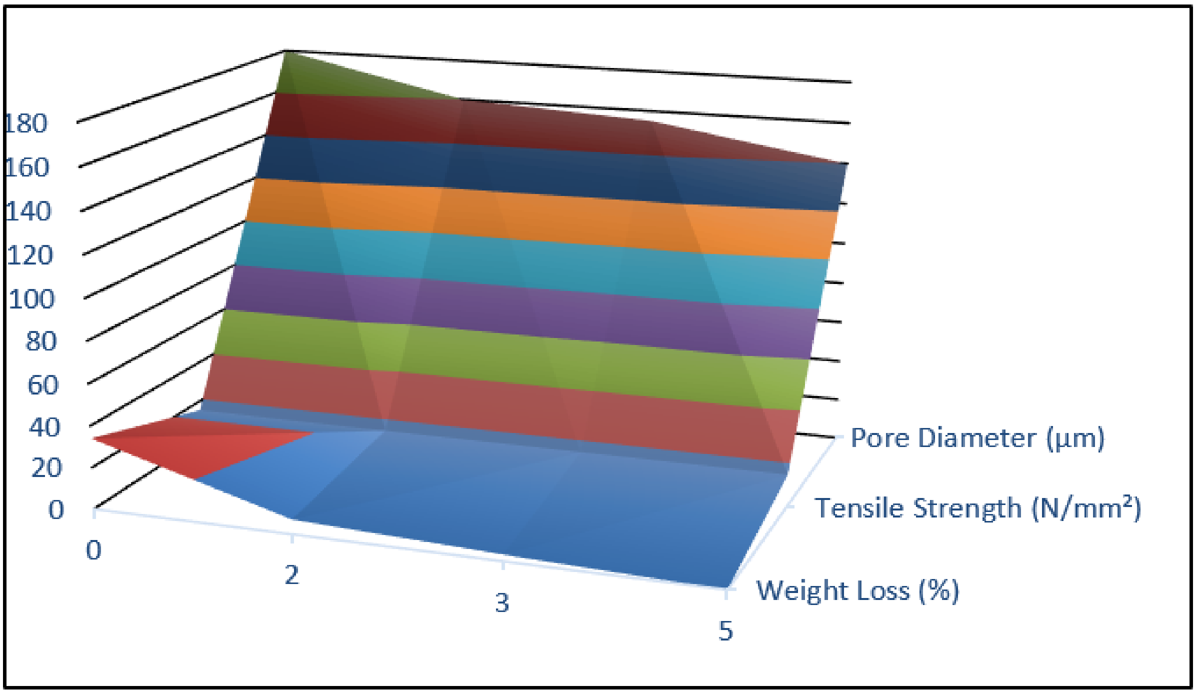

Figure 1. Cross-sectional images of sengon wood under different treatment conditions at 50× magnification.

3.4. Integrated discussion and environmental implications.

The findings demonstrate that nano-urea treatment significantly enhances antifungal resistance without adversely affecting the mechanical properties of sengon wood. These results confirm its potential as a multifunctional material for wood protection. From an environmental perspective, nano-urea supports the development of sustainable material systems by reducing reliance on hazardous chemical preservatives [10, 12, 22]. The application of such green technology aligns with recent advancements in the preparation of delignified wood fibers for absorbent applications [25] and the enhancement of oriented strand board performance for eco-friendly construction [26]. By reducing dependence on aggressive hazardous chemicals, these green nanomaterials may help mitigate environmental contamination risks [10,23]. Furthermore, extending the operational lifespan of biomass resources through eco-friendly modifications, such as heat-treated extracts or nano-based coatings, is essential for sustainable environmental management [9, 24, 27]. Nevertheless, although nano-urea demonstrates promising environmental advantages compared with conventional heavy metal-based preservatives, comprehensive life-cycle assessment and ecotoxicity evaluation remain necessary. Particular attention should be given to the long-term environmental fate of nano-urea residues, nitrogen release behavior, and potential accumulation in surrounding ecosystems during prolonged service conditions.

3.5. Limitations and future research.

Despite the promising results obtained in this study, several limitations should be acknowledged. First, the present work was limited to controlled laboratory conditions and focused on a relatively simplified wood–fungus interaction system involving only two fungal species, namely *Aspergillus niger* and *Trichoderma viride*. In natural environments, wood degradation is typically driven by a far more complex microbial ecosystem, where multiple fungal species, bacteria, and environmental factors such as fluctuating humidity, temperature variation, and UV exposure interact simultaneously. These complex interactions may significantly alter degradation kinetics and could lead to different performance outcomes compared with those observed under controlled conditions [28]. Therefore, the antifungal effectiveness of nano-urea observed in this study may not fully represent real-world service conditions.

Second, while this study demonstrates the potential of nano-urea as a wood preservative, its application scope remains relatively narrow, focusing primarily on antifungal protection and mechanical enhancement. Recent advances in wood engineering, particularly in multifunctional materials such as UV-shielding transparent wood and high-performance bio-composites, indicate that wood-based materials can be engineered for multiple advanced functionalities beyond preservation alone [29]. In this context, nano-urea could potentially be explored not only as a protective agent but also as a multifunctional additive that contributes to optical modification, surface chemistry tuning, or hybrid composite development. However, such applications remain unexplored and require systematic investigation.

Future research should therefore extend beyond the current experimental scope to address several key areas. Long-term durability testing under real environmental conditions is essential to evaluate the stability and effectiveness of nano-urea-treated wood over extended service periods, particularly under variable humidity, rainfall, and biological exposure. Comparative studies with conventional preservatives such as borates, copper-based systems, and emerging nano-metal oxides are also necessary to establish benchmark performance and economic feasibility. In addition, comprehensive environmental impact assessments should be conducted to evaluate the fate of nano-urea residues, including nitrogen leaching behavior, soil transformation pathways, and potential ecotoxicological effects on surrounding ecosystems. Finally, optimization of nano-urea concentration and application methods, including alternative impregnation techniques such as vacuum-pressure treatment or surface coating strategies, may further enhance penetration efficiency, performance consistency, and scalability for industrial applications.

4. Conclusions

This study demonstrates that nano-urea treatment effectively enhances the performance of sengon wood (*Falcataria moluccana*) in terms of antifungal resistance, mechanical properties, and microstructural characteristics. The results showed a substantial reduction in fungal degradation, with weight loss decreasing from 34.0 ± 1.2% in untreated samples to 0.0 ± 0.0% in wood treated with 5% nano-urea. In addition, tensile strength exhibited a gradual improvement across increasing treatment concentrations, indicating that nano-urea does not compromise and may even slightly enhance the mechanical integrity of the wood. Statistical analysis using one-way ANOVA confirmed that the differences among treatment groups were significant ($p < 0.05$). Microstructural analysis further supported these findings by showing that nano-urea effectively penetrates the wood matrix, leading to reduced pore diameter and increased fiber density. This densification of the internal structure contributes to improved dimensional stability, reduced permeability, and enhanced resistance to biological attack. The observed structural modifications suggest that nano-urea functions not only as an antifungal agent but also as a reinforcing modifier that strengthens inter-fiber interactions within the lignocellulosic network. From a broader perspective, this study contributes to the advancement of sustainable wood preservation technologies. Nano-urea offers an environmentally friendly alternative to conventional chemical preservatives, aligning with global efforts in pollution prevention and reduction of hazardous chemical use. Unlike traditional preservatives that often rely on heavy metal-based compounds or toxic synthetic chemicals, nano-urea provides a nitrogen-based approach that delivers effective antifungal protection while maintaining mechanical integrity and potentially reducing long-term environmental persistence. Moreover, improving wood durability through such treatments can extend service life, reduce material replacement frequency, and ultimately lower overall resource consumption in construction and timber-based industries. However, this study is not without limitations. The experiments were conducted under controlled laboratory conditions with a relatively limited sample size, which may not fully represent the variability of real-world environmental exposure. As a result, the long-term performance, durability, and environmental behavior of nano-urea-treated wood under field conditions remain uncertain and require further investigation. Future research should therefore focus on long-term field exposure studies to evaluate durability under natural weathering conditions, comparative assessments with conventional wood preservatives to establish performance benchmarks, and comprehensive environmental impact analyses to understand the fate of nano-urea residues, particularly in relation to nitrogen cycling and ecosystem effects. In addition, optimization of nano-urea concentration, penetration techniques, and application methods will be essential to improve treatment efficiency, scalability, and industrial feasibility. Nano-urea represents a promising, sustainable, and effective solution for enhancing wood durability and performance. Its multifunctional role as both a protective and reinforcing agent highlights its potential for application in environmentally conscious construction, advanced wood-based composites, green building materials, and sustainable timber preservation systems aimed at extending the service life of tropical wood resources.

Acknowledgments

The authors would like to express their sincere gratitude to the laboratory team at Cendekia Nano Tech Hutama, Semarang, Indonesia, for providing technical support and facilities during the experimental work. Appreciation is also extended to all individuals and colleagues who contributed to the successful completion of this research. The authors gratefully acknowledge the institutional support provided by their affiliated university and research partners. Any financial or material support received for this study is also sincerely appreciated.

Author Contribution

Muhammad Latif conceptualized the research idea, designed the methodology, conducted data analysis, and prepared the original manuscript draft. Kusrin contributed to the development of the research methodology and assisted in data collection and experimental work. Bambang Purnijanto was responsible for supervision, provided critical review, and contributed to the interpretation of the results. Diah Rahmawati supported data collection, assisted in data organization, and contributed to manuscript revision and editing. All authors have read and approved the final version of the manuscript.

Competing Interest

All authors should disclose any financial, personal, or professional relationships that might influence or appear to influence their research.

Data Availability

The data generated and analyzed in this study are available from the corresponding author upon reasonable request.

References

[1] Goodell, B.; Nielsen, G. (2023). Wood biodeterioration. Springer Handbook of Wood Science and Technology, Springer: Cham. https://doi.org/10.1007/978-3-030-81315-4_4.

[2] Fukasawa, Y. (2021). Ecological impacts of fungal wood decay types. *Ecological Research*, *36*(6), 910–931. https://doi.org/10.1111/1440-1703.12260.

[3] Li, T.; Cui, L.; Song, X.; et al. (2022). Wood decay fungi: A global research analysis. *Journal of Soils and Sediments*, *22*, 1688–1702. https://doi.org/10.1007/s11368-022-03225-9.

[4] Martín, J.A.; López, R. (2023). Biological deterioration and natural durability of wood in Europe. *Forests*, *14*, 283. https://doi.org/10.3390/f14020283.

[5] Bari, E.; Ohno, K.; Yilgor, N.; Singh, A.P.; Morrell, J.J.; Pizzi, A.; Ghanbary, M.A.T.; Ribera, J. (2021). Characterizing fungal decay of beech wood. *Microorganisms*, *9*, 247. https://doi.org/10.3390/microorganisms9020247.

[6] Cui, D.; Xue, J.; Cao, J. (2023). Dual-fungi competition and wood degradation. *Industrial Crops and Products*, *198*, 116643. https://doi.org/10.1016/j.indcrop.2023.116643.

[7] Perera, P.; Herath, H.; Paranagama, P.A.; Wijesinghe, P.; Attanayake, R.N. (2023). Wood decay fungi and biodeterioration processes. *PLoS ONE*, *18*(7), e0288133. https://doi.org/10.1371/journal.pone.2023.0288133.

[8] Vani, C.N.; Prajwal, S.; Sundararaj, R.; Dhamodaran, T.K. (2022). Chemical preservatives in wood protection. In: Sundararaj, R. (Ed.), Science of Wood Degradation and its Protection. *Springer*, Singapore. https://doi.org/10.1007/978-981-16-8797-6_16.

[9] Evans, P.D.; Matsunaga, H.; Preston, A.F.; et al. (2022). Wood protection for carbon sequestration: A review of existing approaches and future directions. *Current Forestry Reports*, *8*, 181–198. https://doi.org/10.1007/s40725-022-00166-x.

[10] Mohamed, M.G.; Ahmed, N.M.; Mohamed, W.S.; Ibrahim, A.H.; Mohamed, H.M. (2024). Eco-friendly formulations for enhancing protection of ceramic artifacts. *Journal of Cultural Heritage*, *67*, 404–413. https://doi.org/10.1016/j.culher.2024.04.003.

[11] Akpan, E.I.; Wetzel, B.; Friedrich, K. (2021). Eco-friendly and sustainable processing of wood-based materials. *Green Chemistry*, *23*, 1–15. https://doi.org/10.1039/D0GC04430J.

[12] Calovi, M.; Zanardi, A.; Rossi, S. (2024). Recent advances in bio-based wood protective systems: A comprehensive review. *Applied Sciences*, *14*, 736. https://doi.org/10.3390/app14020736.

[13] Rajput, H.; Rajan, P.; Li, S.; Stratton, G.W.; Murray, G.; He, Q. (2023). Development of wood preservatives to prevent biodeterioration. *Journal of Wood Chemistry and Technology*, *43*(6), 371–389. https://doi.org/10.1080/02773813.2023.2284161.

[14] Athulya, R.; Nandini, J.; Bhoi, T.K.; Sundararaj, R. (2024). Recent advances of nanotechnology in wood protection: A comprehensive review. *Wood Material Science & Engineering*, *19*(2), 279–290. https://doi.org/10.1080/17480272.2023.2239800.

[15] Darajat, A.Z.; Wahyudi, I.; Narto; Bahanawan, A.; Augustina, S. (2025). Characteristics of wood sponge from sengon wood. *Journal of Renewable Materials*, *13*(8), 1661–1681. https://doi.org/10.32604/jrm.2025.02024-0081.

[16] Khademibami, L.; Bobadilha, G.S. (2022). Recent developments in wood protection research in academia: A review. *Frontiers in Forests and Global Change*, *5*, 793177. https://doi.org/10.3389/ffgc.2022.793177.

[17] Dissanayake, W.; de Silva, M.; Munaweera, I.; Karunaratne, V.; Kottegoda, N. (2024). Nanotechnology-based urea delivery systems as climate-smart fertilizers. In: Nanofertilizer Delivery, Effects and Application Methods. *Elsevier*, 71–95. https://doi.org/10.1016/B978-0-443-13332-9.00020-4.

[18] Tapia-Hernández, J.A.; Madera-Santana, T.J.; Rodríguez-Félix, F.; Barreras-Urbina, C.G. (2022). Controlled and prolonged release systems of urea from nanomaterials. *Journal of Nanomaterials*, *2022*, 5697803. https://doi.org/10.1155/2022/5697803.

[19] Singh, P.P.; Priyam, A.; Singh, J.; Gupta, N. (2023). Urea-based nanomaterials for enhanced crop productivity. *Scientia Horticulturae*, *315*, 111988. https://doi.org/10.1016/j.scienta.2023.111988.

[20] Upadhyay, P.K.; Dey, A.; Singh, V.K.; Dwivedi, B.S.; Singh, T.; et al. (2023). Conjoint application of nano-urea with fertilizers for sustainable crop production. *PLoS ONE*, *18*(7), e0284009. https://doi.org/10.1371/journal.pone.0284009.

[21] Geweely, N.S.; Abu Taleb, A.M.; Grenni, P.; Caneva, G.; Atwa, D.M.; Plaisier, J.R.; Ibrahim, S. (2024). Eco-friendly preservation of Pharaonic wooden artifacts using natural green products. *Applied Sciences*, *14*, 5023. https://doi.org/10.3390/app14125023.

[22] Pan, M.; Li, S.; Huang, T.; et al. (2024). An advanced wood preservative based on Stellera chamaejasme root extract with high antifungal activity. *Advanced Composites and Hybrid Materials*, *7*, 74. https://doi.org/10.1007/s42114-024-00885-8.

[23] Šimůnková, K.; Hýsek, Š.; Reinprecht, L.; et al. (2022). Lavender oil as eco-friendly alternative for wood protection against termites. *Scientific Reports*, *12*, 1909. https://doi.org/10.1038/s41598-022-05959-5.

[24] Cai, Y.; Wu, Y.; Yang, F.; Gan, J.; Wang, Y.; Zhang, J. (2021). Wood sponge reinforced with polyvinyl alcohol for sustainable oil–water separation. *ACS Omega*, *6*(19), 12866–12876. https://doi.org/10.1021/acsomega.1c01280.

[25] Jiang, C.; Yu, G.; Wang, P.; Yao, Z.; Mu, L.; Li, Q.; Shi, Y. (2024). Preparation of delignified wood fibers for absorbent applications. *Industrial Crops and Products*, *219*, 119097. https://doi.org/10.1016/j.indcrop.2024.119097.

[26] Abobakr, H.; Raji, M.; Essabir, H.; Bensalah, M.O.; Bouhfid, R.; Qaiss, A.K. (2024). Enhancing oriented strand board performance using wheat straw for eco-friendly construction. *Construction and Building Materials*, *417*, 135135. https://doi.org/10.1016/j.conbuildmat.2024.135135.

[27] Bi, Z.; Morrell, J.J.; Lei, Y.; Yan, L.; Ji, M. (2022). Eco-friendly modification of wood cell walls with heat-treated wood extracts. *Industrial Crops and Products*, *184*, 115079. https://doi.org/10.1016/j.indcrop.2022.115079.

[28] Manici, L.M.; De Meo, I.; Saccà, M.L.; Ceotto, E.; Caputo, F.; Paletto, A. (2023). Fungal interactions influencing wood degradation. *Ecological Indicators*, *151*, 110312. https://doi.org/10.1016/j.ecolind.2023.110312.

[29] Hai, L.V.; Cho, S.W.; Kwon, G.J.; Lee, D.Y.; Ma, S.Y.; Bandi, R.; Kim, J.K.; Han, S.Y.; Dadigala, R.; Lee, S.H. (2023). Fabrication of eco-friendly transparent wood for UV-shielding functionality. *Industrial Crops and Products*, *201*, 116918. https://doi.org/10.1016/j.indcrop.2023.116918.