Effects of Different Incising Pretreatments in Improving Permeability in Two Refractory Wood Species

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For many product and applications, the penetration of preservatives or modification substances into wood species should be deep and homogeneous. Caucasian spruce and European larch are resistant to impregnation. This study compared how different incising pre-processes increased the retention of impregnation materials and the depth of their penetration into the structures of these refractory wood species. Mechanical, biological, and laser incising pretreatments were applied to increase the permeability of sapwood samples before the impregnation. To compare the uptake of the wood preservatives transverse and longitudinal to the axial tracheids in the samples, the cross-sections of some of the samples that had been subjected to different incising pretreatments were covered with a polyurethane-based paint. All wood samples were impregnated using a vacuum method with Celcure C_4 new generation preservatives. The study compared the possible effects of these different incising pretreatments on the uptake of preservatives into the tracheids in the spruce and larch woods in both longitudinal and transverse directions. The results showed that the copper (Cu) uptake levels increased in these refractory wood species, especially in the transverse direction, after the different incising pretreatments. Moreover, the results showed it is very important to choose the most suitable pretreatment method for the refractory tree species before impregnation.

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INTRODUCTION

High permeability is desirable when applying preservatives and wood-modification substances to protect wood against fungi, wood-boring insects, marine-boring organisms, and other harmful factors or to increase specific wood properties. For many product and applications, the penetration of preservative solutions and modification substances into wood should be deep and homogeneous (Lehringer *et al*. 2010; Dale *et al*. 2019; Nath *et al*. 2020a,b). Therefore, it is very important for the forestry industry to increase the permeability of wood species that are resistant to impregnation. One of the industry's solutions to increase the permeability of both refractory wood species and the heartwood parts of trees is the use of different incising methods. Incising improves intracellular fluid flow in woods with low permeability during preservative treatment processes (Nath *et al*. 2020a,b). For example, the presence of pit aspiration and extractives in Douglas fir wood and in Japanese hybrid woods (Japanese larch and Sakhalin fir), is what causes these tree species to be classified as very resistant to impregnation. To allow the wood of such species to be impregnated to a minimum level of retention and penetration, it is recommended that they be incised before the impregnation process (Islam *et al*. 2007).

The use of mechanical and laser incising methods improves the treatability of both heartwood and the sapwood of resistant-to-impregnate tree species. Studies on the mechanical incising and treatability of refractory wood species have generally focused on the penetration and retention levels of treated wood (Perrin 1978; Morris 1995; Winandy *et al*. 1995; Kartal 2002) and their effects on mechanical strength (Winandy and Morrell 1998; Winandy *et al*. 2022). On the other hand, studies on laser incising have related to improving the permeability of wood (Ruddick 1991), the interaction of laser beams with the anatomical properties of wood (Wang *et al*. 2013; Nath *et al*. 2020a, 2022), the effect of laser incising on the strength properties of wood (Suzuki *et al*. 1996; Morrell *et al*. 1998; Kortsalioudakis *et al*. 2015), and the effects of laser incising on the chemical properties of the regions of wood tissue affected by the laser beam heat (Barcikowski *et al*. 2006; Wang *et al*. 2013).

There are also some studies on various non-biological permeability enhancing methods. These include the cryogenic treatment (Yorur and Kayahan 2018), extraction treatment (Iida *et al*. 2002), microwave treatment (Listyanto *et al*. 2013; Xu *et al*. 2015; Poonia *et al*. 2016; Terziev *et al*. 2020), pre-compression (Chech 1971; Watanabe *et al*. 1998; Kortsalioudakis *et al*. 2015), pre-freezing (Erickson and Peterson 1969; Cooper *et al*. 1970), pre-steaming (Simpson 1976; Harris *et al*. 1989; Hansmann *et al*. 2002; Dashti *et al*. 2012), and smoke heating (Ishiguri *et al*. 2003). There are also studies that focused on bleach (sodium hypochlorite (NaClO)) and acid treatment (Yıldız *et al*. 2008).

Bacteria (Ünligil 1972; Clausen 1995; Kobayashi *et al*. 1998a,b; Hansmann *et al*. 2002; Pánek and Reinprecht 2011; Yıldız *et al*. 2012; Tajrishi *et al*. 2021), enzymes (Durmaz *et al*. 2015), and blue stain fungi (Lehringer *et al*. 2010; Danihelová *et al*. 2018) have also been used to increase the permeability of wood. In the forest products industry, the impact of controlled decay by wood rot fungi has been studied for years. It is one of the biotechnological applications used to increase the permeability of wood, because it does not have excessively harmful effects on other wood properties, especially on the mechanical strength (Fuhr *et al*. 2012a, b; Fuhr *et al*. 2013; Schubert *et al*. 2013; Gilani *et al*. 2014; Schubert *et al*. 2014; Gilani and Schwarze 2015; Emaminasab *et al*. 2016; Dale *et al*. 2019; Chang *et al*. 2020; Bakir *et al*. 2021a,b; Tajrishi *et al*. 2021; Bakir *et al*. 2022).

In this study, three different incising pretreatments were applied, and their effectiveness in increasing the permeability of two different refractory wood species was compared. This first pretreatment was bioincising. The biotechnological method of bioincising increases the uptake of impregnation in low-permeability wood species such as spruce by incubating *Physisporinus vitreus*, a white rot fungus that belongs to the Basidiomycetes class (Lehringer *et al*. 2009b; Lehringer *et al*. 2010; Schubert and Schwarze 2011). The second pretreatment was mechanical incising, where small slits are opened in the wood by running toothed rollers parallel to the fibers (Perrin 1978; Winandy *et al*. 1995; Morris 1995). The third pretreatment was laser incising, where a high-powered carbon dioxide (CO_2) laser creates deep needle-shaped cavities in the wood. This improves the liquid impregnation capacity and results in a higher liquid penetration rate (Nath *et al*. 2020a,b).

There have been many studies on increasing the permeability of wood species that are resistant to impregnation. However, there have been no studies on the comparative effects of these different incising methods on the uptake and penetration of new generation copper (Cu)-containing wood preservatives. Many up-to-date scientific studies have been conducted at the micro level with biotechnological methods and laser applications, but their significance has not been explored further. The importance of the present study lies in its comparison of mechanical incising as well as bio- and laser incision at the macro level.

EXPERIMENTAL

Test Materials

Defect-free, kiln-dried sapwood samples were obtained from Caucasian spruce (*Picea orientalis* L. Link) grown in the Artvin province of Turkey and European larch (*Larix decidua* Mill.) grown in Karabula in the Krasnoyarskiy Kray region of Russia. All wood samples measured 120 mm × 30 mm × 30 mm (longitudinal × radial × tangential). The samples were shortly end-matched; therefore, for each species, they were cut out of the same original full-length parent boards and then allocated to different treatments. Eventually, there were 20 samples of spruce sapwood impregnated without pretreatment, 20 samples of larch sapwood impregnated without pretreatment, 20 samples of spruce sapwood impregnated after bioincising pretreatment, 20 samples of larch sapwood impregnated after bioincising pretreatment, 20 samples of spruce sapwood impregnated after mechanical incising pretreatment, 20 samples of larch sapwood impregnated after mechanical incising pretreatment, 20 samples of spruce sapwood impregnated after laser incising pretreatment, and 20 samples of larch sapwood impregnated after laser incising pretreatment. The samples were selected so that their growth rings corresponded as closely as possible to minimize any influence of natural variability. The radial and tangential orientation of the growth rings were strictly maintained.

Bioincising Pretreatment

Before the bioincising pretreatments, the wood samples were conditioned for 2 weeks in a climate chamber at 20 °C and 65% relative humidity. Glass jars with dimensions of 170 mm × 100 mm × 100 mm (length × width × height) were used in the bioincising process because the wood samples required a larger volume than that of the Kolle flasks required in the BS EN 113-1 (2020) standard. The metal lids of the jars used in the *P. vitreus* incubation processes were first pierced in a circle with a punch tool. The hole was clogged with cotton wool to meet the air and humidity requirement of the fungi in the climate chamber more easily. The wood samples were placed directly into the glass jars, which already contained 4% malt extract agar (MEA) nutrient medium previously inoculated with the fungal strain. Wet vermiculite was also added under sterile conditions. The air-dried sapwood samples were exposed to *P. vitreus* FP 103669-T white rot fungus for 8 weeks at 26 °C and 75% relative humidity to induce a weight loss of approximately 10%. From the literature, a weight loss of 10% from minor strength losses of less than 10% in the wood by bioincising was considered. The efficiency of the incubation periods and proper growth of *P. vitreus* depend on all conditions (*i.e.*, nutrient, temperature, water activity, oxygen, and pH) being favorable. Homogeneous bio-incising depends on the complete coverage of the wood surface. For a successful upscaling to industrial application, construction, and other mass loading applications, a uniform colonization of the substrate and controlled fungal activity must be achieved to ensure a homogenous distribution of wood modification substances (Fig. 1).

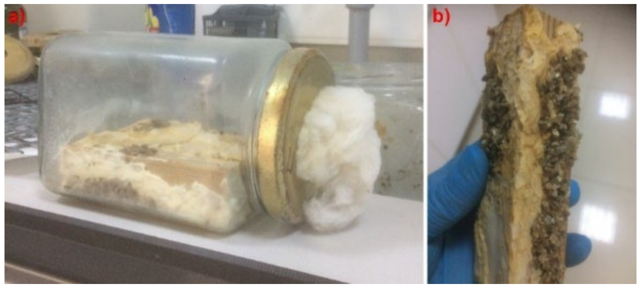

Fig. 1. Images of the a) heterogeneous and b) homogeneous colonization of wood samples by *P. vitreus* fungus in glass jars

The kiln-dried samples were weighed before and after the bioincising. The percentage weight loss of each sample after bioincising was then calculated according to Eq. 1,

$$WL\ (\%) = \{(W_0 - W_1)|\ W_0\} \times 100 \tag{1}$$

where *WL* is the weight loss of the sample (%), W_0 is the oven-dried weight of the sample before treatment (g), and W_1 is the oven-dried weight of samples after treatment (g).

Mechanical Incising Pretreatment

Some Caucasian spruce and European larch samples were mechanically incised using the same incision density pattern (10,000 incisions/m^2) (Fig. 2), incision depth (10 mm), and diameter (2 mm). The radial and tangential surfaces of the samples were mechanically incised (Fig. 3). Before the mechanical incising pretreatments, the wood samples were conditioned for 2 weeks in a climate chamber at 20 °C and 65% relative humidity.

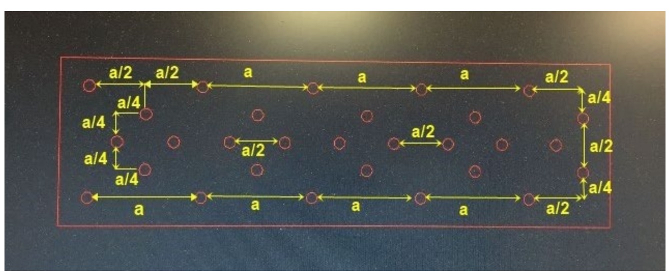

Fig. 2. Mechanical and laser incising patterns on radial and tangential surfaces and distances between holes in transverse and longitudinal directions

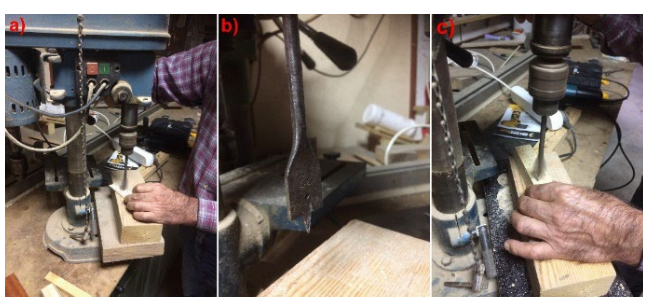

Fig. 3. Images depicting the a) preparation of a wood surface die (10,000 incision/m^2) for all mechanical incising operations, b) the depth of the spade drill bit (10 mm), and c) the incision of wood samples by the spade drill bit

The oven-dried samples were weighed before and after the mechanical incising pretreatments. The percentage weight loss of each sample after mechanical incising was then calculated according to Eq. 1.

Laser Incising Pretreatment

The holes were drilled with a CO_2 laser (VLS6.60; Universal Laser Systems, Scottsdale, AZ, USA) in the radial and tangential surfaces of the Caucasian spruce and European larch samples by controlling the irradiating time with power at 60 W, a speed setting of 4.0 m/s, and a high 30 mm. The same incising pattern was used for all specimens, as shown in Fig. 4. The incising density was the same for both the mechanical incising and the laser incising pretreatment, *i.e.*, 10,000 holes/m^2 (Fig. 2), drilled to a depth of 10 mm and with a diameter of 2 mm for each incision (Islam *et al*. 2008).

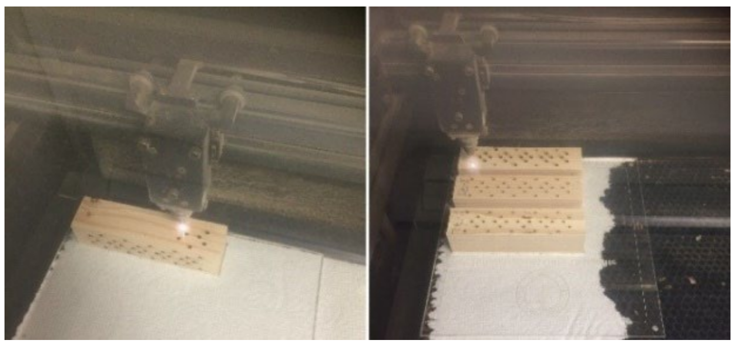

Fig. 4. The incision of wood samples by a CO_2 laser

The oven-dried samples were weighed before and after the laser incising pretreatment, and the percentage weight loss of each sample after laser incising was then calculated according to Eq. 1.

Impregnation Treatments

Some spruce and larch sapwood samples were not treated with any incising process so that they could serve as controls. Together with the pre-incised spruce and larch sapwood samples, they were subsequently treated with Celcure C_4 wood preservative solution to detect and compare the permeability of the samples. Celcure C_4 is a water-based wood preservative that contains an alkaline copper quaternary system and two organic co-biocides (benzalkonium chloride and cyproconazole). In determining the concentration of the preservative solution, based on market share and, more importantly, direct exposure route, the present study focused on materials rated for above-ground use. So, the concentration of Celcure C_4 solution for impregnation processes was 3%. Vacuum methods (40 min, 40 mbar) were applied in the impregnation processes according to the BS EN 113-1 (2020) standard. Some samples' end-grain surfaces (cross sections) were sealed with a polyurethane coating before treatment to compare the uptake in the transverse directions of preservative solutions into these surfaces. On the other hand, the other samples' longitudinal surfaces (radial and tangential sections) are sealed with polyurethane coatings to determine the uptake in the longitudinal directions. The preservative-treated samples were then stored at 20 °C for 2 weeks for a good fixation of the preservatives. Table 1 shows the test samples and procedures followed in the study.

Table 1. Test Samples and Procedures Followed in the Study

Wood Species	Pretreatment Method	With Polyurethane sealing	Wood Preservative	Treatment	Number of Wood Samples
Caucasian spruce	None	End-grain surfaces	Celcure C_4	Vacuum	10
Caucasian spruce	Bioincised	End-grain surfaces	Celcure C_4	Vacuum	10
Caucasian spruce	Mechanically incised	End-grain surfaces	Celcure C_4	Vacuum	10
Caucasian spruce	Laser incised	End-grain surfaces	Celcure C_4	Vacuum	10
Caucasian spruce	None	Longitudinal surfaces	Celcure C_4	Vacuum	10
Caucasian spruce	Bioincised	Longitudinal surfaces	Celcure C_4	Vacuum	10
Caucasian spruce	Mechanically incised	Longitudinal surfaces	Celcure C_4	Vacuum	10
Caucasian spruce	Laser incised	Longitudinal surfaces	Celcure C_4	Vacuum	10
European larch	None	End-grain surfaces	Celcure C_4	Vacuum	10
European larch	Bioincised	End-grain surfaces	Celcure C_4	Vacuum	10
European larch	Mechanically incised	End-grain surfaces	Celcure C_4	Vacuum	10
European larch	Laser incised	End-grain surfaces	Celcure C_4	Vacuum	10
European larch	None	Longitudinal surfaces	Celcure C_4	Vacuum	10
European larch	Bioincised	Longitudinal surfaces	Celcure C_4	Vacuum	10
European larch	Mechanically incised	Longitudinal surfaces	Celcure C_4	Vacuum	10
European larch	Laser incised	Longitudinal surfaces	Celcure C_4	Vacuum	10

Determination of the Preservative Solution Uptake

The solution uptake in the samples was calculated as the difference between the wet weight of the wood samples after impregnation and the air-dried initial weight before impregnation, according to the BS EN 113-1 (2020) standard. To evaluate the penetration of Cu, the untreated and various pre-incised wood samples were cross-sectioned in the middle, and the penetration of copper was measured after spraying with Chrome azurol S solution (a color indicator of copper) based on the AWPA A69-18 (2021) standard method.

Statistical Analysis

For statistical evaluations, analysis of variance (ANOVA) was used to compare several groups of observations. Using Tukey's test, all the data were statistically compared to identify significant differences at 0.05 probabilities among the mean values of the studied properties within the applications. The ANOVA and the least significant difference tests were conducted using JMP 5.0 statistical software (SAS Institute, Cary, NC, USA).

RESULTS AND DISCUSSION

Differences in Weight Losses from Different Incising Pretreatments

In recent years, there has been a great interest in determining the changes in the physical and mechanical properties of wood as a result of different incising processes because it is important that the physical properties must not be negatively altered and that the treatment should not weaken its mechanical properties after all incising pretreatments. So, Table 2 compared the differences in weight losses in the spruce and larch sapwood samples after the different incising pretreatments. Although there was a significant difference among the bioincising, mechanical incising, and laser incising pretreatments in both spruce and larch sapwoods, there was no significant difference between the same pretreatments of the spruce and larch sapwood samples, except for laser incising.

Table 2. Weight Loss in the Spruce and Larch Sapwood Samples after Bioincising, Mechanical Incising, and Laser Incising Pretreatments

Wood Species	Pretreatment		Sample Weight Loss (%)
Caucasian spruce	Bioincised		9.824 (*0.698*)*a*
	Mechanical incised		1.115 (*0.366*)*d*
	Laser incised		4.020 (*0.866*)*c*
European larch	Bioincised		8.467 (*0.789*)*a*
	Mechanical incised		1.660 (*0.369*)*d*
	Laser incised		6.815 (*0.978*)*b*

Values in parentheses are standard deviations. The same letters in each column indicate that there is no statistical difference between the samples, according to Tukey's test ($p \leq 0.05$).

As shown in Table 2, the weight losses in the spruce and larch sapwood samples after different pretreatments were higher in bioincised samples than in the laser and mechanical incising samples. *P. vitreus* is a wood decay fungus that can show different degradation patterns in the spruce and larch wood samples. However, when mechanical and laser incising processes are applied, only certain parts of the wood tissue are affected, while the entire wood tissue is affected by bioincising processes. Laser and mechanical incising interactions with the refractory wood tissues resulted in local and shallower holes, whereas the fungal hyphae can reach deeper in the bioincising process. Laser incising pretreatments resulted in more weight losses in larch samples than in spruce samples. Nath *et al*. (2020a) reported that wood anatomy and density had a major influence on the effect of CO_2 laser incising when incised at the same CO_2 laser power. In addition, denser woods are more difficult to ablate or incise (Fukuta *et al*. 2016; Nath *et al*. 2020b). Nath *et al*. (2020b) reported the ablation to be greater in lower-density springwood than in latewood of CO_2-TEA (Transverse Excitation Atmospheric) laser-incised pine. In addition, a lower-wavelength laser was shown to give improved incising in dense wood (Nath *et al*. 2020b).

Using Chrome Azurol-S Reagent to Detect the Cu Uptake Levels

Impregnating cross-sections of spruce and larch sapwood samples with chrome azurol-S solution displayed the presence of Cu, since a blue color denotes a positive response (Fig. 5). Because it is a practical, quick, and cheap method of detecting Cu, chrome azurol-S solution is commonly used in wood treatment studies (Milanez *et al*. 2017).

Figure 5 demonstrates that, as a result of the different incising pretreatments, much more wood preservative was absorbed in the Caucasian spruce sapwood samples than in the European larch sapwood samples. The types and prevalence of the resins or some extractives in larch sapwood are believed to promote decreasing preservative uptakes. Larch sapwood has higher resin/extractives content than spruce sapwood (Lüxford 1953; Wu and Hu 1997; Wagner 2010). Matsumura *et al*. (1996) stated that resin removal increased the permeability of Japanese larch heartwood. They found significant correlations between the permeability of samples and the methanol-soluble extractive content. A relation was also found between permeability and the number of resin canals. Similar results were also reported by Ahmed *et al.* (2012) for the resin content. Its distribution may influence a uniform liquid penetration in dried lumber, particularly when resins are migratory at elevated temperatures (Lu *et al.* 1992; Ahmed *et al.* 2012). Caucasian spruce sapwood samples showed that Cu uptake levels after laser and mechanical incising pretreatments were higher than those in the control and bioincised spruce samples (Fig. 5a). In the European larch sapwood samples, Cu uptake levels in bioincised larch samples were higher than in the control samples and in samples pre-incised with other incising processes (Fig. 5b). The results are shown in Table 3 to support these findings.

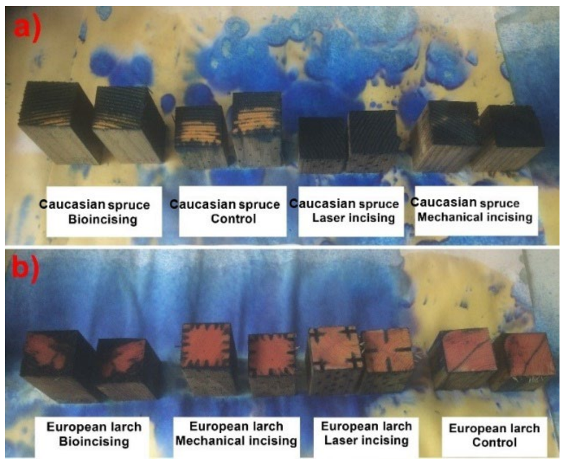

Fig. 5. Using chrome azurol-S reagent to detect Cu uptake levels in a) Caucasian spruce and b) European larch wood samples. The blue colors show positive responses.

Uptake of Preservatives in Transverse and Longitudinal Directions

Table 3 shows the Cu uptake levels (kg/m^3) in the spruce and larch sapwood samples before and after different incising pretreatments. The end-grain surfaces of some samples were sealed with polyurethane, which presented the Cu uptake levels in the transverse directions of the preservative solutions. Unincised wood samples served as the controls to compare the effects of different pretreatments on the permeability of spruce and larch sapwood samples. As the end-grain surfaces of samples were sealed with polyurethane in the spruce and larch samples, Cu uptake levels by Celcure C_4 treatment generally decreased in all pretreatments, except for the bioincising pretreatment of larch sapwood samples. However, no statistically significant changes were observed in the mechanical and laser incising pretreatments of spruce samples, or in the control and bioincising pretreatment of larch samples.

The results for the different pretreatments of spruce samples showed that the uptake of preservatives in the longitudinal directions was higher than the uptake in the transverse directions in the control and in all the pre-incised wood samples. Nath *et al*. (2020b) expressed a similar finding. However, no differences were determined for the mechanically and laser incised spruce samples. Similar results were also determined for the control and in all the pretreatments of the larch sapwood samples, except for the bioincising pretreatment. However, there were not significant differences in the uptake of preservatives in different directions in the control and the various pre-incised larch sapwood samples (Table 3).

Table 3. Cu Uptake Levels (kg/m^3) in Impregnated Spruce and Larch Samples Before and After Bioincising, Mechanical Incising, and Laser Incising Pretreatments

Wood Species	Pretreatment	With Polyurethane Sealing	
		End-grain surfaces – transverse uptake	Longitudinal surfaces - longitudinal uptake
Caucasian spruce	Control (unincised)	7.980 (*1.270*)*cde*	17.877 (*1.268*)*ab*
	Bioincised	9.333 (*0.912*)*c*	18.801 (*0.896*)*ab*
	Mechanically incised	16.472 (*1.92*)*b*	18.854 (*0.929*)*ab*
	Laser incised	19.449 (*0.896*)*ab*	21.731 (*0.897*)*a*
European larch	Control (unincised)	2.016 (*1.268*)*f*	5.146 (*1.268*)*cdef*
	Bioincised	8.183 (*0.992*)*cd*	7.530 (*0.894*)*cd*
	Mechanically incised	2.334 (*0.896*)*ef*	5.750 (*0.688*)*cdef*
	Laser incised	2.331 (*0.896*)*ef*	3.667 (*0.958*)*def*

Values in parentheses are standard deviations. The same letters in each column indicate that there is no statistical difference between the samples according to Tukey's test (p ≤0.05).

Although mechanical incising methods have, to date, proven most effective in assisting in the transverse permeability of wood (Nath *et al*. 2020a), the present study found laser incising to be partially more effective than mechanical incising in the transverse directions in the spruce sapwood.

The Cu uptake in the laser and mechanically incised spruce sapwood samples with polyurethane sealing end-grain surfaces was higher in the bioincised spruce sapwoods than in those control samples. However, there was no significant difference between the bioincised and control spruce samples. Similarly, there was no significant difference between the laser and mechanically incised spruce samples.

While mechanical incisions are effective for enhancing preservative treatment processes, the technique is limited because small holes or complex incision geometries are difficult or impossible to achieve. Laser-incision is a technique that could eradicate these issues. It would allow finer incisions, more complex incision patterns, and deeper incision holes compared to mechanical incision technologies (Nath *et al*. 2020a).

As shown in Table 3, in the spruce sapwood samples with polyurethane sealing longitudinal surfaces, no statistically significant change was observed among the control and all pre-incised spruce sapwood samples. Similarly, there was no significant difference between the control and all pre-incised larch sapwood samples in the larch sapwood samples with polyurethane sealing longitudinal surfaces (Table 3).

In general, the Cu uptake was much higher after bioincising pretreatment compared to the control, mechanical, and laser pretreatments in the larch sapwood samples with polyurethane sealing end-grain surfaces. However, there was no significant difference among the control, mechanical, and laser pretreatments. In this study, *P. vitreus* was more active in larch sapwood than in spruce sapwood samples, with polyurethane sealing end-grain and longitudinal surfaces. It is known that *P. vitreus* used in the bioincising process selectively delignifies the wood and prefers mainly bordered pits primarily containing pectin in the wood (Schwarze 2007; Lehringer *et al*. 2009a, 2010; Schubert and Schwarze 2011; Fuhr *et al*. 2013; Schubert *et al*. 2013; Gilani and Schwarze 2014). *Physisporinus* *vitreus* likely decomposes the aspirated pits in larch sapwood more than in spruce sapwood. However, different amounts of copper in the larch sapwood and spruce sapwood samples may be the result of the chemical components (pectin, cellulose, hemicellulose, and lignin) and substances (extractives, lignans, and phenolic compounds) consumed by *P. vitreus*, which might be different in larch sapwood and spruce sapwood. In addition, visual observations (Fig. 5) and impregnation treatments (Table 3) indicated that the control samples of larch sapwood samples were very resistant to preservative treatment, likely due to the presence of higher resin than in spruce sapwood (Lüxford 1953; Wu and Hu 1997; Wagner 2010) (Table 3). In other words, it is believed that the types and prevalence of the resins or some extractives in larch sapwood promote the increase of *P. vitreus* activity.

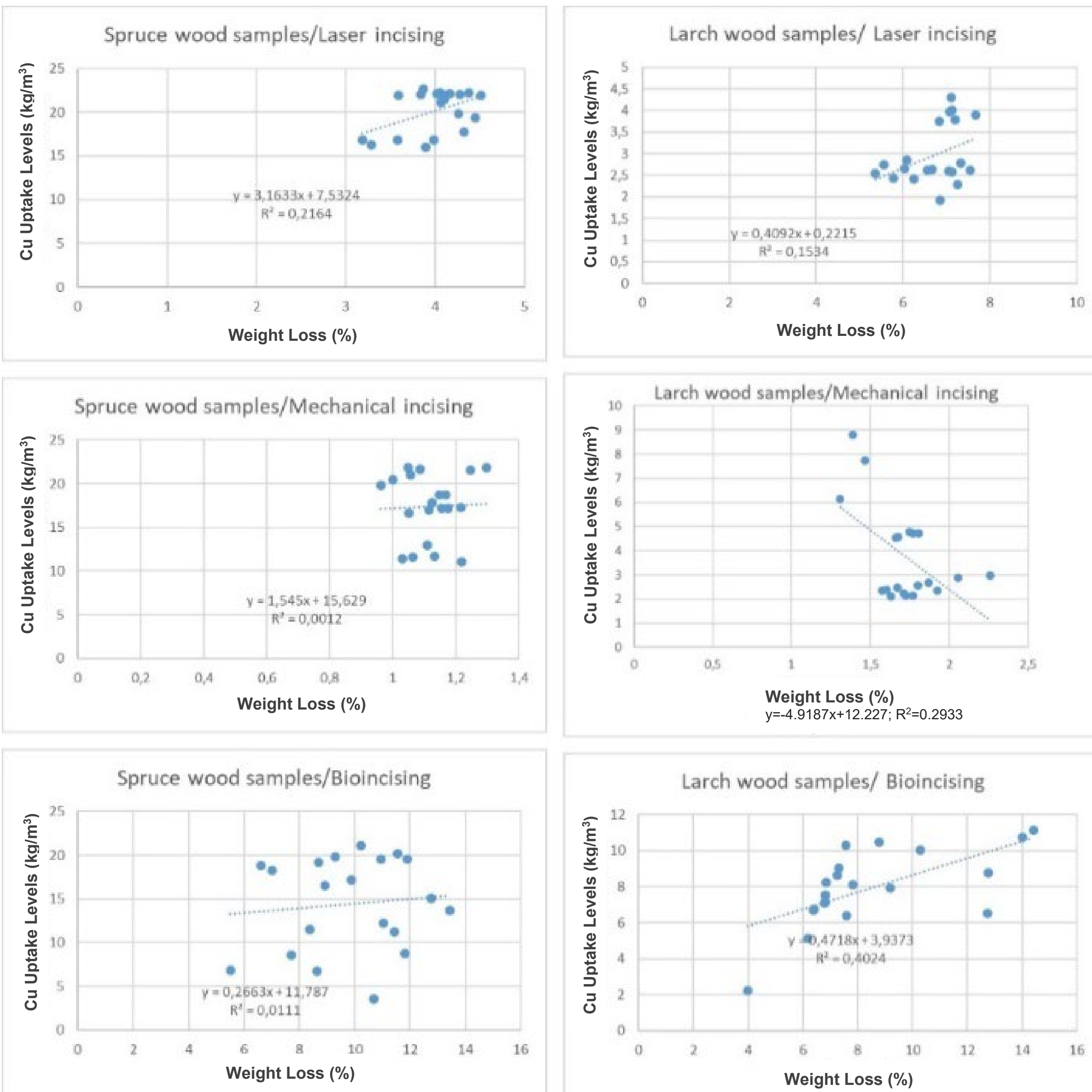

Fig. 6. Correlation between the weight losses and Cu uptake levels in the impregnated spruce and larch wood samples pre-incised with the three different incising methods

After the different incising treatments in both spruce and larch sapwood samples, it was found that the increases in the Cu uptake levels in the samples with polyurethane sealing end-grain surfaces were higher than the increases in the samples with polyurethane sealing longitudinal surfaces. In these cases, it is more appropriate to interpret the comparisons as percentages, which means that Cu uptake levels increased more in the transverse directions than in the longitudinal directions after the incising treatments. In addition, laser and mechanical incising pretreatments resulted in higher Cu uptake levels in the spruce samples than in the larch samples with polyurethane sealing end-grain and longitudinal surfaces (Table 3). It emerged that wood anatomy and density could play a role in incision efficiency, influencing hole depth, diameter, and circularity, and affecting the liquid flow pathways in the spruce and larch sapwood (Nath *et al*. 2022). The average wood density in European larch trees (515 to 560 kg/m^3) (Karlman *et al*. 2005) was higher than that in Caucasian spruce trees (401 to 425 kg/m^3) (Bozkurt *et al*. 1993). Nath *et al*. (2020a) reported that the presence of earlywood and latewood had a significant influence on the incision properties during CO_2 laser incising. Moreover, laser interactions with the denser latewood tissues resulted in shallower holes (Nath *et al*. 2022).

The correlations between the weight losses (%) and changes in the Cu uptake levels (kg/m^3) that occurred in the samples by different incising pretreatments in spruce and larch sapwood samples are seen in Fig. 6. Here, while determining the correlations, the sapwood samples belonging to the with polyurethane sealing end-grain and longitudinal surfaces groups were evaluated together, separately for each pretreatment. In general, as weight losses increased, the Cu uptake levels increased in both spruce and larch sapwoods. However, in spruce sapwood samples pre-incised with laser and mechanical incising methods, the lower weight loss levels had the higher Cu uptake levels (Fig. 6).

Lasers for wood processing were initially meant only for cutting, marking, and engraving, and it was thought that laser incising was not economically viable (Kamke and Peralta 1990; Nath *et al*. 2020b). However, with the further development of laser technologies, it has recently been concluded that laser incising is an efficient technique for creating deep, narrow holes for preservative treatment (Nath *et al*. 2020a).

CONCLUSIONS

1. The Cu uptake levels in the spruce and larch sapwood samples pre-incised with different incising methods increased compared to control samples, except for laser incised larch sapwood with polyurethane sealing longitudinal surfaces. Moreover, there was a much greater increase in Cu uptake levels in the various pre-incised spruce and larch sapwood samples with polyurethane sealing end-grain surfaces than in samples with polyurethane sealing longitudinal surfaces.
2. In this study, *P. vitreus* was more active and effective in larch sapwood than in spruce sapwood samples, with polyurethane sealing end-grain and longitudinal surfaces. In addition, there was more Cu uptake in the bioincised larch sapwood samples than in the laser and mechanically incised larch samples. On the other hand, Cu uptake was much lower in bioincised spruce sapwood samples than in the mechanically and laser incised spruce samples, especially samples with polyurethane sealing end-grain surfaces. Therefore, it is more appropriate to use the laser and mechanical incising for spruce sapwood, and bioincising for larch sapwood, before impregnation.

3. Further chemical (the laser and fungus interactions with compounds and extractives of wood) and anatomical studies (the laser and fungus interactions with refractory wood tissues) are needed to understand why *P. vitreus* increases the permeability of larch sapwood more than that of spruce sapwood, or why laser incising increases the permeability of spruce sapwood more than that of larch sapwood.

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