Influence of Surface Finishing of Hardwood Cross-section on Sound Absorption Performance

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This study aimed to evaluate the sound absorption performance depending on surface finishing of the hardwood cross-section. The sound absorption performance of wood cross-sections was evaluated after band saw cutting, sandpaper polishing, and staining. The sound absorption performance was best following the band saw cutting and no other treatment. On the other hand, stain blocked the pores and decreased the sound absorption performance. This study suggests that finishing methods that preserve the integrity of vessels need to be considered when using wood as a sound-absorbing material.

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Keywords: Sound absorption coefficient; Finishing method; Eco-friendly sound absorber; Sandpaper polishing; Staining

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INTRODUCTION

In November of 2019, the coronavirus disease 2019 (COVID-19) was first reported in Wuhan, China (Haryanto 2020; Jang and Kang 2020), and it has subsequently affected many aspects of the worldwide economy. Foreign travel was restricted, and direct contact with people, including social gatherings, was reduced (Douglas *et al.* 2020; Haryanto 2020). As a consequence, room acoustics are becoming increasingly important as teleconferencing usage in offices increases (Lee and Kumar 2021). Therefore, interest in sound absorption of rooms is increasing (Hara and Shimizu 2022).

Most commercial sound-absorbing materials are made from synthetic fibers (Samsudin *et al.* 2016). However, these materials can cause environmental problems during production or disposal. Synthetic fibers are prone to break down into microplastics, which can pose a threat to marine life and humans who consume them (Almroth *et al.* 2018). Thus, research of sound absorption solutions using eco-friendly (green) materials is active (Bhingare *et al.* 2019; Yang *et al.* 2020; Gliscinska *et al.* 2021). Most green sound-absorbing materials are fibrous materials produced as agricultural by-products (Bhingare *et al.* 2019; Yang *et al.* 2020; Gliscinska *et al.* 2021). Some of these materials have been reported to have sound absorption performance as good as that of commercial synthetic fibers (Lim *et al.* 2018; Putra *et al.* 2018), However, natural fibers are less durable than synthetic fibers and they are difficult to commercialize.

Among eco-friendly materials, it is difficult to find one that is as durable as wood. The specific strength of wood is higher than that of iron and it can be used semi-permanently if preserved properly. The study of wood structures hundreds of years old have demonstrated wood's durability (Høibø *et al.* 2015). Accordingly, research on the use of wood cross-sections as an eco-friendly sound-absorbing material has increased. Tangential and radial wood sections have sound reflecting properties. Because there are few pores in tangential and radial wood sections, it is difficult for sound waves to penetrate inside. However, cross-sections can absorb sound due to their pores (Wassilieff 1996). When a sound wave enters the pores associated with vessels or fibers in the wood cross-section, the internal friction between the sound wave and the pore increases and attenuates the sound energy (Wang *et al.* 2017). In particular, hardwood cross-sections have excellent permeability due to their vessels (Taghiyari 2013).

Excellent permeability permits excellent sound absorption performance (Kang *et al.* 2011; Taghiyari *et al.* 2014; Kang *et al.* 2020). Therefore, Kang *et al.* (2011) suggested that the cross-section of *Liriodendron tulipifera*, which has relatively large and widely distributed vessels, can be used as porous sound-absorbing material. In the porosity analysis of wood cross-section, Jang *et al.* (2020) reported that the pore shape with the greatest influence on the longitudinal permeability of wood is the through-pore porosity. Therefore, Jang and Kang (2021a,b,c) reported that the through-pore porosity of hardwood cross-sections is an important determinant of the sound absorption performance. Accordingly, various physicochemical wood modifications such as steam explosion, microwave treatment, heat treatment, and delignification have been studied to improve the pore structure of wood to increase permeability and further improve through-pore porosity (Kang *et al.* 2008; Wang *et al.* 2014; Chung *et al.* 2017; Kang *et al.* 2021; Kolya and Kang 2021).

Most wood products are polished during the final stages of production (Papp and Csiha 2017). In addition, they may be subjected to stain treatment to increase their durability. However, it was difficult to find a study dealing with how these surface finishing methods affected the sound absorption performance of wood. Therefore, the effect of surface finishing methods on the sound absorption performance was investigated in this study.

MATERIALS AND METHODS

Specimen Preparation

Figure 1 shows the sample preparation for this study. Indonesian *Homalium foetidum* and *Quercus rubra* timber were prepared. Timbers were machined into cylindrical rods with a diameter of 29 mm by lathes. The rods were cut to 10-mm-thick cylindrical samples using a band saw. The 20 samples with no cracks and no knots for each species were selected and divided into two groups of 10 each. The sample production was performed by Saehan Timber Co., Ltd (Ilsan, South Korea). Samples were stored in a laboratory at a temperature of 20 °C and humidity of 45% for one month. Their moisture content was approximately 7%.

Finishing Method and Measurement of Sound Absorption Coefficient

One group of samples was subjected to a sandpaper treatment (Group 1), while the other group of samples was subjected to a staining treatment (Group 2). The sound absorption coefficients of the Group 1 samples were measured using an impedance tube (Type 4206; Brüel & Kjær, Nærum, Denmark) based on the ISO standard 10534-2 (2001).

The samples were polished with 150-grit sandpaper. The polishing time per sample was approximately 10 s, after which the sound absorption coefficient was measured again. The sound absorption coefficient was also measured for the Group 2 samples. The wood stain was applied to the samples three times, and they were air-dried for approximately 24 h before re-measuring the sound absorption coefficient. The wood stain was a water-based transparent color with acrylic resin as the main component and was supplied by KCC Corporation (Seoul, South Korea).

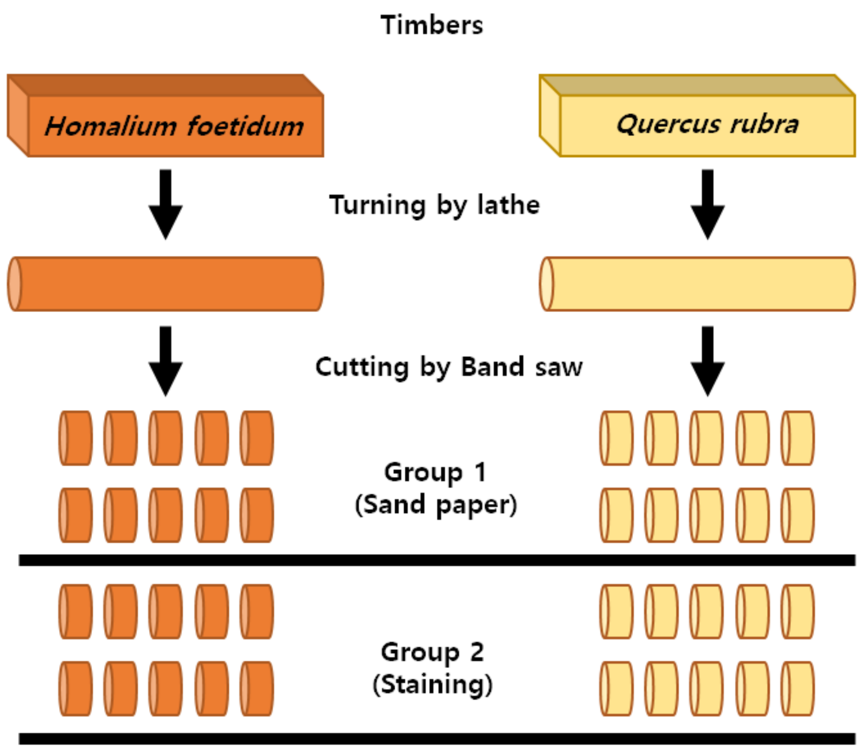

Fig. 1. Sample preparation of the *H. foetidum* and *Quercus rubra* timber

The sound absorption coefficients of all the samples were measured with and without an air back cavity of 3 cm. The sound absorption curves were obtained at the 50-6,400 Hz frequency band. In addition, the noise reduction coefficient (NRC) was measured as the average sound absorption coefficient at various frequencies (250, 500, 1,000, and 2,000 Hz). To close the gap between the sample and the inner wall of the impedance tube, an O-ring was placed in front of the sample (Kang *et al.* 2021). When an air back cavity was applied, O-rings were placed at the front and back sides of the sample.

Scanning Electron Microscope Image Analysis

A scanning electron microscope (SEM) (Genesis-1000; EmCrafts, Sungnam, South Korea) was used to observe the change in vessels according to finishing method for the cross-sections of the *H. foetidum* and Korean *Quercus rubra*. To observe the original shape of the vessels of these species, they were softened with water, gently shaved on the surface with a microtome, dried (80 °C, 5 h), and coated with gold. The specimen vessels were then observed. Next, a sample cut with a band saw, a sample polished with sandpaper, and a sample stained after being cut with a band saw were all observed. All the samples were observed at 200× magnification under the high vacuum mode.

RESULTS AND DISCUSSION

SEM Images Depending on the Finishing Method

Figure 2 shows the cross-sectional SEM images depending on the finishing method. Based on the samples cut with a microtome, the *H. foetidum* was categorized as a diffuse-porous wood with abundant and widely distributed vessels. On the other hand, the *Quercus rubra* was observed in the form of a ring-porous wood with large-diameter vessels distributed along the springwood. The vessels were relatively intact and small pores were observed.

In the samples cut with a band saw, the vessels were damaged slightly compared to the samples cut with a microtome. In addition, the samples polished with the sandpaper showed greater vessel damage than samples cut with a band saw. In the *Quercus rubra*, the vessel damage after the sanding was not more severe than that in the *H. foetidum*. This was probably because the vessels of the *Quercus rubra* were much larger than those of the *H. foetidum*. Finally, in the stained sample, the wood stain blocked the vessels and disrupted their integrity. The degree of damage to the vessels was, from least to greatest, as follows: microtome, band saw, sandpaper, and staining.

(a)

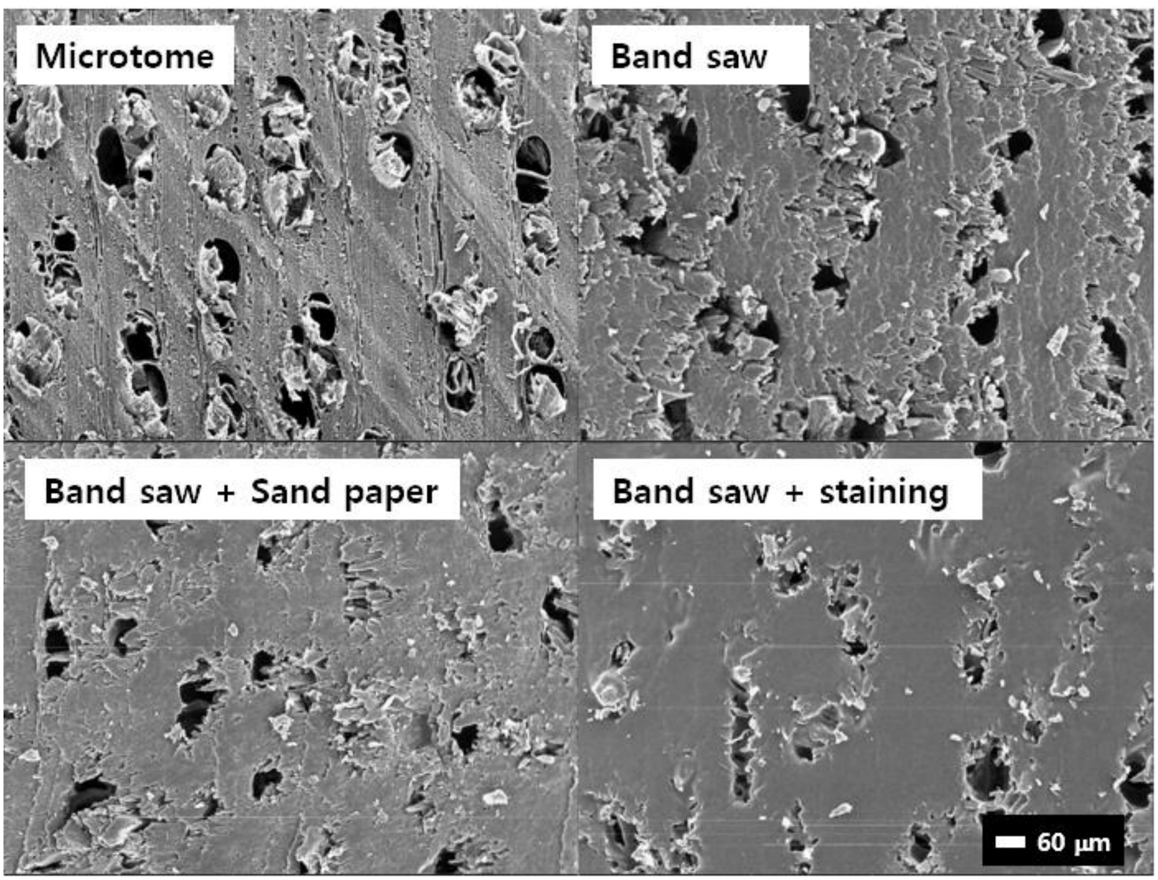

Fig. 2(a). SEM images of the *H. foetidum*

(b)

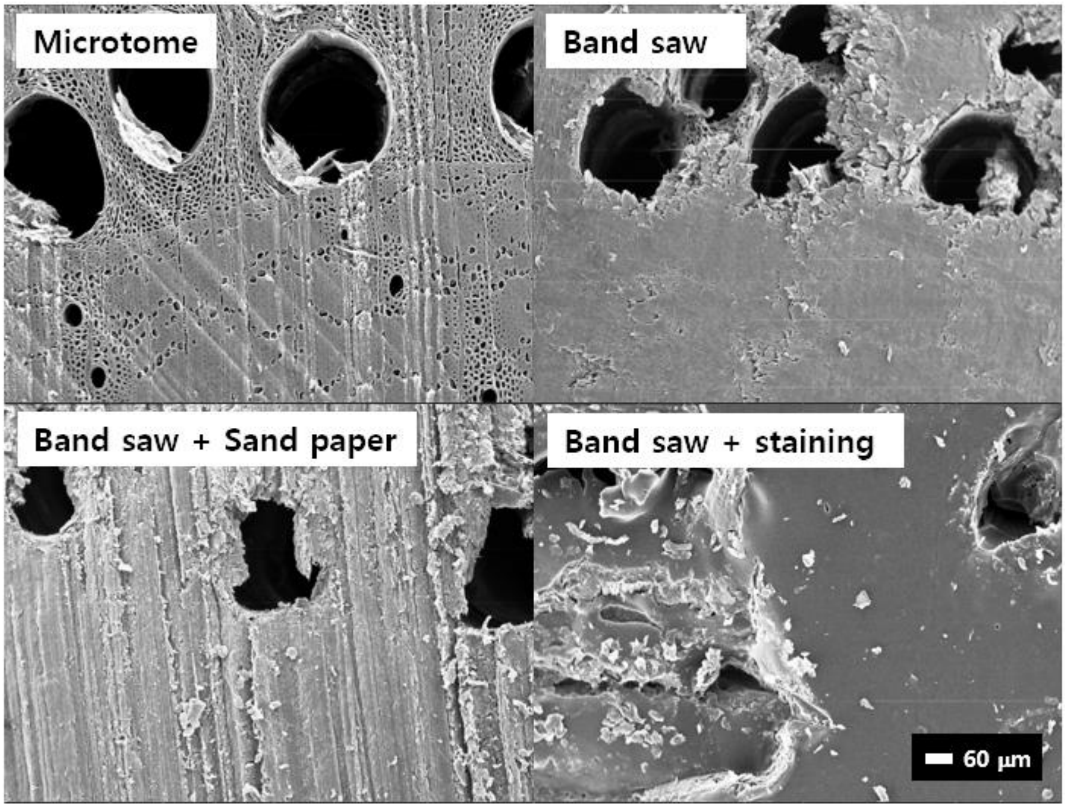

Fig. 2(b). SEM images of the *Quercus rubra*

Sound Absorption Coefficient Depending on the Finishing Method

Figure 3 shows the sound absorption coefficient curve by finishing method with an air back cavity (Fig. 3a: *H. foetidum* and Fig. 3b: *Quercus rubra*). When no air back cavity was applied, the sound absorption coefficient tended to increase as the frequency increased in the *H. foetidum* and *Quercus rubra*. This was a typical sound absorption pattern in porous materials.

However, when an air back cavity was applied, the sound absorption patterns of the two species were different. The *H. foetidum* had a higher sound absorption coefficient within the low frequency region that continued to the higher frequency region. However, in the *Quercus rubra*, a high peak sound absorption coefficient was observed at low frequency, and the sound absorption coefficient gradually decreased at higher frequencies. This was because the combination of the large vessels in the *Quercus rubra* and the air back cavity caused resonance. In conclusion, the cross-section of the *H. foetidum* to which an air back cavity was applied showed porous sound-absorbing properties, while that of *Quercus rubra* showed resonance sound-absorbing properties.

The sound absorption coefficient above the 1000 Hz frequency band of *H. foetidum* finished with sandpaper or staining was lower than that cut with a band saw. Because sanding and staining block the vessels of the cross-section, there is less space for sound waves to penetrate. On the other hand, in *Quercus rubra*, the sound absorption performance of band saw cut and sandpaper finished wood did not seem to differ significantly. The sound absorption performance of stain finish in the above 4500 Hz high-frequency range was lower than that of band saw cut wood because of the lower vessel damage caused by finishing treatment in *Quercus rubra* than in *H. foetidum*.

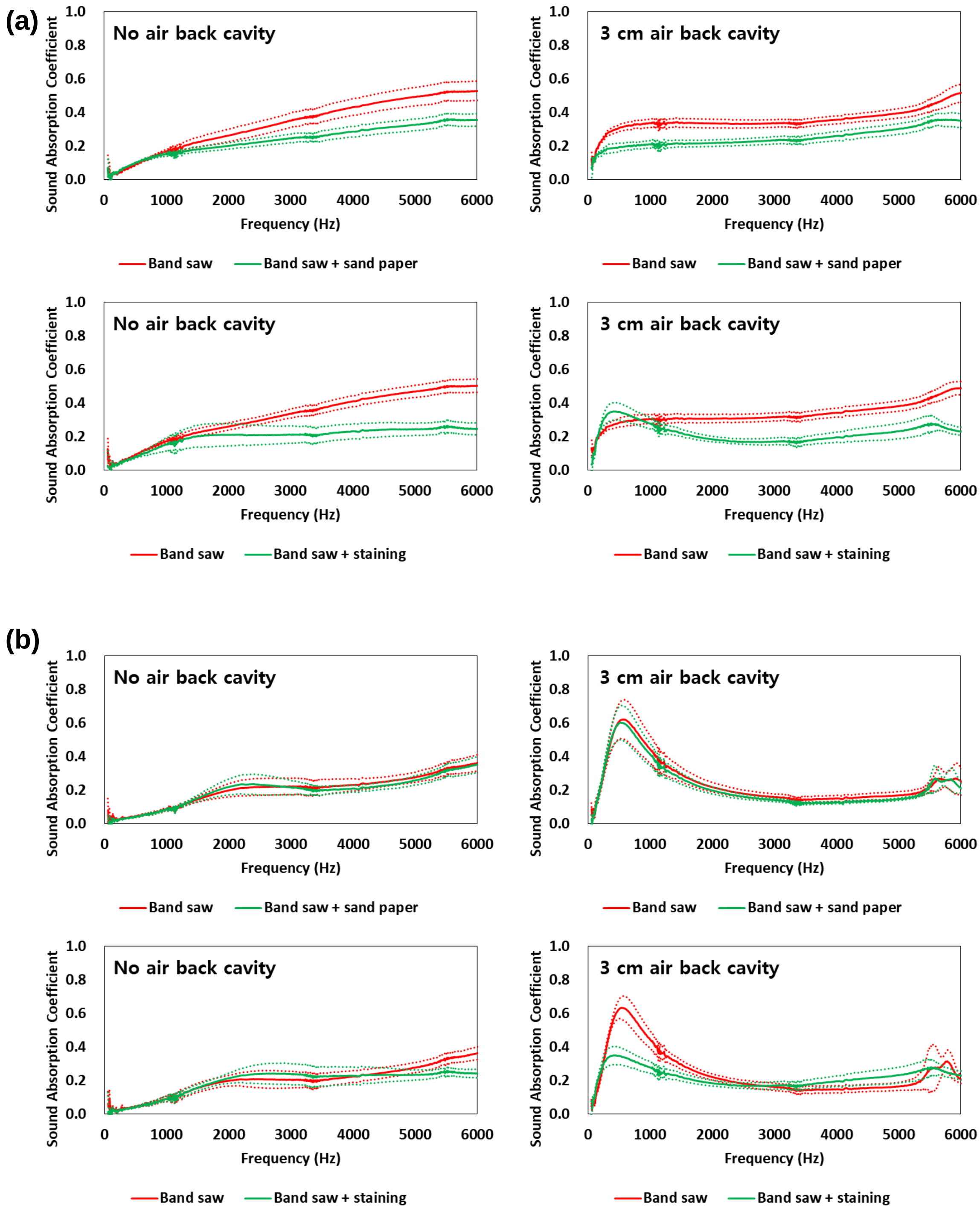

Fig. 3. Sound absorption coefficient curve by finishing method with an air back cavity; (a): *H. foetidum*, (b): *Quercus rubra*. Dotted lines are standard deviations

Table 1 shows the NRC value depending on the finishing method with an air back cavity. The NRC of the sandpaper-treated samples of *H. foetidum* was reduced by approximately 9.2% compared to that of the wood cut with a band saw ($t = 4.169$, $p < 0.001$, paired T-test). When an air cavity was applied, the NRC was reduced by 35.2% ($t = 13.680$,

$p < 0.001$) because the vessels were damaged and blocked by the sandpaper residue. In the stain-treated sample, the sound absorption coefficient decreased further. The NRC of the stain-treated samples was reduced by approximately 14.7% compared to that of the wood cut with a band saw ($t = 2.289$, $p < 0.05$). When a 3 cm air cavity was applied, the NRC was reduced by 44.5% ($t = 7.789$, $p < 0.001$) because the sound absorption was disturbed by the wood stain blocking the vessels. In the *Quercus rubra*, the change in the sound absorption coefficient of the sandpaper-treated sample was not significant, and there was no statistical difference in the NRC ($t = 1.311$, $p = 0.222$). In the sample to which a 3 cm air cavity was applied, the NRC decreased by approximately 3% ($t = 3.461$, $p < 0.05$).

This was presumed to be because the change due to the damage was relatively small because the *Quercus rubra* possesses relatively larger vessels than the *H. foetidum*. In the stain-treated samples without an air cavity, the difference in the sound absorption performance was not significant, and there was no statistical difference in the NRC ($t = -1.801$, $p = 0.105$). It seemed that the large vessels without an air back cavity did little to absorb sound. However, when the air cavity was applied, the sound absorption peak at low frequency was lower than that of the untreated sample. The NRC was reduced by approximately 31.2% compared to that of the band saw-cut sample ($t = 9.144$, $p < 0.001$). This was presumably because the hole for resonance had become smaller.

Table 1. NRC and Sound Absorption Coefficients Depending on the Finishing Method with an Air Back Cavity (SD is standard deviation)

Surface Treatment	Air Back Cavity	*H. foetidum*	*Quercus rubra*
Band saw	n/a	0.141	0.089
SD		0.011	0.008
Band saw + sandpaper		0.128	0.093
SD		0.008	0.010
Band saw	3 cm	0.307	0.394
SD		0.021	0.051
Band saw + sandpaper		0.199	0.383
SD		0.019	0.048
Band saw	n/a	0.143	0.091
SD		0.007	0.009
Band saw + staining		0.122	0.093
SD		0.025	0.007
Band saw	3 cm	0.283	0.404
SD		0.022	0.025
Band saw + staining		0.157	0.278
SD		0.046	0.030

Consequently, in the ring-porous wood with relatively large vessels, the degradation in sound absorption performance due to sandpaper treatment was relatively low. However, the use of sandpaper on the diffuse-porous wood cross-sections led to the deterioration of the sound absorption performance. Therefore, when manufacturing a diffuse-porous wood cross-section block for production of an eco-friendly sound-absorbing material, it is necessary to devise a cutting method that does not damage vessels and to develop a wood stain that does not block vessels. If these limitations can be overcome, hardwood cross-sections will be valuable materials as eco-friendly sound-absorbing materials.

CONCLUSIONS

1. Diffuse-porous *H. foetidum* wood acted as a porous sound absorber, and ring-porous *Quercus rubra* acted as a resonance absorber.
2. Staining showed the greatest decrease in the sound absorption performance, followed by sanding and band saw cutting.

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AUTHORS' CONTRIBUTIONS

Eun-Suk Jang is the first author of this study. He designed the study, conducted all experiments, and was a major contributor in the original writing, reviewing, and editing of the manuscript. Chun-Won Kang is the corresponding author, he was the supervisor of this project and contributed by reviewing and editing. All authors read and approved the final manuscript.

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