Effect of Borate Treatment on Mechanical and Fire Properties of Cross-laminated Timber Manufactured from Poplar and Spruce

Zatollah Abadian,[a] Vahid Tazakor Rezaei ,[b,*] Seyed Eshagh Ebadi ,[b] Mohammad Topa Esfandiarei,[b] and Mojtaba Soltani [b]

Effects of a 12% borate solution treatment on the mechanical properties and fire resistance of three-layer cross-laminated timber (CLT) panels were evaluated for poplar (*Populus alba*) and spruce (*Picea abies*) woods. Mechanical testing (modulus of elasticity (MOE), modulus of rupture (MOR)) followed ANSI/APA PRG 320 (2018), and fire performance was assessed *via* ASTM E69 (2014). The borate treatment did not cause statistically significant changes in the MOE or MOR of poplar ($p > 0.10$); however, for spruce, a statistically significant reduction was observed in both MOE (14.5% reduction, $p = 0.08$) and MOR (31.3% reduction, $p = 0.05$) at the 90% confidence level. Inherent mechanical properties differed significantly, with poplar CLT exhibiting higher MOE and MOR than spruce. In contrast, the borate treatment significantly improved fire resistance by increasing the time to ignition (43 to 62% increase) and reducing mass loss (14 to 30% reduction) for both species. Spruce CLT demonstrated higher inherent fire resistance than poplar in both treated and untreated states. The findings indicated that borate treatment effectively enhanced the fire performance of CLT without compromising its mechanical integrity. Consequently, borate-treated poplar CLT presents a viable material for non-structural applications requiring fire resistance, offering the potential to reduce reliance on imported softwoods.

DOI: 10.15376/biores.22.1.466-478

Keywords: Cross-laminated timber; Fire retardancy; Borate; Poplar; Spruce; Modulus of elasticity; Bending strength

Contact information: a: Department of Wood and Paper Science and Technology, Faculty of Nature Resources, Cha.C., Islamic Azad University, Chalus, Iran.; b: Department of Wood and Paper Science and Technology, Faculty of Nature Resources, Cha.C., Islamic Azad University, Chalus, Iran;
** Corresponding author: tazakor@iau.ac.ir*

INTRODUCTION

Recent years have seen increased interest in enhancing the durability and fire resistance of wood for construction applications. Treatment of wood with borate-containing compounds is widely regarded as an effective approach for improving fire resistance while maintaining or minimally affecting mechanical properties. The global cross-laminated timber (CLT) market was valued at approximately USD 2.1 billion in 2023 and is projected to reach USD 4.9 billion by 2032, growing at a compound annual growth rate (CAGR) of 9.8% (Global Market Insights 2024). This rapid growth is driven by increasing demand for sustainable construction materials, particularly in multi-story residential and commercial buildings. However, the CLT industry's heavy reliance on

imported softwood species such as Norway spruce (*Picea abies*) presents significant supply chain vulnerabilities and cost challenges for countries without extensive softwood forests. Iran, with over 180,000 hectares of poplar plantations, has a substantial untapped resource that could potentially supply domestic CLT production while reducing import dependency by an estimated 40 to 60% (Forestry Organization of Iran 2023). Arian and Vlosky (2023) emphasized that poplar plantations are the main domestic source of wood raw material for the Iranian wood products industry, while imports, primarily from, Russia remain essential due to insufficient domestic supply. They also noted that the Iranian wood industry faces challenges such as lack of access to quality raw materials and reliance on imported softwoods, supporting the rationale for developing value-added products such as CLT from native poplar.

The 12% borate concentration used in this work (1:1 ratio of boric acid to borax) was selected based on a systematic review of the literature. Previous studies have shown that borate concentrations below 10% provide insufficient fire resistance for structural applications (LeVan and Winandy 1990; Kartal and Green 2003), while concentrations exceeding 15% can lead to significant reductions in mechanical properties, with MOR reductions of up to 31% reported at 15% concentration (Toker *et al*. 2009). The 12% concentration was identified as an optimal balance point that provides adequate fire resistance while minimizing mechanical property degradation, aligning with recommendations of the American Wood Protection Association (AWPA 2020). Bagheri *et al*. (2022) demonstrated that borate treatment significantly increases the fire resistance of engineered wood products, such as cross-laminated timber (CLT), without compromising key physical and mechanical characteristics. Similarly, Yan *et al*. (2024) confirmed the combined effects of thermal and borate treatments on wood hardness and durability.

Duquette (2024) investigated the long-term durability of borate-treated wood structures against environmental and biological factors, validating the efficacy of this treatment for above-ground applications. Zhang *et al*. (2023) reported species-specific variations in mechanical properties and dimensional stability following borate treatment, emphasizing the importance of evaluating different wood species individually. Li *et al*. (2024) and Soares *et al*. (2024) highlighted the effectiveness of fire-retardant coatings in reducing wood surface combustibility, providing context for alternative fire protection methods, while Klippel *et al*. (2014) report emphasized the role of layer thickness and proper treatment in structural fire resistance of CLT elements. Additionally, Doruk (2025) showed that sodium borate treatment enhances wood adhesion and reduces cracking, and Can *et al*. (2010) reported improved dimensional stability and bending strength in borate-treated wood.

The rising demand for sustainable building materials has driven interest in CLT, an engineered product derived from renewable wood resources (Gagnon and Pirvu 2013). CLT panels, composed of cross-oriented lumber layers, provide high mechanical strength, dimensional stability, and a lower carbon footprint relative to conventional construction materials (Brandner *et al*. 2016). Various wood species are utilized in CLT production. Poplar (*Populus alba*), a fast-growing native species, offers a low-cost raw material (Sandberg *et al*. 2023). In contrast, spruce (*Picea abies*), widely used in European CLT manufacturing, is favored for its desirable mechanical properties and consistent quality (Brandner *et al*. 2016).

A key limitation of wood in construction is its inherent combustibility. The limited fire resistance of untreated CLT presents safety concerns (Frangi *et al*. 2019). Boron-based

compounds, such as boric acid and borax, substantially improve wood's thermal resistance by various mechanisms, including formation of a protective glassy layer that insulates the wood, reduction of flammable volatile gases, and endothermic reactions that lower substrate temperature (LeVan and Winandy 1990; Kartal and Green 2003).

Although borate treatments serve as effective fire retardants, their impact on mechanical properties differ. Some studies report negligible effects or slight improvements at optimal concentrations (Caldeira 2010), while others indicate that higher borate loadings may reduce mechanical strength (Li *et al*. 2025). Notably, most research has focused on solid wood or other panel products, resulting in insufficient data on borate-treated CLT's performance, particularly when produced from less traditional species such as poplar. In the present study, CLT panels were bonded using a commercial one-component polyurethane (PUR) adhesive. The choice of PUR adhesive was based on its excellent adhesion to treated wood, resistance to moisture, and widespread use in engineered wood products. It is important to note that the adhesive type may influence the overall performance of CLT, particularly under fire exposure, as different adhesives may exhibit varying degrees of thermal stability and tolerance to borate particles.

Study Objectives

1. To evaluate the effect of a 12% borate treatment on the flexural properties (Bagheri *et al*. 2022), including modulus of elasticity (MOE) and modulus of rupture (MOR), of CLT panels manufactured from poplar and spruce.
2. To assess the change in fire resistance of borate-treated CLT panels using standardized flammability tests.
3. To systematically compare the post-treatment performance of poplar and spruce CLT panels, evaluating the feasibility of substituting fast-growing native poplar for imported spruce in specific applications while considering economic and availability advantages.

EXPERIMENTAL

Raw Material Preparation

Wood boards of poplar (*Populus alba*) and Norway spruce (*Picea abies*) with dimensions of 25 mm (thickness) × 210 mm (width) × 2000 mm (length) were procured. All boards were conditioned in an indoor environment for two months to achieve an equilibrium moisture content of approximately 12%. Initial physical and mechanical properties, including density and static bending properties, were determined in accordance with ASTM D143 (2014).

The average specific gravity (oven-dry basis) of the poplar (*Populus alba*) lumber was 0.40 ± 0.02, corresponding to an average density of 410 ± 25 kg/m^3 at 12% moisture content. The Norway spruce (*Picea abies*) lumber had an average specific gravity of 0.41 ± 0.02, corresponding to an average density of 430 ± 20 kg/m^3 at 12% moisture content. These values are consistent with previously reported ranges for these species: 0.35 to 0.50 for *Populus alba* and 0.32 to 0.43 for (*Picea abies)* (Šoškić *et al*. 2007; Wood Database 2023).

Moisture content was measured in accordance with ASTM D4442-16 (Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials) using the oven-dry method (103 ± 2 °C for 24 hours, until constant mass was achieved). The final moisture content of all boards prior to CLT fabrication was verified to

be 12 ± 1.5% using a resistance-type moisture meter (Delmhorst Model J-2000) in accordance with ASTM D4444-13.

Borate Treatment and CLT Fabrication

The conditioned boards were planed to a final thickness of 15 mm and ripped to a width of 100 mm. A 12% (w/w) aqueous fire-retardant solution was prepared using a 1:1 ratio by mass of technical grade boric acid (H_3BO_3) to borax decahydrate ($Na_2B_4O_7 \times 10H_2O$). The lamellas were fully immersed in the treatment solution for 60 h at ambient temperature (~20 °C). After immersion, the treated lamellas were kiln-dried to a moisture content of 12%.

A commercial one-component polyurethane (PUR) adhesive was used for CLT assembly, applied at a spread rate of 300 g/m^2. Three-layer CLT panels with a cross-ply configuration (0°/90°/0°) were assembled (Fig. 1). The layup was pressed at a pressure of 51 kg/cm^2 and a platen temperature of 27 °C for a press time of 360 min.

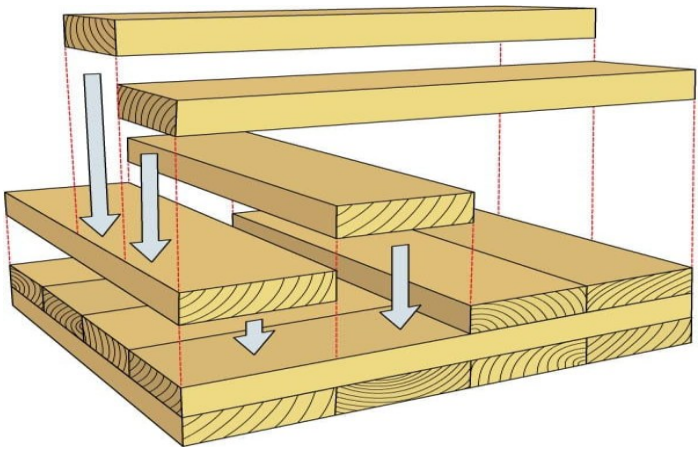


Fig. 1. How the boards are placed in the CLT panels



Fig. 2. Bending test perpendicular to the CLT surface, in the transverse direction of the panel

Testing and Evaluation

Mechanical testing

The experimental design consisted of four treatment groups (2 species × 2 treatment levels: treated/untreated). For mechanical testing, 20 CLT panels were manufactured (5 panels per treatment group). From each panel, four bending specimens were cut, resulting in a total of 80 bending specimens (20 specimens per group). Following a two-week conditioning period at 21 °C and 65% relative humidity, the CLT panels were cut into specimens for a three-point bending test. The modulus of elasticity (MOE) and modulus of rupture (MOR) were determined in accordance with ANSI/APA PRG 320 (2018) using a universal testing machine (Fig. 2).

Fire performance testing

For fire testing, 20 specimens were prepared (5 specimens per treatment group). The fire resistance of the CLT specimens was evaluated according to the ASTM E69 (2014) standard test method for combustibility using a fire-tube apparatus. Specimens with final dimensions of 200 mm (length) × 100 mm (width) × 45 mm (total thickness) were prepared. The following specific conditions were maintained:

- *Flame source*: Bunsen burner with a 1.5 cm diameter tube
- *Flame temperature*: 850 ± 50 °C (measured by a Type-K thermocouple positioned 5 cm above the burner)
- *Flame height*: 5.0 ± 0.5 cm (blue inner cone)
- Specimen angle: 45° relative to the horizontal plane
- *Burner position*: Flame was applied to the lower edge of the specimen, 2.0 cm from the bottom
- *Test duration*: 10 minutes of flame exposure, followed by monitoring until flaming and glowing ceased
- *Gas pressure*: 0.9 bar (natural gas, methane content > 90%)

Each specimen was mounted at a 45° angle, and a standard Bunsen burner flame was applied to the lower edge. The time to sustained ignition, total flame duration, glowing time, and percentage mass loss after the test were recorded (Fig. 3).



Fig. 3. Burner nozzle and fire test specimen position

The following operational definitions were used for each measured parameter:

- *Time to Ignition*: The time (in seconds) from initial flame application to the first appearance of sustained flaming on the specimen surface, defined as flaming lasting for more than 5 seconds (consistent with ASTM E176-21a).
- *Flaming Duration*: The total time (in seconds) from ignition to the point when all visible flame on the specimen surface is extinguished.
- *Glowing Duration*: The total time (in seconds) from flame extinction to the point when all visible glowing combustion (incandescence without flame) ceases, as determined by visual observation in a darkened testing area.
- *Mass Loss*: The percentage of initial specimen mass lost during the entire combustion test, calculated as: Mass Loss (%) = [(Initial Mass - Final Mass) / Initial Mass] × 100, where Final Mass was measured after the specimen had cooled to room temperature (20 ± 2 °C).

Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using SPSS software (Version 26.0, IBM Corp., Armonk, NY, USA). The significance of differences between mean values was determined using Tukey's honestly significant difference (HSD) *post hoc* test at a 90% confidence level ($\alpha = 0.10$). The assumption of normality was verified using the Shapiro-Wilk test. A 90% confidence level was selected because it is widely used in studies where the effects are not distinct enough, or the level of random error is too large to justify a higher level of significance. This level of confidence provides a more balanced assessment of the treatment effects, particularly given the inherent variability in wood properties.

RESULTS AND DISCUSSION

Mechanical Properties

The three-point bending test results for CLT panels manufactured from poplar and spruce are presented in Figs. 4 and 5.

Statistical analysis at the 90% confidence level ($\alpha = 0.10$) revealed that borate treatment did not cause a significant reduction in MOE or MOR for poplar ($p > 0.10$). This finding is consistent with previous studies indicating that moderate borate treatments preserve the mechanical integrity of wood (Li *et al.* 2017). However, for spruce, the treatment resulted in a notable reduction in mechanical properties, which was statistically significant at the 90% confidence level (MOE: $p = 0.08$; MOR: $p = 0.05$). For structural applications, the numerical reduction of 14.5% in MOE and 31.3% in MOR for spruce should be practically considered, aligning with the NFPA recommendation of a 10% reduction in allowable design stresses for fire-retardant-treated wood (NFPA 1973; LeVan and Winandy 1990). A significant difference ($p < 0.05$) was observed between the two wood species. Statistical analysis at the 90% confidence level ($\alpha = 0.10$) revealed the following results (Fig. 4):

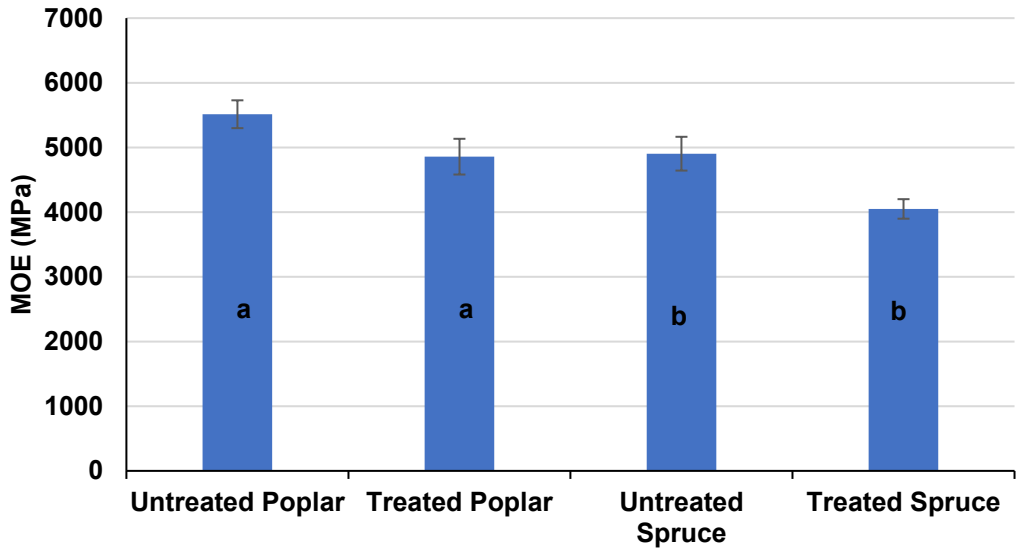


Fig. 4. Elastic resistance (MOE) of CLTs manufactured in the longitudinal direction. Error bars represent 90% confidence intervals (n = 5). Different letters indicate significant differences at α = 0.10.

In the case of poplar, the difference between untreated (5,514 MPa) and treated (4,858 MPa) specimens was not statistically significant ($p > 0.10$). However, for spruce, the difference between untreated (4,904 MPa) and treated (4,050 MPa) specimens was statistically significant ($p = 0.08 < 0.10$), indicating a notable reduction in MOE after borate treatment. When comparing the species, untreated poplar exhibited significantly higher MOE than untreated spruce ($p = 0.06 < 0.10$). Treated poplar also showed higher MOE than treated spruce ($p = 0.04 < 0.10$).

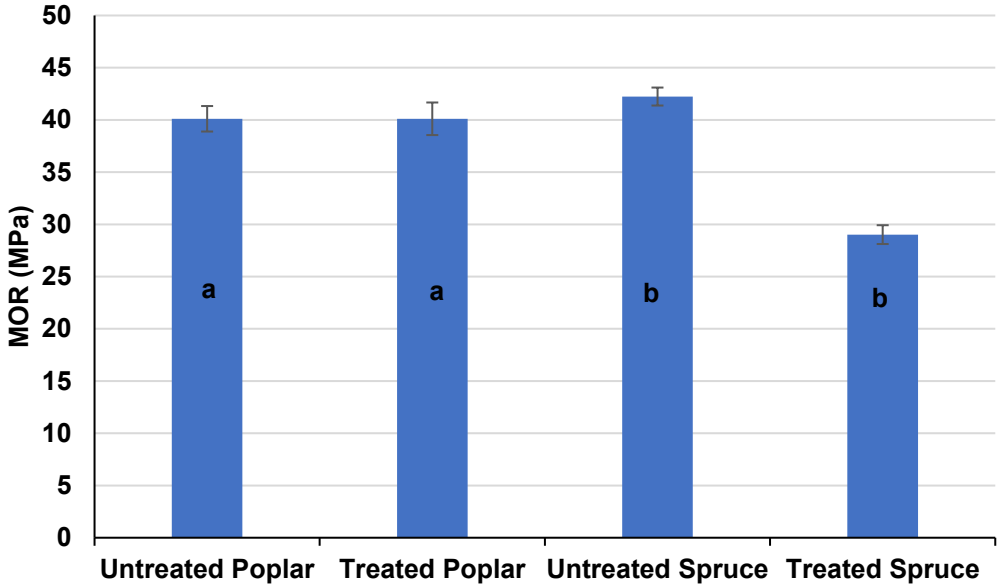


Fig. 5. Flexural strength (MOR) of CLTs manufactured in the longitudinal direction. Error bars represent 90% confidence intervals (n = 5). Different letters indicate significant differences at α = 0.10.

For poplar, the difference between untreated (40.11 MPa) and treated (40.11 MPa) specimens was not statistically significant ($p > 0.10$). However, for spruce the difference between untreated (42.2 MPa) and treated (29.0 MPa) specimens was statistically significant ($p = 0.05 < 0.10$), indicating a marked reduction in MOR after borate treatment. Untreated poplar and untreated spruce showed no significant difference in MOR ($p > 0.10$). However, treated poplar exhibited significantly higher MOR than treated spruce ($p = 0.03 < 0.10$). These results indicate that the effect of borate treatment on mechanical properties is species-dependent, with spruce showing a more pronounced reduction in both MOE and MOR compared to poplar. The practical implications of these reductions should be considered for structural applications, particularly for spruce CLT. Poplar CLT panels exhibited higher average MOE and MOR values compared to spruce CLT. This difference can be attributed to the anatomical structure and higher fiber density of the specific poplar resource used in this study (Wimmer *et al*. 2002)

Fire Performance

The fire performance results are presented in Fig. 6. Borate treatment significantly enhanced ($p < 0.01$) the fire resistance of CLT panels from both species. The time to sustained ignition increased markedly (43 to 62% increase), and the percentage of mass **loss** after testing decreased significantly in treated specimens compared to their untreated counterparts (14 to 30% reduction) (Table 1). This improvement is due to the mode of action of borates, which form a molten glass layer upon heating that acts as a thermal barrier, hinders oxygen access, and suppresses the release of combustible volatiles (Lyon *et al.* 2007).

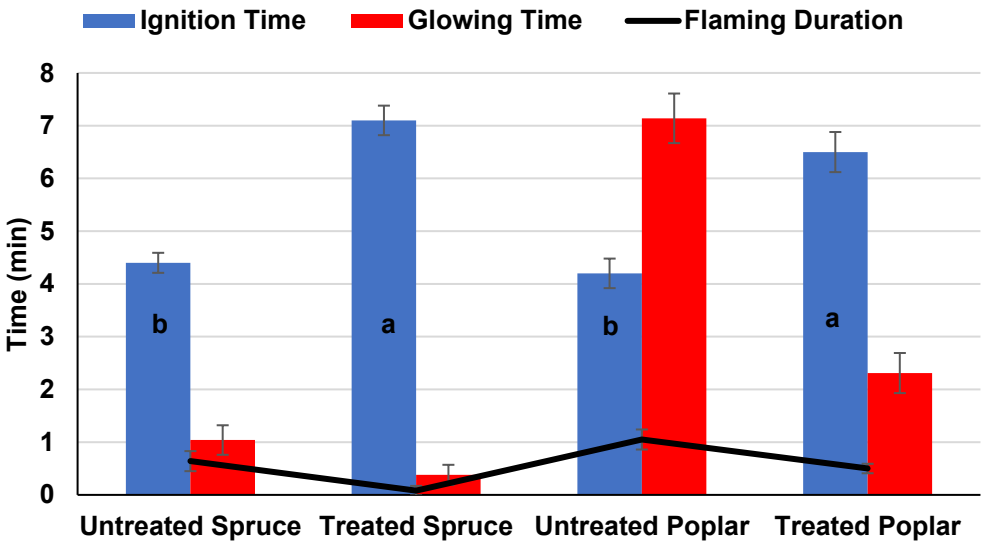


Fig. 6. Comparison of critical times for CLT made from treated and untreated poplar and spruce. Error bars represent 90% confidence intervals (n = 5). Different letters indicate significant differences at α = 0.10. Note: The flame duration for treated spruce was nearly zero (flame was extinguished immediately after ignition).

A statistically significant difference ($p < 0.05$) was also found between the two wood species. At the 90% confidence level ($\alpha = 0.10$), borate treatment significantly enhanced the fire resistance of CLT panels from both species. Time to ignition increased by 43 to 62% in treated specimens compared to untreated controls.

The effect of treatment was statistically significant for both species ($p < 0.10$). Mass loss decreased by 14 to 30% in treated specimens. The effect of treatment was statistically significant for both species ($p < 0.10$). When comparing the species, spruce CLT demonstrated significantly better inherent fire resistance than poplar CLT, as evidenced by longer ignition times and lower mass loss in both treated and untreated conditions ($p < 0.10$).

Spruce CLT demonstrated better inherent fire resistance than poplar CLT, as evidenced by longer ignition times and lower mass loss in both treated and untreated conditions (Table 1).

Table 1. Fire Performance Results of CLT Specimens According to ASTM E69 (2014)

Parameter	Treated Spruce CLT	Treated Poplar CLT	Untreated Spruce CLT	Untreated Poplar CLT	ASTM E69 (2014)
Time to Ignition (min)	7.1 ± 0.3	6.5 ± 0.4	4.4 ± 0.2	4.2 ± 0.3	≥ 5
Mass Loss (%)	9.1 ± 0.5	12.3 ± 0.8	10.6 ± 0.7	15.6 ± 0.9	≤ 15

The higher fire-resistance of spruce was likely related to the higher natural density and different chemical composition (*e.g.*, lignin and extractives content), which can influence its pyrolysis behavior and thermal stability (White and Dietenberger 2001). Specifically, spruce (*Picea abies*) typically contains 27 to 30% lignin, while poplar (*Populus alba*) contains 20 to 25% lignin (Fengel and Wegener 1989). Lignin, being more thermally stable than cellulose and hemicellulose, contributes to greater char formation during pyrolysis (35 to 40% of original mass for spruce *vs.* 25 to 30% for poplar). Spruce contains higher levels of extractives (3 to 5% *vs.* 1 to 2% in poplar), including resin acids and phenolic compounds that can act as natural flame retardants (Rowell 2005). The tracheid structure of spruce (softwood) with thicker cell walls and smaller lumina compared to the vessel elements of poplar (hardwood) affects thermal conductivity and oxygen diffusion during combustion.

Previous studies have confirmed the significant role of borate treatments in enhancing wood durability and fire resistance. Bagheri *et al*. (2022) and Yan L *et al*. (2019) demonstrated the improvements of borate treatment on mechanical properties and hardness of engineered wood products. Similarly, Duquette (2024) and Var and Kardaş (2019) reported improved long-term stability and physical properties in borate-treated wood.

Fire-retardant coatings and optimized structural configurations have also been shown to improve wood fire performance (Huang *et al*. 2024; IAFSS 2024). Additionally, Doruk (2025) highlighted the benefits of sodium borate treatment in enhancing wood adhesion and reducing cracking.

The present findings align with this body of research, confirming borate treatment's effectiveness in improving wood durability and fire resistance while preserving mechanical properties (Yan *et al*. 2019; Bagheri *et al*. 2022; Zhang 2023; Duquette 2024). The results further support the substitution of imported spruce with fast-growing native poplar for CLT applications, offering an economically and environmentally advantageous alternative.

CONCLUSIONS

This study evaluated the substitution of imported spruce with fast-growing native poplar in engineered wood products such as cross-laminated timber (CLT). The findings revealed that:

1. Borate-treated poplar CLT offers higher mechanical bending properties (MOE: 4,858 MPa; MOR: 40.11 MPa) and adequate fire resistance (time to ignition: 6.5 min; mass loss: 12.3%) compared to spruce CLT (MOE: 4,050 MPa; MOR: 29.0 MPa; time to ignition: 7.1 min; mass loss: 9.1%).
2. Borate-treated poplar is a viable, sustainable alternative to imported spruce for non-structural and semi-structural applications (such as interior partitions and cladding), facilitating increased utilization of native species and reducing reliance on imported materials.
3. The use of a 12% borate solution (1:1 boric acid/borax) significantly enhanced fire performance and ignition time in both poplar and spruce CLT increasing ignition time by 43 to 62% and reducing mass loss by 14 to 30% without compromising flexural properties such as MOE and MOR at the 90% confidence level.
4. Inherent differences between the species were observed: poplar CLT demonstrated superior mechanical performance in bending tests, while spruce CLT exhibited inherently greater fire resistance.
5. These results position borate-treated poplar CLT as a suitable material for non-structural and semi-structural uses where improved fire performance is critical. This research supports the use of fast-growing poplar, contributing to the advancement of environmentally responsible construction practices and lessening dependence on traditional softwood species. This aligns with the broader observation by Arian and Vlosky (2023) that the Iranian wood industry must reduce its reliance on imported raw materials and develop domestic value-added products to achieve sustainable growth.

ACKNOWLEDGMENTS

The authors express their sincere gratitude to Islamic Azad University, Chalous Branch, for supporting this research study; Noshirvani University of Technology, Concrete Structures Laboratory, for conducting mechanical tests with the assistance of Dr. Elyasi; National University of Skills, for performing physical tests; and Sandal Wood Industries, for manufacturing the CLT panels.

Conflict of Interest

The authors declare that there are no conflicts of interest that could have influenced the research or publication of this manuscript.

Use of Generative AI

The authors used ChatGPT (OpenAI, USA) solely for English language editing. The content, data, and scientific interpretation were fully produced and verified by the authors.

REFERENCES CITED

American Wood Protection Association (AWPA). (2020). *Book of Standards*. (Available from: https://store.awpa.com)

Arian, A., and Vlosky, R. P. (2023). "An overview of the wood products sector in Iran: 2007–2022," *Journal of Forest Business Research* 2(2), 146-169. https://doi.org/10.62320/jfbr.v2i2.40

ANSI/APA PRG 320 (2018). "Standard for performance-rated cross-laminated timber," APA - The Engineered Wood Association, Tacoma, WA, USA.

ASTM D4442-16. (2016). "Standard test methods for direct moisture content measurement of wood and wood-based materials," ASTM International, West Conshohocken, PA.

ASTM D143 (2014). "Standard test methods for small clear specimens of timber," ASTM International, West Conshohocken, PA, USA.

ASTM E69 (2014). "Standard test method for combustible properties of treated wood by the fire-tube apparatus," ASTM International, West Conshohocken, PA, USA.

Bagheri, S., Alinejad, M., Ohno, K., Hasburgh, L., Arango, R., and Nejad, M. (2022). "Improving durability of cross laminated timber (CLT) with borate treatment," *Journal of Wood Science* 68(1), article 34. https://doi.org/10.1186/s10086-022-02041-6

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., and Thiel, A. (2016). "Cross laminated timber (CLT): Overview and development," *European Journal of Wood and Wood Products* 74(3), 331-351. https://doi.org/10.1007/s00107-015-0999-5

Caldeira, F. (2010). "Boron in wood preservation. A review in its physico-chemical aspects," *Silva Lusitana* 18(2), 179-196.

Can, A., Yildiz, S., Yildiz, U. C., and Tomak, E. D. (2010). "Effects of boron impregnation and heat treatment on some physical and mechanical properties of spruce and pine wood," in: *Uluslararası Türk-Japon Çevre ve Ormancılık Sempozyumu,* Bildiriler kitabı II, Trabzon, Turkey *[International Turkish-Japanese Symposium on Environment and Forestry,* Proceedings Book II, Trabzon, Turkey], pp. 753-766. https://doi.org/10.13140/RG.2.1.5135.8807

Doruk, Ş., Yildirim, M. N., and Özcan, S. (2025). "Effect of sodium borate on adhesion resistance of varnished surfaces," *Drewno Wood* 68, article 216. https://doi.org/10.53502/wood-205211

Duquette, B. (2024). *Durability of 34-year-old Preservative Treated Test Structures in Mississippi*, Ph.D. Dissertation, Mississippi State University, Starkville, MS, USA.

Fengel, D., and Wegener, G. (2011). *Wood: Chemistry, Ultrastructure, Reactions*, Walter de Gruyter, Berlin. https://doi.org/10.1515/9783110839654

Forestry Organization of Iran. (2023). "Iran's forest resources and plantations annual report," Tehran: Ministry of Agriculture. (in Persian).

Frangi, A., Fontana, M., Hugi, E., and Jübstl, R. (2019). "Experimental analysis of cross-laminated timber panels in fire," *Fire Safety Journal* 44, 1078–1087. https://doi.org/10.1016/j.firesaf.2009.07.007

Gagnon, S., and Pirvu, C. (2013). *CLT Handbook: Cross-Laminated Timber*, FPInnovations, Québec, Canada.

Global Market Insights. (2024). "Cross-laminated timber (CLT) market size, by application, by end-use, by type & forecast, 2024-2032," Report ID: GMI4096.

Kartal, S. N., and Green, F. (2003). "Leachability of boron from wood treated with natural and semi-synthetic polymers and calcium precipitating agent," *Holz als Roh- und Werkstoff* 61(5), 388-389. https://doi.org/10.1007/s00107-003-0413-6

LeVan, S. L., and Winandy, J. E. (1990). "Effects of fire-retardant treatments on wood strength: A review," *Wood and Fiber Science* 22(1), 113-131.

Li, J., Liu, Y., Zhang, J., Sun, X., Li, M., Yu, C., Han, Z., Wei, P., and Liu, T. (2025). "Enhanced fire-retardant, smoke-suppressing, and ultra-strong mechanical properties of non-adhesive laminated wood through borate ion crosslinking" *Industrial Crops and Products* 224, article 120412. https://doi.org/10.1016/j.indcrop.2024.120412

Li, Y., Cao, C. F., Chen, Z. Y., Liu, S. C., Bae, J., and Tang, L. C. (2024). "Waterborne intumescent fire-retardant polymer composite coatings: A review," *Polymers* 16(16), article 2353. https://doi.org/10.3390/polym16162353

Li, L., Yu, J., Cai, H., and Lu, F. (2017). "The effect of boric acid and borax treatments on the fire resistance of bamboo filament," *BioResources* 12(3), 5296-5307. https://doi.org/10.15376/biores.12.3.5296-5307

Lyon, R. E., Janssens, M. L., and Dietenberger, M. A. (2007). "Fire response of polymer composites," in: *SFPE Handbook of Fire Protection Engineering*, 4th Ed., National Fire Protection Association, Quincy, MA, USA, pp. 3-1-3-62.

NFPA. (1973). "Allowable stresses for fire-retardant treated wood," National Forest Products Association (Historical document).

Rowell, R. M. (2005). *Handbook of Wood Chemistry and Wood Composites*, CRC Press, Boca Raton. https://doi.org/10.1201/9780203492437

Sandberg, D., Kutnar, A., and Mantanis, G. (2023). "Wood modification technologies – A review," *iForest - Biogeosciences and Forestry* 10(6), 895-908. https://doi.org/10.3832/ifor2380-010

Soares, I., Ferreira, J. L., Silva, H., and Rodrigues, M. P. (2024). "Fire-retardant and fire-resistant coatings: From industry to the potential use on cultural heritage," *Journal of Cultural Heritage* 68, 316-327. https://doi.org/10.1016/j.culher.2024.06.014

Šoškić, B., Govedar, Z., Todorović, N., and Petrović, D. (2007). "Basic physical properties of spruce wood (*Picea abies* Karst.) from plantations," *Bulletin of the Faculty of Forestry* 96, 97-110.

Toker, H., Baysal, E., Simsek, H., Senel, A., Sonmez, A., Altinok, M., Ozcifci, A., and Yapici, F. (2009). "Effects of some environmentally-friendly fire-retardant boron compounds on modulus of rupture and modulus of elasticity of wood," *Wood Research* 54(1), 77-88.

White, R. H., and Dietenberger, M. A. (2001). "Wood products: Thermal degradation and fire," in: *Reference Module in Materials Science and Materials Engineering*, Elsevier Science Ltd, pp. 9712-9716. https://doi.org/10.1016/b978-0-12-803581-8.03338-5

Wimmer, R., Lucas, B. N., Oliver, W. C., and Tsui, T. Y. (2002). "Longitudinal hardness and Young's modulus of spruce tracheid secondary walls using nanoindentation technique," *Wood Science and Technology* 31(2), 131-141. https://doi.org/10.1007/BF00705928

Wood Database. (2023). "Poplar (*Populus alba*) and Norway spruce (*Picea abies*) species profiles," The Wood Database, Available from: https://www.wood-database.com

Yan, L., and Morrell, J. J. (2019). "Kinetic color analysis for assessing the effects of borate and glycerol on thermal modification of wood," *Wood Science and Technology* 53(1), 263-274. https://doi.org/10.1007/s00226-018-1072-4

Yan, L., and Morrell, J. J. (2019). "Kinetic color analysis for assessing the effects of borate and glycerol on thermal modification of wood," *Wood Science and Technology* 53(1), 263-274. https://doi.org/10.1007/s00226-018-1072-4

Zhang, K., Saito, Y., Kurokochi, Y., Maeda, K., Arakawa, T., Izawa, N., and Okano, T. (2023). "Effects of boron compounds impregnation on the physical and vibro-mechanical properties of spruce (*Picea* sp.)," *Holzforschung* 77(2), 106-118. https://doi.org/10.1515/hf-2022-0139

Article submitted: December 15, 2025; Peer review completed: August 29, 2026; Revised version received: September 28, 2026; Accepted: September 19, 2026; Published: November 18, 2026.
DOI: 10.15376/biores.22.1.466-478