Optimal Impregnation Amounts of Flame Retardant for Semi-combustible Hinoki Cypress (*Chamaecyparis obtusa*) Plywood

Eun-Suk Jang,[a,c] Yasuyo Anno,[d] Woo-Chan Park,[e] and Hee-Jun Park,[b]

This study aimed to determine the amount of flame retardant for semi-combustible performance required to comply with the Ministry of Land, Infrastructure, and Transport Notice 2023-24 for hinoki cypress (*Chamaecyparis obtusa*) plywood, which is commonly used as a building material. A cone calorimeter was used to observe the changes in the total heat release (THR) depending on the solid content of the flame-retardant impregnation (SCFI). The relationship between the SCFI and THR was expressed as an exponential function. The solid content of the flame-retardant impregnation required to meet the prescribed standard of 8.0 MJ/m² was 108 kg/m³ (semi-combustible performance standards) for hinoki cypress plywood.

DOI: 10.15376/biores.20.4.9595-9605

Keywords: Optimal impregnation amount; Flame retardant; Semi-combustible performance; Hinoki cypress plywood; Building material; Impregnation

Contact information: a: Research Institute of Human Ecology, College of Human Ecology, Jeonbuk National University, Jeonju 54896, South Korea; b: Department of Housing Environmental Design, College of Human Ecology, Jeonbuk National University, Jeonju 54896, South Korea; c: Sambo Scientific Co., Ltd., R&D Center, Seoul 07258, South Korea; d: NS Wood Science R&D Center, Sakaiminato 6840075, Japan; e: Dai Hyun Wood Science R&D Center, Incheon, 22857 Korea;
** Corresponding author: phjun@jbnu.ac.kr*

INTRODUCTION

The global timber construction market is growing steadily owing to urbanization, sustainable building regulations, and technological advancements. According to the UN, 68% of the population is expected to live in urban areas by 2050 (UN 2018), and India requires an additional 25 million housing units annually (Housing 2019). Thus, the demand for plywood as a low-cost, highly efficient structural material is rapidly increasing (Rustiadini and Novianti 2025; Sapenti *et al.* 2025).

Plywood is typically produced from various tree species, including pine, poplar, beech, and birch (Cordier *et al.* 2025). Hinoki plywood stands out for its exceptional durability and natural antibacterial properties, making it the preferred choice for premium architectural applications (Ikei *et al.* 2018; Jang 2022). Despite these advantages, wood remains an inherently flammable material with limited fire safety. Several flame-retardant technologies have been developed (Kolya and Kang 2024; Maake *et al.* 2025).

The vacuum-pressure impregnation method for flame-retardant treatment is considered highly effective. It involves injecting flame-retardant chemicals into the inner structure of the wood, thereby limiting ignition potential and reducing smoke and toxic gas production (Ali *et al.* 2019; Mali *et al.* 2022; Jang *et al.* 2024a,b,c; Jo *et al.* 2024).

The quantity of flame retardant used in the process not only affects fire safety but also influences mechanical strength, shrinkage behavior, ease of installation, and overall economic performance (Li *et al.* 2025). Therefore, optimizing the impregnation amount is critical.

According to regulatory standards established by Korea's Ministry of Land, Infrastructure, and Transport (MOLIT), building finishing materials and fire prevention structures must exhibit total heat release (THR) values not exceeding 8 MJ/m² tested by KS F ISO 5660-1 (MOLIT Notice 2023-24, 2023).

To qualify as a flame retardant, a material must demonstrate a total heat release (THR) of no more than 8 MJ/m² within the initial 5 min of exposure to heat. The peak heat release rate (HRR) must also remain below 200 kW/m² for a continuous duration of at least 10 s. The specimen must not exhibit any penetrative damage, such as cracking, melting, or perforation, after 5 min. On the other hand, semi-combustible materials were evaluated over a 10-minute heating period. They must maintain a THR not exceeding 8 MJ/m², ensure that the HRR does not surpass 200 kW/m² for 10 s or longer, and avoid any critical structural breaches such as cracks that compromise the integrity of the specimen after 10 min of heating.

Even if the flame retardant does not fully penetrate the wood matrix, the material remains eligible for fire-safe exterior use provided it complies with the prescribed thermal emission criterion. Nonetheless, insufficient impregnation of flame retardants may compromise fire-protection capabilities. Conversely, excessive impregnation can lead to extended treatment times and unnecessary consumption of retardant agents, which increases manufacturing costs and may result in the inefficient use of flame-retardant materials.

In a previous study, the authors conducted cone calorimetric tests to evaluate the variation in THR as a function of the solid content of the flame-retardant impregnation (SCFI). Through simple linear regression analysis, it was determined that, to meet the flame-retardant standard of 8 MJ/m², the required SCFI values were 93.9 kg/m³ for Korean larch and 144.6 kg/m³ for Japanese cedar. Based on these findings, the optimal flame-retardant impregnation levels for both wood species were identified (Jo *et al.* 2024).

Previous studies have evaluated THR in SCFI on solid wood as a flame-retardant material. This study focused on structural hinoki plywood as a semi-combustible material. This paper briefly investigated the semi-combustible performance of hinoki plywood under various impregnation conditions and identified the optimal treatment amount. Although pretreating veneers with flame retardants before plywood fabrication can enhance fire safety, the altered surface energy of the veneer during bonding may lead to significant adhesion issues (Buksans and Kalnina 2024). In addition, mechanical strength reduction and increased surface roughness were consistently observed in plywood manufactured with flame-retardant-treated veneers at all treatment concentrations.

Consequently, the present approach focuses on impregnation of flame-retardant to structural plywood to achieve semi-combustible capability. The goal is to satisfy both safety and economic requirements in construction applications. This study contributes to improved fire safety in wood-based buildings by advancing beyond basic flame retardancy to achieve semi-noncombustible performance, while also promoting the sustainable use of natural resources in architectural design.

EXPERIMENTAL

Plywood Preparation

Air-dried structural hinoki cypress plywood was obtained from NS Wood Science in Japan. Two hundred sheets of plywood were prepared. The sample dimensions were 1,820 mm (length) x 910 mm (width) x 12 mm (thickness) (Fig. 1). The air-dried gravity of the plywood was approximately 0.48 ± 0.02. The specimens had a mean moisture content of 10.06 ± 0.02%.

Water-soluble Flame Retardant

Water-soluble flame retardant was manufactured by Safewood Co., Ltd. (Jeonju, Korea). This flame retardant was developed and patented by the authors' research team (Park 2013). The flame-retardant formulation contained approximately 27% solids by weight. The flame retardant contained the following components: dibasic ammonium phosphate, ammonium polyphosphate, anhydrous sodium borate, with the remaining consisting of other ingredients, and water.

The flame retardants employed in this study were inorganic non-halogenated compounds. This formulation enhanced the combustion resistance of wood through the synergistic effects of phosphorus- and boron-based components. Upon exposure to heat, the system promoted the formation of a char layer and an intumescent layer, effectively inhibiting the ingress of oxygen and heat. Specifically, ammonium polyphosphate (APP) functions as an intumescent flame retardant, markedly reducing both the HRR and THR (Yan 2014; Sauerbier *et al*. 2020).

In addition, anhydrous sodium borate contributes to smoke suppression and mitigates toxic gas emissions. Owing to their low toxicity and environmental compatibility, these flame retardants are well-suited for applications in wood-based materials (Jian *et al*. 2023; Li *et al*. 2023).

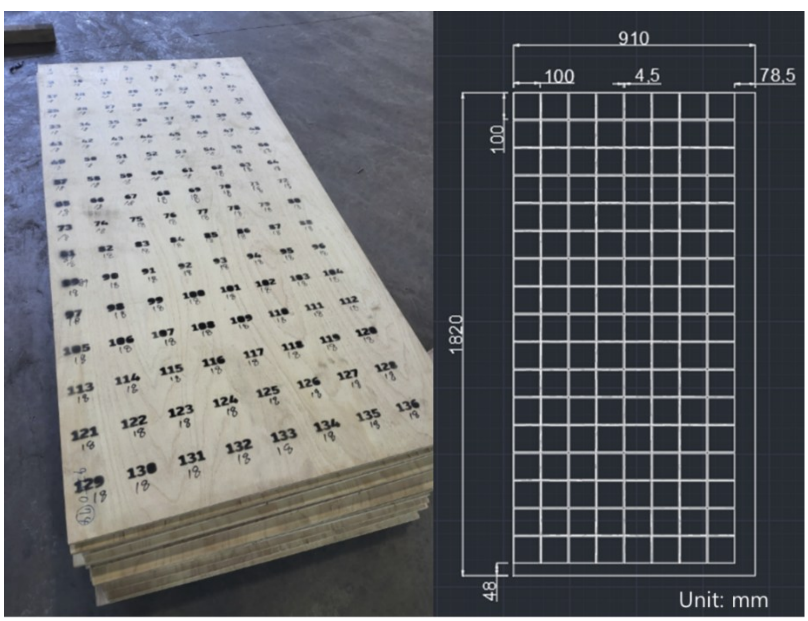


Fig. 1. Plywood sample preparation (left: actual-sized hinoki plywood, right: marking test pieces for the cone calorimeter test)

Vacuum-pressure Impregnation

The flame-retardant treatment in this study was conducted using a vacuum-pressure wood impregnation system at Daihyun Timber Co., Ltd. in Incheon, South Korea. The inner diameter of the impregnation chamber was 1,800 mm, and its length was 16,000 mm (Fig. 2).

Initially, the plywood specimens were placed inside the chamber and exposed to a vacuum level of − 0.1 MPa for approximately 10 min, facilitated by a vacuum pump. After the decompression stage, the flame-retardant solution was introduced into the chamber and applied to the samples at a pressure of 1.96 MPa *via* a pressurized delivery mechanism. The degree of impregnation was monitored by measuring the mass of each specimen at 1.0 h intervals over a 10 h period. The flame-retardant impregnation rate was calculated according to Eq. 1 (Wen *et al*. 2014; Jo *et al*. 2024),

$$\mathrm{FI} = \frac{\mathrm{m_2} - \mathrm{m_1}}{\mathrm{V}} \tag{1}$$

where m_1 is the sample mass before flame-retardant impregnation (kg), m_2 is the sample mass after flame-retardant impregnation (kg), and V is the sample volume (m^3).

The SCFI was determined to be 27% of the total flame retardant impregnation by mass. Based on this solid content ratio, 26 hinoki cypress plywood specimens were selected for further posttreatment analyses.

Fig. 2. Vacuum-pressure impregnation chamber

Cone Calorimeter Test

To evaluate the flame retardancy of domestically sourced hinoki cypress plywood subjected to vacuum pressure impregnation, cone calorimetry (Fig. 3) was performed following the KS F ISO 5660-1 semi-combustible performance standard protocol. Before testing, all specimens were stabilized to a constant mass under controlled environmental conditions of 23 °C and 50% relative humidity. The moisture content was maintained at approximately 11%. The test procedure involved exposing each sample to a cone-shaped radiant heater and an electrical igniter, delivering a consistent heat flux of 50 kW/m² over a 10 min period. The distance between the test specimen and radiant heat source was 25 mm.

During the combustion phase, the emitted gases were ignited, and the rate of oxygen consumption was monitored continuously. The THR was calculated based on this oxygen consumption, using a standard conversion factor of 13.1 × 10^3 kJ/kg of oxygen. This measurement quantifies the heat output associated with sample combustion and serves as a key indicator of the flame-retardant efficacy of the material.

Flame-retardant materials must exhibit a THR not exceeding 8 MJ/m^2 within the first 5 min of heating; a peak HRR below 200 kW/m^2 sustained for at least 10 s; and no evidence of cracks, holes, or melting penetrating the specimen after 5 min. By contrast, semi-combustible materials are required to maintain a THR of no more than 8 MJ/m^2 within 10 min, a peak HRR not exceeding 200 kW/m^2 for a minimum of 10 s, and no harmful cracks or penetration through the specimen after 10 min of heating.

The suitability of Hinoki plywood was evaluated as a semi-combustible material. The cone calorimeter test was conducted at the Tottori Prefecture Forestry Experiment Station, Japan, and KCL (Korea Conformity Laboratories), Korea.

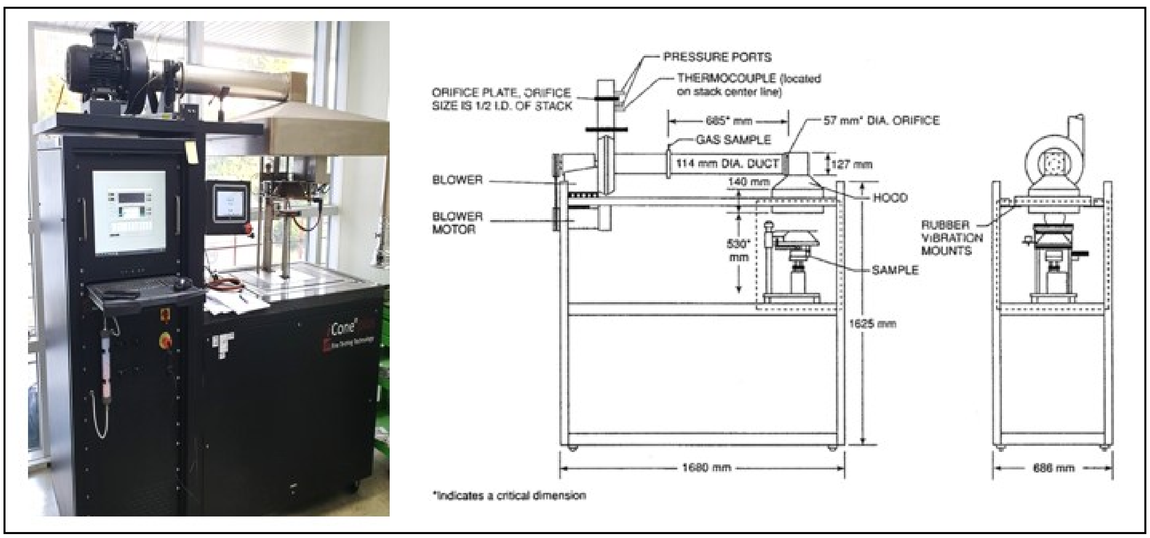


Fig. 3. Schematic diagram of cone calorimeter tester (Jang *et al*. 2025)

RESULTS AND DISCUSSION

SCFI and THR

Figure 4 illustrates the relationship between the SCFI and THR for each of the 26 hinoki cypress plywood samples, based on KS F ISO 5660-1. The sample numbers were assigned according to increasing SCFI values. Orange bars represent the SCFI values, and the dashed gray line indicates the THR values. The graph employs dual vertical axes: the left axis quantifies SCFI (0 to 350 kg/m^3), and the right axis depicts THR (0 to 25 MJ/m^2). The horizontal red dashed line marks the semi-combustible performance threshold of 8 MJ/m^2, as stipulated by the MOLIT notice no. 2023-24 (2023).

The chart reveals a general trend in which a higher SCFI corresponds to a lower THR. The results of this study indicate that, to meet the threshold of 8 MJ/m^2, SCFI must be impregnated at a level of 112 kg/m³ (sample number 9) or higher.

All hinoki plywood samples numbered 9 and above exhibited a THR of 8 MJ/m² or less within 10 min and maintained a maximum HRR of 200 kW/m² for at least 10 s.

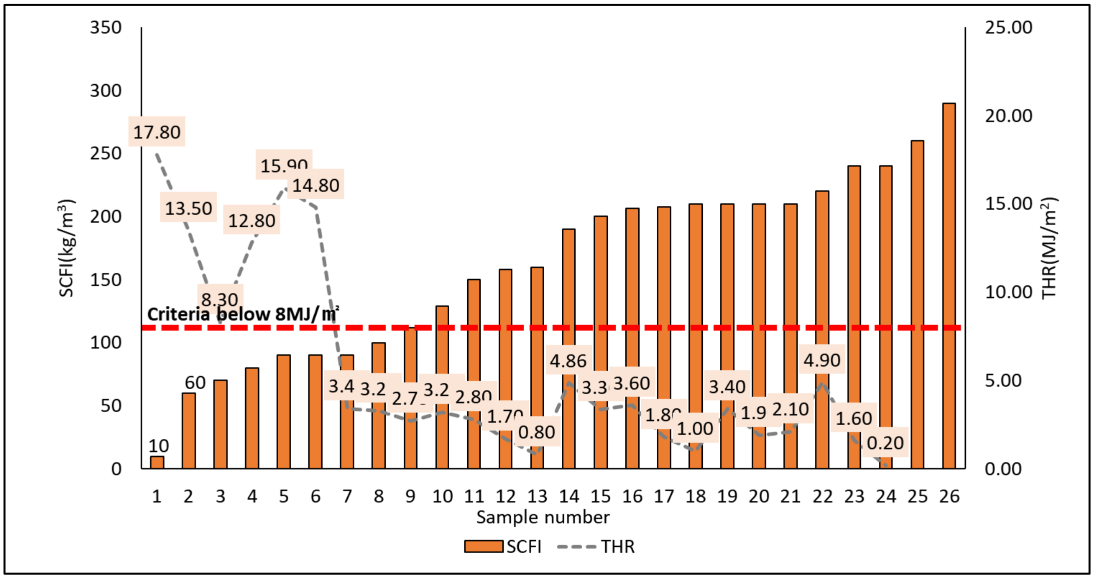


Fig. 4. Total heat released and solid content of flame-retardant impregnation of Hinoki cypress plywood (n=26)

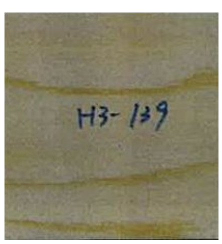
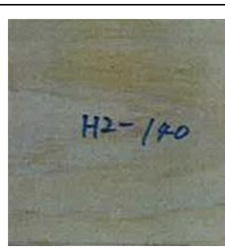
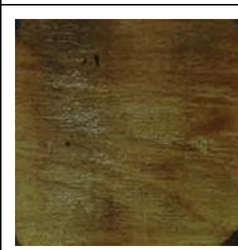
Visual Inspection

Table 1 shows the pre- and post-test changes in the semi-combustible hinoki plywood samples treated with flame retardants, measured using a cone calorimeter according to KS F ISO 5660-1. The total heat release (THR) of these samples remained below 8 MJ/m² after 10 minutes of heating.

Sample 9 is a representative sample that exhibits the minimum SCFI, meeting the semi-noncombustibility criteria. After testing, the front side directly exposed to the heater showed clear signs of charring, whereas the rear side showed only minor charring. No cracks were found that would affect the structural performance of the plywood. This indicates that heat source did not penetrate the thickness of the sample, demonstrating effective heat shielding. Samples 10 to 16 also exhibited charring on the front side; however, the back side was barely damaged, demonstrating that the flame retardant effectively inhibited heat diffusion across the surface.

These results suggest that the flame-retardant hinoki plywood has the potential to maintain its structural integrity for more than 10 min in a real-world fire environment, potentially providing occupants with sufficient time to evacuate. In particular, minimal carbonization on the backside can have a positive effect on reducing heat transfer and maintaining structural stability. Therefore, we believe that flame-retardant-treated hinoki structural plywood has sufficient potential as a fire-safe interior building finishing material. Further quantitative safety assessments using large-scale fire simulations and full-scale tests are required. The heat shielding performance may vary depending on different wood species, thickness, and flame-retardant depth; therefore, repeated testing under various conditions is essential to ensure consistent and reliable results.

Table 1. Post-test Visual Assessment of Specimens Following Cone Calorimeter Testing

Sample Number	Before test		After test	
	Front Side	Back Side	Front Side	Back Side
9				
10				
11				
12				
16				
17				

Regression Analysis

Figure 5 shows the analysis of the correlation between the THR and the SCFI of hinoki cypress plywood, which revealed a distinct exponential decreasing trend between the two variables. The resulting trend line is expressed as an exponential function:

$$Y = 36.085e^{-0.014X} \quad (2)$$

In Eq. 2, *Y* is the SCFI (kg/m^3) and *X* is the THR (MJ/m^2).

The model's coefficient of determination (R^2) was 0.8486, demonstrating its high explanatory power for the effect of THR on SCFI. This indicates that the SCFI decreases exponentially as the THR increases, suggesting a close correlation between the heat dissipation characteristics and the structural density of hinoki cypress plywood. Equation 2 showed that, to meet the MOLIT notice 2023-24 standard of 8 MJ/m^2, the SCFI must be greater than 108 kg/m^3.

In a previous study, it was found that SCFIs of 93.9 kg/m^3 and 144.6 kg/m^3 were required to meet the flame-retardant performance criteria for Korean larch and Japanese cedar, respectively (Jo *et al*. 2024). However, hinoki plywood required more SCFI than that for Japanese cedar and Korean larch, indicating that the required SCFI varies depending on the wood species. Therefore, further investigation is needed to determine the SCFI required to satisfy the flame-retardant performance of variable construction wood species.

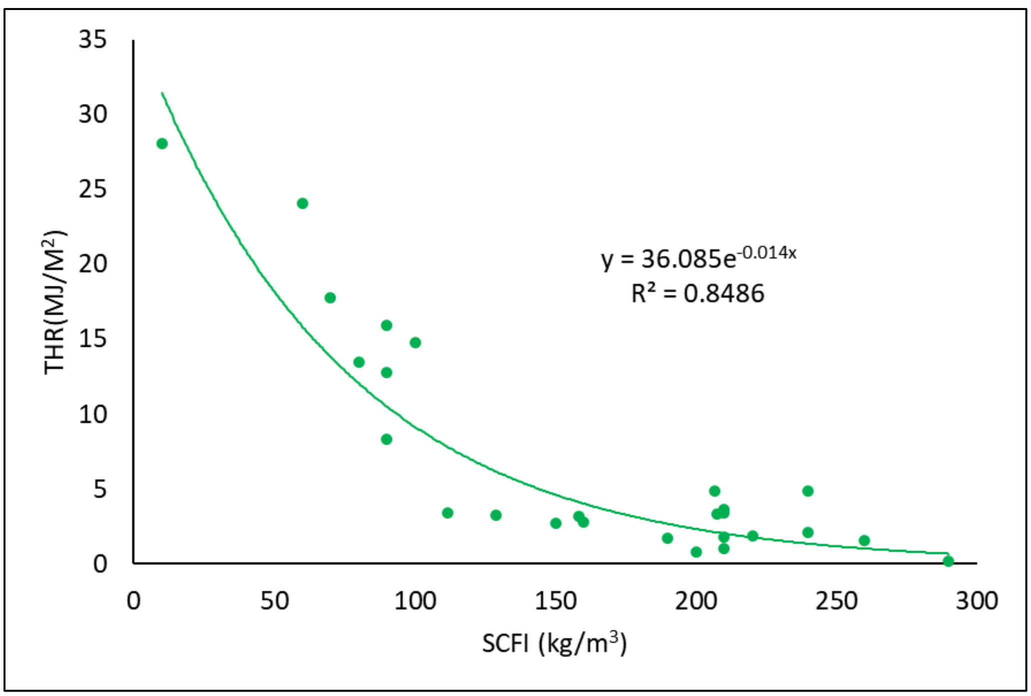


Fig. 5. The regression analysis results with THR and SCFI

CONCLUSIONS

1. A clear correlation between the specific chemical flame-retardant impregnation (SCFI) level and Total Heat Release (THR) was observed, with the THR exhibiting an exponential decrease as the SCFI increased. This finding suggests that the effective penetration of flame retardants into the wood matrix significantly suppresses the heat release during combustion.
2. The minimum SCFI required to satisfy the semi-combustible performance criteria set by the Ministry of Land, Infrastructure and Transport (THR $\leq$ 8 MJ/m^2) was determined to be 108 kg/m^3 for 12-mm hinoki cypress plywood.
3. The identified SCFI threshold for the flame-retardant treatment of Hinoki plywood can serve as a practical baseline for industrial manufacturing processes. This offers a means to optimize flame-retardant usage, thereby minimizing unnecessary cost increases and avoiding the degradation of mechanical properties due to excessive chemical loading. Notably, this study adopted a posttreatment approach applied to finished plywood, effectively mitigating the issue of reduced bond strength and enhancing the feasibility for large-scale applications.

ACKNOWLEDGEMENTS

This research was funded by the R&D Program for Forest Science Technology in Korea (FTIS-RS-2024-00400728).

AUTHORS' CONTRIBUTIONS

ES JANG: First author, Conceptualization, Methodology, Data analysis, Writing - original draft, and Writing - review & editing, Y ANNO and WC PARK: Experiment, Data analysis and Writing - review & editing, HJ PARK: Corresponding author, Supervision and Writing - review & editing. All authors read and approved of the final manuscript.

REFERENCES CITED

Ali, S., Hussain, S. A., and Tohir, M. Z. M. (2019). "Fire test and effects of fire retardant on the natural ability of timber: A review," *Pertanika Journal of Science and Technology* 27(2), 867-895.

Buksans, E., and Kalnina, I. (2024). "Improvement of reaction to fire performance of birch plywood by veneer soaking method," in: *23rd International Scientific Conference Engineering for Rural Development,* May 22-24, Jelgava, Latvia, pp. 460-466.

Cordier, M., Johannsen, N., Kietz, B., Berthold, D., and Mai, C. (2025). "Plywood manufacturing using various combinations of hardwood species," *Forests* 16(4), article 622. DOI: 10.3390/f16040622

Housing (2019). "India will Need 25 Million more Affordable Housing Units by 2030," https://housing.com/news/india-will-need-25-million-more-affordable-housing-units-rics-and-knight-frank-report/. Accessed 15-July 2025

Ikei, H., Song, C., and Miyazaki, Y. (2018). "Physiological effects of touching hinoki cypress (*Chamaecyparis obtusa*)," *Journal of Wood Science* 64(3), 226-236.

Jang, E.-S. (2022). "Investigation of sound absorption ability of hinoki cypress (*Chamaecyparis obtusa*) cubes," *Journal of the Korean Wood Science and Technology* 50(5), 365-374. DOI: 10.1007/s10086-017-1691-7

Jang, E.-S., Jo, S.-U., and Park, H.-J. (2024a). "Effect of grooving pretreatment on flame retardant vacuum-pressure impregnation performance of full-size timbers," *Journal of Wood Science* 70(1), article 57. DOI: 10.1186/s10086-024-02172-y

Jang, E.-S., Kang, X. J., Jo, S.-U., and Park, H.-J. (2024b). "Preliminary investigation on the vacuum pressure impregnation performance of flame retardant for larch (*Larix kaempferi*) depending on grooving type," *BioResources* 19(4), 9606-9615. DOI: 10.15376/biores.19.4.9606-9615

Jang, E.-S., Yong, W.-J., Jo, S.-U., Kang, C.-W., and Park, H.-J. (2024c). "Evaluation of flame retardant impregnation in perforated hinoki (*Chamaecyparis obtusa*) plywood: Flame retardant impregnation in perforated Hinoki plywood," *Wood and Fiber Science* 56(1), 43-50. DOI: 10.22382/wfs-2024-006

Jang, E.-S., Jo, S.-U., and Park, H.-J. (2025). "Fire safety performance of Radiata pine-magnesium-laminated (RML) board for building material," *BioResources* 20(3), 5620-5632. DOI: 10.15376/biores.20.3.5620-5632

Jian, H., Liang, Y., Deng, C., Xu, J., Liu, Y., Shi, J., Wen, M., and Park, H. J. (2023). "Research progress on the improvement of flame retardancy, hydrophobicity, and antibacterial properties of wood surfaces," *Polymers* 15(4), article 951. DOI: 10.3390/polym15040951

Jo, S.-U., Chae, H.-B., Park, H.-J., and Jang, E.-S. (2024). "The optimal impregnation amounts of flame-retardant for Korean larch and Japanese cedar building materials," *Wood Research* 69(1), 179-186. DOI: 10.37763/wr.1336-4561/69.1.179186

Kolya, H., and Kang, C.-W. (2024). "Eco-friendly polymer nanocomposite coatings for next-generation fire retardants for building materials," *Polymers* 16(14), article 2045.

Li, J., Han, X., Yao, S., Guo, D., and Chu, F. (2025). "Reinforcing flame retardancy, dimensional stability, and high strength of woods for structural applications through surface densification and chemical modification," *Industrial Crops and Products* 223120175. DOI: 10.3390/polym16142045

Li, J., Zhao, H., Liu, H., Sun, J., Wu, J., Liu, Q., Zheng, Y., and Zheng, P. (2023). "Recent advances in metal-family flame retardants: A review," *RSC Advances* 13, 22639-22662. DOI: 10.1039/d3ra03536k

Maake, T., Asante, J. K., Mhike, W., and Mwakikunga, B. (2025). "Fire-retardant wood polymer composite to be used as building materials for south african formal and informal dwellings—A review," *Fire* 8(2), article 81. DOI: 10.3390/fire8020081

Mali, P., Sonawane, N., Patil, V., Lokhande, G., Mawale, R., and Pawar, N. (2022). "Morphology of wood degradation and flame retardants wood coating technology: An overview," *International Wood Products Journal* 13(1), 21-40. DOI: 10.1080/20426445.2021.2011552

Park, H. J. (2013). Flame-retardant resin for wood impregnation. Korean Patent KR10-2014-0023853A. Published February 27, 2014.

Rustiadini, M., and Novianti, T. (2025). "Comparison of plywood export competitiveness of Indonesia and China in the Asian+ 3 market and its influencing factors," *Jurnal Manajemen and Agribisnis* 22(1), 79-91. DOI: 10.17358/jma.22.1.79

Sapenti, A. D., Sari, R. K., Hermawan, D., Antov, P., Dudeva, V., and Lubis, M. A. R. (2025). "Formaldehyde-free plywood composites bonded with polyurethane adhesive derived from lignin-polyvinyl alcohol-based polyol," *Discover Sustainability* 6(1), article 112. DOI: 10.1007/s43621-025-00880-z

Sauerbier, P., Mayer, A. K., Emmerich, L., amd Militz, H. (2020). “Fire retardant treatment of wood – State of the art and future perspectives,” *Wood & Fire Safety*, WFS 2020, Springer, Cham. DOI: 10.1007/978-3-030-41235-7_14

UN (2018). *World Urbanization Prospects*, The 2018 revision. https://population.un.org/wup/. Accessed 15-July 2025

Wen, M. Y., Kang, C. W., and Park, H. J. (2014). "Impregnation and mechanical properties of three softwoods treated with a new fire retardant chemical," *BioResources* 9(3), 4529-4539. DOI: 10.1007/s10086-014-1408-0

Yan, Y. (2014). “The fabrication and properties characterization of wood-based flame retardant composites,” *Journal of Nanomaterials*, article ID 878357. DOI: 10.1155/2014/878357

Article submitted: August 1, 2025; Peer review compeleted: August 24, 2025; Revised version received and accepted: August 30, 2025; Published: September 12, 2025.
DOI: 10.15376/biores.20.4.9595-9605