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# COMPARATIVE SURFACE ROUGHNESS EVOLUTION OF 33 JAPANESE HARDWOODS AFTER WATER AND FIRE-RETARDANT TREATMENTS USING 3D OPTICAL PROFILOMETRY

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## ABSTRACT

In this study, we assessed the surface roughness of 33 Japanese hardwood species by 3D optical profilometry (ISO 25178) and examined the influence of water and fire-retardant treatments. The surface roughness on cross, radial, and tangential sections was evaluated using the arithmetic mean height (Sa) parameter. Measurements were performed on untreated samples and repeated on the same spots after water treatment and NF300 fire-retardant treatment. Surface roughness varied widely across species and anatomical sections and tended to decrease with increasing wood density. The surface roughness increased with both treatments compared to the untreated wood. The maximum increase was on tangential surfaces after NF300 treatment, where the mean Sa value increased from 30.14 ± 17.05 μm to 42.05 ± 19.60 μm (39.5%). The statistical analysis showed a significant difference between the untreated and NF300-treated tangential surfaces ($p = 0.011$).

KEYWORDS: Surface roughness, hardwood, fire-retardant treatment, water treatment, optical profilometer, wood anatomy.

## INTRODUCTION

Wood is one of the most commonly used natural materials in construction, furniture, flooring, and interior applications because of its favourable mechanical properties, aesthetic appearance, renewability, and environmental sustainability (Schubert et al. 2022; Strobel et al. 2017; Wimmers 2017). The quality of the wood surface is an important factor affecting visual appearance, tactile perception, coating performance, adhesive bonding, and machining efficiency (Csanády et al. 2015). Among the various surface characteristics, surface roughness is one of the most important parameters associated with wood surface quality and has been widely used to evaluate machining performance and subsequent finishing processes (Hiziroglu 1996; Todaro et al. 2015; Zhong et al. 2013). Many factors affect the wood surface roughness, including anatomical structure, density, moisture content, machining parameters, cutting conditions, and tool sharpness (Korkut & Donertas 2007). The surface topography and roughness development after machining are strongly influenced by the anatomical characteristics of the wood, including vessel size and distribution, cell wall thickness, ray structure, and the arrangement of growth rings (Kang et al. 2023,2024). Previous studies have reported higher roughness values in coarse-textured woods than in fine-textured species, due to larger pores and greater anatomical heterogeneity (Thoma et al. 2015). Surface roughness also affects coating adhesion, paint consumption, wettability, and the tactile properties of finished wood products (Kamboj et al. 2020; Kilic et al. 2006).

In actual use, the wood surfaces are often exposed to moisture or treated with protective chemicals to increase durability and fire safety (Popescu & Pfriem 2020). As water is absorbed, swelling of the wood cell walls and dimensional changes may occur, potentially altering the surface morphology and roughness (Arzola-Villegas et al. 2019). Similarly, fire-retardant treatments are commonly used to reduce the combustibility of wood products used in buildings and public facilities (Kolya et al. 2026; Marney & Russell 2008). However, the microtopography of the wood surface may be modified by the penetration of aqueous fire-retardant solutions into the wood tissue and the subsequent deposition of their chemical constituents. The impact of machining parameters, sanding conditions, and wood species on surface roughness has been studied by many researchers (Fujiwara et al. 2005; Papp & Csiha 2017; Pelit & Arısüt 2023). However, the effects of water and fire-retardant treatments on the surface roughness of a range of hardwood species remain underexplored in the literature.

Moreover, most previous studies have focused on only a few species, and roughness has been evaluated using two-dimensional parameters. A comparative evaluation of a large number of hardwood species is scientifically important because it enables the identification of general trends linking wood density, anatomical characteristics, and treatment-induced surface roughness changes. Such information can improve the prediction of coating performance and surface quality across diverse hardwood resources and provide a broader understanding of species-dependent responses to moisture and fire-retardant treatments.

Therefore, the present study aimed to investigate the effects of water- and fire-retardant treatment on the surface roughness of 33 Japanese hardwood species using a 3D optical profilometer in accordance with ISO 25178-2: 2012. The surface roughness was analysed on cross, radial, and tangential sections using the arithmetic mean height (Sa) parameter. Furthermore, the relationships between wood density, anatomical orientation, and treatment-induced changes in roughness were investigated. The novelty of this study lies in the comprehensive comparison of 33 hardwood species using 3D optical surface characterization, and in the direct evaluation of surface roughness changes caused by water and fire-retardant treatments at the same measurement locations across different anatomical sections.

## MATERIAL AND METHODS

## Sample preparation

Thirty-three Japanese hardwood species obtained from the Miyazaki Research Forest, Japan, were used in this study. The specimens were prepared as cubic blocks (20 × 20 × 20 mm; radial × tangential × longitudinal) from the respective hardwood species. All surfaces were prepared using the same sawing procedure and were not subjected to additional sanding or polishing prior to roughness measurement. All specimens were conditioned under laboratory conditions before testing. Only one specimen per species was analysed; therefore, the results represent comparative trends among species rather than statistically replicated measurements within each species. The moisture content of the specimens ranged from 2.81% to 9.12%, while density varied between 0.40 and 0.94 g $cm^{-3}$. The species used in this study are listed in Tab 1.

*Tab. 1: List of 33 Japanese hardwood species, including moisture content and density values.*

| No | English name | Scientific name | Moisture content (%) | Density (g $cm^{-3}$) |
|---|---|---|---|---|
| 1 | Autumn Olive | *Elaeagnus umbellata* | 8.34 | 0.74 |
| 2 | Japanese Spicebush | *Lindera praecox* | 8.22 | 0.64 |
| 3 | Isonoki | *Distylium racemosum* | 6.49 | 0.60 |
| 4 | Japanese False Holly | *Ilex serrata* | 5.86 | 0.71 |
| 5 | Japanese Pagoda Tree | *Maackia amurensis* | 4.84 | 0.74 |
| 6 | Japanese Holly | *Ilex crenata* | 6.78 | 0.89 |
| 7 | Persimmon | *Diospyros kaki* | 9.12 | 0.75 |
| 8 | Kanakugi Tree | *Lindera erythrocarpa* | 7.22 | 0.59 |
| 9 | Japanese Winterhazel | *Stachyurus praecox* | 7.6 | 0.63 |
| 10 | Harlequin Glorybower | *Clerodendrum trichotomum* | 5.23 | 0.54 |
| 11 | Kumano Dogwood | *Cornus controversa* | 7.79 | 0.79 |
| 12 | Koshiabura | *Eleutherococcus sciadophylloides* | 5.57 | 0.48 |
| 13 | Japanese Star Anise | *Illicium anisatum* | 9.06 | 0.73 |
| 14 | Japanese tarrow tree | *Neoshirakia japonica* | 7.46 | 0.66 |
| 15 | White Lindera | *Lindera triloba* | 6.91 | 0.71 |
| 16 | Tanna Sawafutagi | *Symplocos prunifolia* | 8.34 | 0.86 |
| 17 | Tsukushi Akebono Azalea | *Rhododendron nudipes* | 7.45 | 0.79 |
| 18 | Tsukushi Yabutsugi | *Weigela hortensis* | 8.39 | 0.83 |
| 19 | Spindle Tree | *Euonymus oxyphyllus* | 8.19 | 0.82 |
| 20 | Japanese Elderberry | *Sambucus racemosa* | 7.35 | 0.56 |
| 21 | Chinese Sumac | *Rhus javanica* | 4.61 | 0.46 |
| 22 | Japanese Andromeda | *Lyonia ovalifolia* | 7.07 | 0.83 |
| 23 | Panicle Hydrangea | *Hydrangea paniculata* | 7.54 | 0.87 |
| 24 | Snowbell Tree | *Symplocos myrtacea* | 7.71 | 0.83 |
| 25 | Sacred Sarcandra | *Eurya japonica* | 7.36 | 0.78 |
| 26 | Round-leaved Ash | *Fraxinus sieboldiana* | 7.78 | 0.75 |
| 27 | Three-leaved Azalea | *Rhododendron dilatatum* | 5.13 | 0.71 |
| 28 | Paperbush | *Edgeworthia chrysantha* | 2.81 | 0.40 |
| 29 | Miyama Viburnum | *Viburnum wrightii* | 8.02 | 0.94 |
| 30 | Japanese Lacquer Tree | *Toxicodendron orientale* | 7.01 | 0.59 |
| 31 | Japanese Mulberry | *Morus australis* | 6.3 | 0.60 |
| 32 | Mountain Willow | *Salix pierotii* | 7.73 | 0.63 |
| 33 | Japanese Clethra | *Clethra barbinervis* | 6.51 | 0.74 |

## Water and fire-retardant treatments

At first, surface roughness measurements were conducted on untreated specimens for all species, which were named the control. After the initial surface roughness measurement, distilled water was applied uniformly to the measurement surface using a soft brush until the surface became completely wetted. Surface roughness was then measured immediately after water application at the same measurement location. The specimens were subsequently air-dried under laboratory conditions (~20–25°C) for more than one week before NF300 (commercial water-based fire-retardant formulation, Samwha paint company, Ansan city, Korea) treatment. It was used as received without further dilution. It was applied uniformly to the specimen surface using the same application procedure as the water treatment. After treatment, the specimens were dried under laboratory conditions prior to roughness measurement. This procedure enabled a direct comparison of the roughness changes induced by water and chemical treatments with the control surface. Application rate, solution uptake, coating thickness, and chemical retention were not measured in the present study.

**Surface roughness estimation**

Surface roughness was evaluated using a 3D optical profilometer (VR-6000, Keyence, Japan). Measurements were performed using a ×50 objective lens over a 4.5 × 6.0 mm scan area with lateral and vertical resolutions of 5.9 μm and 0.1 μm, respectively. One scan was acquired for each measurement location, and no additional filtering or cut-off wavelength was applied during analysis. The arithmetic mean height (Sa) defined in ISO 25178 was used as the primary roughness parameter. To enable direct comparison among untreated, water-treated, and NF300-treated conditions, all measurements were conducted at the same predefined location on each surface. The measurement coordinates were relocated for each treatment condition to minimize positional variation during repeated measurements.

**Statistical analysis**

Statistical analyses were performed using Minitab 22 (Minitab Inc., State College, PA, USA). Surface roughness (Sa) values were expressed as mean ± standard deviation. Differences between untreated (CT) vs WT and CT vs NF300-treated (NFT) tangential surfaces were evaluated using a two-sample t-test assuming unequal variances based on species-level average roughness values ($n = 33$). The null hypothesis ($H_0$) assumed no difference between the mean roughness values of the two groups ($H_0$: $\mu_1 - \mu_2 = 0$), whereas the alternative hypothesis ($H_1$) assumed a significant difference ($H_1$: $\mu_1 - \mu_2 \neq 0$). Boxplots were also generated to visualize the distribution and variability of surface roughness among treatment groups.

## RESULTS AND DISCUSSION

**Surface roughness of control woods**

The surface roughness (Sa) values of the untreated specimens were highly variable among the 33 Japanese hardwood species and among the three anatomical sections (Tab. 2). The average roughness values of untreated cross, radial, and tangential surfaces were 24.21 ± 12.51 μm, 35.82 ± 24.58 μm, and 30.14 ± 17.05 μm, respectively. The anatomical planes presented the greatest mean roughness in the radial surface, followed by the tangential and cross sections. The observed variation in surface roughness among species is likely related to differences in density and anatomical structure. Lower-density species generally exhibited higher roughness values, which is consistent with previous studies reporting that woods with larger vessels, higher porosity, and thinner cell walls are more susceptible to machining-induced surface irregularities (Thoma et al. 2015). Similarly, Kang et al. (2023, 2024) reported that wood anatomical characteristics, including vessel distribution and ray structure, strongly influence surface topography measured by three-dimensional optical profilometry. For example, relatively higher roughness values were observed for low-density species such as Chinese Sumac (0.46 g $cm^{-3}$), Koshiabura (0.48 g $cm^{-3}$) (Fig. 1), and Harlequin Glorybower (0.54 g $cm^{-3}$). Conversely, several denser species generally exhibited smoother surfaces than lower-density species. These observations are in good agreement with previous reports, although density was not the only determining factor of surface quality. The size, distribution, and characteristics of vessels, as well as the arrangement of fibres, also strongly influence surface morphology (Fujiwara et al. 2005; Todaro et al. 2015).

**Effect of water treatment on surface roughness**

Water treatment increased the mean roughness of all the anatomical sections. Mean Sa increased from 24.21 ± 12.51 to 32.87 ± 17.16 μm in cross section, 35.82 ± 24.58 to 40.33 ± 25.28 μm in radial section, and 30.14 ± 17.05 to 36.70 ± 23.67 μm in tangential section. The roughness increased by approximately 35.8%, 12.6%, and 21.8% in the cross, radial, and tangential sections, respectively, compared to control wood samples.

The increase in roughness is mainly attributed to moisture-induced swelling of wood cell walls. This swelling primarily occurs in the amorphous regions of the cell wall, causing localized dimensional changes that increase surface irregularities (Glass & Zelinka, 2021; Rowell, 2005; Siau, 1995). Similar moisture-induced changes in wood dimensions and surface morphology have also been reported by Arzola-Villegas et al. (Arzola-Villegas et al., 2019). Species with lower density and higher porosity tended to show greater increases in roughness because the larger lumens and greater void volume allow greater water penetration. For example, Paperbush (0.40 g $cm^{-3}$), Chinese Sumac (0.46 g $cm^{-3}$), Koshiabura (0.48 g $cm^{-3}$) (Fig. 1), and Harlequin Glorybower (0.54 g $cm^{-3}$) showed relatively large increases in roughness after water treatment. In contrast, high-density species such as Miyama Viburnum (0.94 g $cm^{-3}$) and Japanese Holly (0.89 g $cm^{-3}$) were relatively less affected and thus more resistant to deformation caused by moisture. These findings are consistent with previous reports indicating that wood density and anatomical structure strongly influence moisture absorption and the resulting surface characteristics. The relatively narrow range of initial moisture content (2.81–9.12%) suggests that its influence on roughness changes was smaller than that of density and anatomical structure.

*Tab. 2: Average surface roughness (Sa, μm) of cross, radial, and tangential sections under control, water-treated, and NF300-treated conditions.*

| No. | Cross section | | | Radial | | | Tangential | | |
|---|---|---|---|---|---|---|---|---|---|
| | Control (CC) | Water (WC) | NF300 (NFC) | Control (CR) | Water (WR) | NF300 (NFR) | Control (CT) | Water (WT) | NF300 (NFT) |
| 1 | 13.08 | 24.01 | 17.14 | 15.28 | 31.72 | 54.96 | 33.14 | 11.97 | 20.69 |
| 2 | 23.02 | 29.90 | 20.15 | 5.02 | 37.14 | 26.60 | 5.39 | 6.92 | 39.53 |
| 3 | 33.07 | 73.64 | 70.72 | 80.46 | 28.63 | 58.88 | 40.01 | 93.09 | 84.62 |
| 4 | 17.28 | 23.55 | 12.94 | 15.47 | 31.65 | 44.88 | 17.89 | 24.31 | 41.26 |
| 5 | 45.85 | 61.91 | 37.85 | 27.38 | 27.83 | 14.00 | 19.23 | 31.61 | 36.59 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6 | 21.62 | 35.47 | 50.69 | 22.87 | 39.48 | 51.57 | 20.53 | 27.43 | 55.78 |
| 7 | 22.67 | 24.68 | 17.55 | 35.89 | 34.70 | 38.14 | 27.30 | 49.61 | 34.64 |
| 8 | 23.74 | 35.94 | 46.89 | 29.47 | 24.88 | 36.32 | 19.45 | 21.62 | 43.84 |
| 9 | 20.41 | 24.84 | 37.14 | 51.19 | 41.51 | 55.90 | 33.66 | 40.87 | 56.98 |
| 10 | 43.03 | 46.12 | 63.47 | 71.38 | 46.70 | 72.23 | 63.82 | 90.18 | 60.34 |
| 11 | 6.07 | 10.78 | 21.04 | 15.76 | 12.34 | 58.05 | 28.11 | 16.49 | 33.14 |
| 12 | 25.35 | 17.66 | 69.21 | 21.13 | 18.31 | 65.05 | 44.07 | 54.52 | 61.81 |
| 13 | 33.44 | 42.77 | 22.94 | 24.23 | 32.45 | 42.26 | 12.56 | 14.39 | 22.40 |
| 14 | 11.61 | 21.13 | 18.25 | 16.32 | 18.78 | 14.27 | 18.71 | 13.91 | 32.40 |
| 15 | 15.25 | 19.89 | 44.44 | 17.72 | 25.52 | 17.06 | 9.98 | 13.22 | 31.91 |
| 16 | 29.42 | 40.83 | 23.56 | 48.02 | 46.81 | 50.35 | 29.37 | 36.20 | 30.03 |
| 17 | 13.99 | 20.90 | 9.97 | 51.89 | 58.24 | 20.32 | 33.76 | 41.89 | 24.51 |
| 18 | 23.32 | 25.77 | 17.63 | 13.21 | 17.87 | 7.61 | 23.33 | 36.20 | 19.32 |
| 19 | 15.65 | 16.40 | 22.06 | 14.34 | 16.61 | 33.70 | 5.32 | 5.98 | 9.85 |
| 20 | 22.07 | 42.40 | 6.98 | 47.23 | 78.89 | 59.73 | 82.97 | 104.48 | 79.12 |
| 21 | 58.38 | 61.95 | 41.79 | 96.91 | 124.67 | 92.46 | 60.44 | 53.95 | 80.04 |
| 22 | 12.87 | 16.63 | 18.69 | 17.06 | 16.51 | 17.09 | 34.75 | 42.74 | 39.20 |
| 23 | 27.51 | 36.09 | 24.21 | 20.68 | 24.82 | 28.11 | 16.76 | 24.11 | 45.68 |
| 24 | 19.73 | 24.57 | 39.85 | 42.00 | 55.75 | 65.93 | 43.38 | 50.29 | 65.81 |
| 25 | 7.88 | 10.30 | 25.64 | 51.62 | 76.39 | 22.79 | 16.36 | 21.34 | 26.06 |
| 26 | 28.50 | 49.22 | 22.69 | 97.83 | 83.57 | 26.98 | 22.10 | 30.89 | 20.52 |
| 27 | 12.27 | 18.95 | 17.95 | 49.34 | 55.22 | 34.81 | 23.01 | 35.83 | 28.27 |
| 28 | 45.21 | 64.63 | 64.27 | 13.55 | 19.04 | 13.70 | 16.64 | 14.45 | 68.89 |
| 29 | 24.45 | 31.50 | 34.78 | 41.13 | 50.63 | 25.23 | 51.56 | 51.55 | 20.09 |
| 30 | 11.60 | 14.08 | 17.77 | 36.59 | 42.38 | 46.38 | 35.42 | 31.66 | 28.30 |
| 31 | 16.03 | 20.64 | 8.56 | 62.64 | 78.97 | 39.72 | 27.15 | 30.65 | 51.28 |
| 32 | 25.43 | 32.99 | 10.68 | 14.89 | 14.80 | 43.32 | 40.47 | 46.95 | 35.44 |
| 33 | 49.07 | 64.59 | 67.71 | 13.48 | 18.12 | 68.57 | 38.07 | 41.83 | 59.29 |
| Avg. | 24.21 | 32.87 | 31.07 | 35.82 | 40.33 | 40.82 | 30.14 | 36.70 | 42.05 |
| Stdv. | 12.51 | 17.16 | 19.12 | 24.58 | 25.28 | 20.43 | 17.05 | 23.67 | 19.60 |

**Effect of NF300 treatment on surface roughness**

The average surface roughness of the cross, radial, and tangential sections increased from 24.21, 35.82, and 30.14 µm to 31.07, 40.82, and 42.05 µm, respectively, after NF300 treatment. The tangential section was found to have the greatest increase (39.5%), followed by cross (28.3%) and radial (14.0%) sections (Tab. 2). The increase in roughness may be attributed to the penetration and deposition of fire-retardant compounds within vessel lumens and surface pores, together with swelling and subsequent shrinkage of cell-wall components during drying. These processes can generate additional surface irregularities and modify the micro-topography of the wood surface (Fazeli & Talaei 2020). Similar increases in surface irregularity following fire-retardant treatment have also been reported previously (Popescu & Pfriem 2020). Lower-density species generally exhibited higher surface roughness after NF300 treatment, consistent with the significant negative correlation observed between wood density and NFT surface roughness. In contrast, several denser species exhibited relatively lower roughness after NF300 treatment, which may be associated with their more compact anatomical structures. These observations are consistent with previous studies demonstrating that the response of wood to fire-retardant treatment is strongly influenced by both density and anatomical structure. Therefore, the results suggest that the influence of NF300 on wood surface roughness is highly dependent on wood density and anatomical features (Fig. 1).

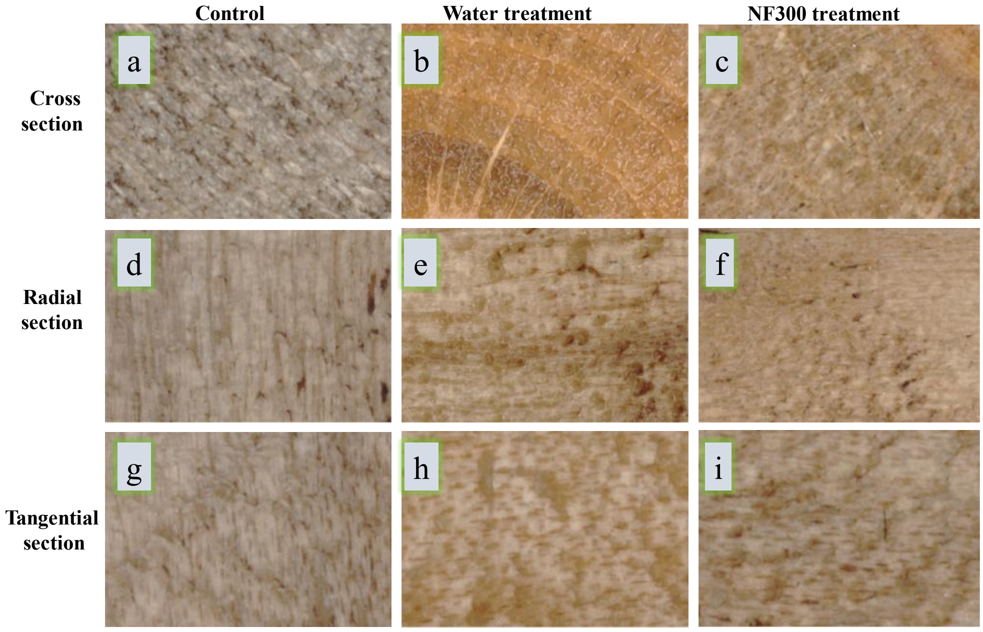


*Fig. 1: Optical surface images showing changes in the surface morphology of Koshiabura (density = 0.48 g $cm^{-3}$) after water and NF300 fire-retardant treatments. Images correspond to the cross section (a–c), radial section (d–f), and tangential section (g–i) under untreated control, water-treated, and NF300-treated conditions, respectively.*

**Statistical analysis**

Fig. 2a and Tab. 2 show that surface roughness increased after both water and NF300 treatments, with the highest values observed for the NF300-treated tangential surface (NFT; 42.05 ± 19.60 µm) compared with the untreated tangential surface (CT; 30.14 ± 17.05 µm). To evaluate the significance of this increase, a two-sample t-test assuming unequal variances was performed between the CT and NFT groups (n = 33). The analysis yielded a t-value of −2.63, 62 degrees of freedom, and a p-value of 0.011 (Fig 2b). Since $p < 0.05$, the null hypothesis was rejected, indicating that the NF300 treatment significantly increased the surface roughness of the tangential surface at the 95% confidence level. In contrast, statistical analysis between the CT and WT groups showed no significant difference (t = −0.90, df = 61, p = 0.372), indicating that water treatment alone did not significantly affect surface roughness.

**Relationship between density and surface roughness**

Figs. 2c-d illustrate the relationship between wood density and tangential surface roughness of CT and NFT. Surface roughness tended to decrease with increasing density, although considerable variation among species was observed. Linear regression analysis revealed a weak negative correlation for untreated specimens (CT; r = −0.293, $R^2$ = 0.086, p = 0.098) and a moderate, statistically significant negative correlation after NF300 treatment (NFT; r = −0.584, $R^2$ = 0.342, $p < 0.001$). NF300 treatment increased roughness in most species, consistent with the significant difference detected by the t-test. A similar relationship between wood density, anatomical characteristics, and surface quality has been reported in previous studies (Fujiwara et al. 2005; Kang et al. 2023; Thoma et al. 2015). The greater roughness observed in some lower-density species may be attributed to enhanced penetration and retention of the fire-retardant solution. However, the scattered distribution of the data indicates that density alone cannot fully explain the observed variation in surface roughness, and species-specific anatomical characteristics also play an important role. Future studies should include replicated specimens per species to improve statistical robustness.

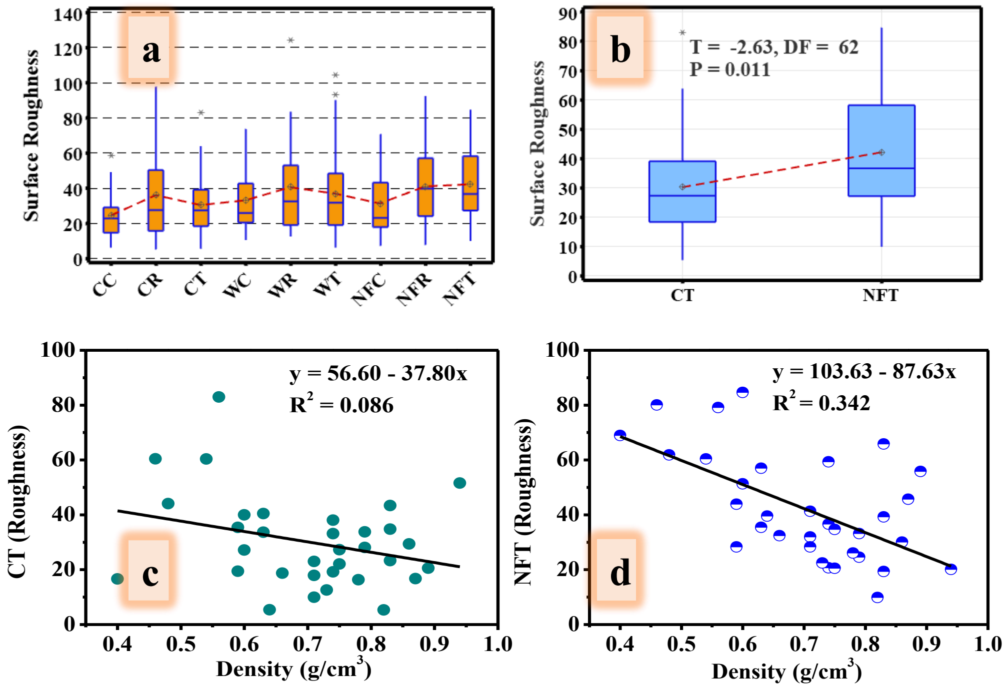


*Fig. 2: Surface roughness analysis of 33 Japanese hardwood species: (a) boxplots of roughness under control, water-treated, and NF300-treated conditions for cross, radial, and tangential surfaces; (b) statistical comparison of untreated (CT) and NF300-treated (NFT) tangential surfaces; (c) relationship between density and roughness for CT; and (d) relationship between density and roughness for NFT.*

## CONCLUSIONS

This study investigated the effects of water and fire-retardant chemical treatments on the surface roughness of 33 Japanese hardwood species using 3D optical profilometry. Surface roughness varied considerably among species and anatomical sections. An overall tendency for surface roughness to decrease with increasing wood density was observed, although anatomical differences among species also contributed to the observed variation. Both water and NF300 treatments increased surface roughness compared with control wood. The greatest increase occurred on tangential surfaces after NF300 treatment, where the average roughness increased from 30.14 ± 17.05 μm to 42.05 ± 19.60 μm (39.5%). Statistical analysis confirmed a significant difference between untreated and NF300-treated tangential surfaces ($p = 0.011$). The results indicate that treatment-induced changes in surface topography depend on both anatomical orientation and wood structure. These findings improve understanding of how moisture and fire-retardant treatments modify hardwood surfaces and provide useful information for optimizing finishing, coating, and surface-engineering of applications.

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