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ORIGINAL ARTICLE

Comparison of Sound Absorption Performance between Fresh and Air-dried Leaves by Leaf Composition in *Quercus glauca*

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Abstract

The purpose of this study was to determine the optimal sound absorption conditions by comparing the sound absorption characteristics of fresh and air-dried leaves of *Quercus glauca*, the main species of evergreen broadleaf trees (EBLT) in southern Korea. The sound absorption coefficients (SACs) obtained under 18 conditions were comparatively analyzed. The SAC of air-dried leaves improved significantly with increasing leaf layer thickness. The highest average SAC in the fresh leaf group was 0.617, which was observed under the condition of a leaf specimen size of 0.5 × 0.5 cm^2 and a leaf layer thickness of 1.75 cm. In a group of air-dried leaves, this was 0.615 under the condition of a leaf specimen size of 0.5 × 0.5 cm^2 and a leaf layer thickness of 2.50 cm. The maximum value of SAC for each wavelength was observed under the condition of a leaf layer thickness of 2.50 cm consisting of 0.5 × 0.5 cm^2 leaf specimens, ranging from 1,400 Hz to 1,500 Hz.

Key words : Sound absorption coefficient, Evergreen broad-leaved tree, Impedance measurement tube, Air-dried leaf

1. Introduction

An assessment report by the Intergovernmental Panel on Climate Change (IPCC) indicates that greenhouse gas emissions are increasing due to fossil fuel-dependent energy consumption (IPCC, 2014). Recently, the Korea Forest Service established a strategy to promote the achievement of carbon neutrality in the forest sector by 2050. Under this vision of the best nature-based solution for net-zero, the sustainable use of forest biomass and the promotion of related industries are key to promoting the use of forest biomass and wood (Korea Forest Service, 2021). In this context, there are increasingly high expectations for the resource and biomass use value of warm temperate evergreen broad-leaved tree (EBLT) species, whose growth distribution is gradually expanding to the southern regions as a result of global warming. The distribution area (10,000 ha) of evergreen broad-leaved forest (EBLF) is expected to expand from the southwest coast to the interior and north along the coastline (Korea Forest Service, 2002). As the growth distribution zones such as *Quercus acuta*, *Castanopsis sieboldii*, and *Machilus thunbergii*, which are representative EBLT species along the coastline, gradually expand, expectations for resource utilization are gradually increasing. Recent fieldwork on island forests has shown that the growth distribution of EBLT species is moving further north from the Wando, Wido, Eocheongdo, and Oeyeondo Islands in Korea. In

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Table 1. Leaf characteristics for *Q. glauca*

Classification	Leaf area (cm^2)	Length (cm)	Width (cm)	Thickness (mm)	Moisture content (%)	
					Fresh leaf	Air-dried leaf
Q. glauca leaf	14.83	10.47	1.40	0.380	71.69	12.32

Note : The obtained data is the average of three samples.

addition, according to climate change scenarios Representative Concentration Pathway (RCP) 4.5 and 8.5 W/m^2, the distribution of warm- temperate EBLT species such as *Quercus acuta* was seen to be as gradually moving northward and expanding (Park et al., 2016). Forests are the largest carbon pool on Earth (Vashum and Jayakumar, 2012) and the constituent tree species of warm-temperate and subtropical forest zones in Korea have the potential to play a major role in adapting to climate change and mitigating global warming (Korea Forest Service, 2018; Han et al., 2020). In this regard, EBLF and EBLT in the southern region of Korea also play an important role in absorbing and retaining carbon from the environment, and forestry by-products, such as leaves and twigs, are increasingly expected to be utilized as future resources. Recently, as interest in sustainable environmental conservation and maintenance has increased, the demand for an improvement of the natural environment with respect to the circular bioeconomy of well-being has also increased, and the wide range of noise reduction fields in living environments is no exception (Koizumi et al., 2002; Ersoy and Küçük, 2009; Bujoreanu et al., 2017). Industrial sound absorbing materials generally use synthetic fibers, sponges, glass or rock wool, foams, and fabrics. However, these synthetic materials can cause environmental pollution when discarded as well as having disadvantages in terms of a virtuous cycle of resources. Recently, various studies on the noise reduction effect of wood materials and their processing, including forestry by-products, which are eco-friendly materials, have been continuously conducted. For wood materials, oak mushroom logs (Kang et al., 2008), and for wood treatment, wood substrates (Kang and Park, 2001), wood structure and gravity by carbon and heat treatment (Byeon et al., 2010; Won et al., 2015, Kang et al., 2019c), wood by delignification (Kang and Lee, 2005), and resonators by hole position (Hwang et al., 2008) have been studied. With respect to forestry by-products, palm fiber (Nor et al., 2004), bamboo fiber (Koizumi et al., 2002), bark particle mat (Kang et al., 2019b), composite particle boards (Iswanto et al., 2020; Kang and Kang, 2015), Korean traditional natural wallpaper (Jang et al., 2018), and recycled materials (Choi, 2001) have been studied. Compared with existing wood-based synthetic products, the leaves of EBLT, a by-product of forestry, are known to have the advantages of lower gravity and are more suitable for use (Jung et al., 2020). In addition, these EBLT species contribute to providing a comfortable living environment by attenuating noise, such as street trees and windbreak forests, regardless of the season, even in the standing state. The main goal of this study was to determine the optimal sound-absorbing morphology according to the leaf fragment size and thickness composition of fresh and air-dried leaf samples of *Quercus glauca*.

2. Materials and Methods

2.1. Processing of sound absorbing materials

The sound absorption coefficient (SAC) was measured based on leaf specimen size and leaf layer thickness to analyze the characteristics of fresh and air-dried leaves of *Quercus glauca*, an evergreen broad-leaved tree (EBLT). *Q. glauca* in the beech family (Fagaceae) is a well-known ring-cupped oak or Japanese blue oak. In the Korean Peninsula, *Q.*

Table 2. Sound absorption characteristics and density of *Q. glauca* by leaf treatment level

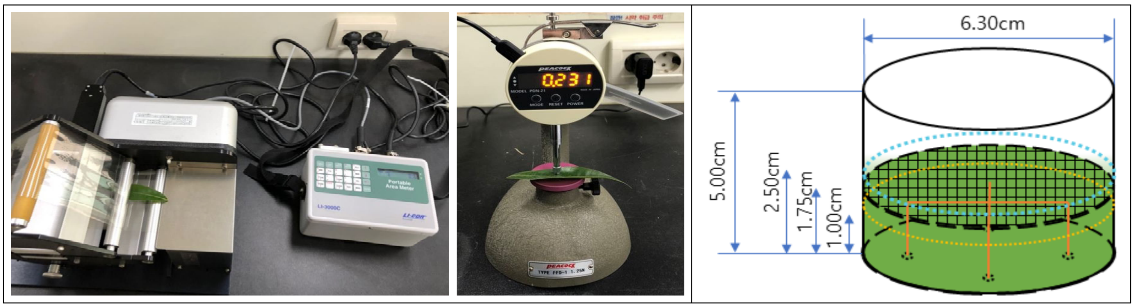
Specimen type	Leaf layer thickness (cm)	Leaf specimen unit size					
		0.5 × 0.5 (cm)		1.0 × 1.0 (cm)		2.0 × 2.0 (cm)	
		SAC avg.	ρ (g/cm^3)	SAC avg.	ρ (g/cm^3)	SAC avg.	ρ (g/cm^3)
Fresh leaf	1.00	0.394±0.011Cc	0.29	0.474± 0.003Bb	0.27	0.555± 0.010Aab	0.27
	1.75	0.617±0.004Aa	0.27	0.584± 0.002Ba	0.28	0.566± 0.013Ca	0.27
	2.50	0.586±0.010Ab	0.29	0.594± 0.018Aa	0.29	0.532± 0.016Bb	0.28
Air-dried leaf	1.00	0.325±0.005Bc	0.16	0.324± 0.17Bc	0.13	0.445± 0.011Ab	0.10
	1.75	0.521±0.006Bb	0.16	0.551± 0.016Ab	0.13	0.573± 0.003Aa	0.11
	2.50	0.615±0.003Aa	0.16	0.591± 0.003ABa	0.13	0.568± 0.018Ba	0.11

SAC: The SAC of each sample was measured 100 times. Three replicate tests were conducted on each sample, and the mean values of the test results were obtained.
A-C means that different capital letters in a row within each size differ significantly ($p<0.05$).
a-c means that different small letters in a column within each thickness differ significantly ($p<0.05$).
avg means average value.

glauca is distributed in subtropical and warm temperate forest areas, from which leaf samples were collected for this study. The collected leaf specimens were estimated using a thickness measuring instrument (PDN-21, Peacock, Japan) and a leaf area measuring instrument (Li-3000C, Licor). Using a measuring straw cutter, the specimen was cut into three specimen sizes: 0.5 × 0.5 cm^2, 1.0 × 1.0 cm^2, and 2.0 × 2.0 cm^2 (Jung et al., 2020). As shown in Fig. 1, all specimens in the form of biomass materials were achieved under the same pressure condition with the same configurations of density 0.0256kgf/㎠. The leaves of evergreen *Q. glauca* were dried to an average moisture content of approximately 12% -13% for two weeks in a constant temperature and humidity room (20℃±1℃, 65±2%), with an average moisture content of the air-dried leaves of 12.73 (Table 1).

2.2. Estimation of sound absorption coefficient

To obtain the SAC, the impedance tube method was used to measure the acoustic characteristics of a material sample using an impedance tube equipped with a microphone. The measurement principle can be divided into two main types: a method using the standing wave ratio and a transfer function method (Hakamada et al., 2006). In this study, the sound absorption characteristics of leaves were investigated using the transfer function method. (Fig. 2). The impedance-measuring tube used in this study was equipped with two microphones and was designed to estimate sound absorption characteristics (Type 4206A, B&K, Denmark) as shown on the right side of Fig. 2, a sign analyzer unit (Type 2035, B&K, Denmark), a power amplifier (Type 2706, B&K, Denmark), and two microphones (Type 2670, B&K, Denmark), as shown on the left side of Fig. 2 (User manual, 2002). The sound frequency range was 100~3,200 Hz in a middle-type impedance measurement tube. SAC was determined according to ASTM International (2016). SAC is a representative parameter for observing the acoustic properties of sound-absorbing materials that play a key role in noise attenuation (Kang et al., 2019a, 2019c). The SAC of each sample was measured 100 times (Jung et al., 2020). Three replicate tests were conducted on each sample, and the mean values of the test results were obtained. After the experimental measurement of SAC, the average SAC was calculated by dividing the denominator by the numerator in the frequency range of the measurement using the following equation (1) (Won et al., 2015):



(a) Area and thickness measurements of *Q. glauca* leaf biomass materials

(b) Schematic diagram of the composition of the sample

0.5㎝ × 0.5㎝   1.0㎝ × 1.0㎝   2.0㎝ × 2.0㎝

(c) Leaf specimen filler prepared by unit size

(d) Samples completed with 3 levels of leaf layer thickness under the same pressure conditions (0.0256 kgf/㎠) for measurment

Fig. 1. Leaf specimens and sample preparation of *Q. glauca* for sound absorption coefficient (SAC) determination.

$$Sound\ absorption\ coefficient = \frac{Total\ absorption}{Total\ number\ of\ measurement} \quad \cdots\cdots\cdots\cdots (1)$$

Finally, the SAC used and estimated for the analysis is shown in Table 2, and was statistically analyzed by Duncan's multiple range test using PASW Statistics 18.0 (SPSS Inc., Chicago, IL, USA). Statistical tests on the effects of SAC were performed to compare fresh and air-dried leaves.

3. Results and Discussion

3.1. Effect of leaf layer thickness on the sound absorption coefficient

To analyze the effect of fresh and air-dried leaves of *Q. glauca* on SAC, samples of three levels with leaf thicknesses of 1.00 cm, 1.75 cm, and 2.00 cm were analyzed. Each sample consisted of three leaf specimen unit sizes of 0.5 × 0.5 ㎠, 1.0 × 1.0 ㎠, and 2.0 × 2.0 ㎠ under the same pressure. Table 2 shows the average of 100 SAC measurements for each treatment group for the fresh and air-dried leaf samples. SAC within the air-dried leaf sample group increased significantly as the thickness of the leaf layer increased for all leaf specimen unit sizes (Table 2). That is, as the thickness of the air-dried leaf layer increased, the sound absorption effect increased further. In particular, for small leaf specimens, the sound absorption effect due to the increase in leaf layer thickness was more sensitive, and the SAC was relatively increased. In air-dried leaf samples with a sample unit size of 0.5 × 0.5 ㎠, when the leaf layer thickness was increased from 1.0 cm (SAC 0.325) to 2.5 cm (SAC 0.615), the difference in SAC was 0.290. This result corresponds to an increase of 228% compared to an increase of 0.123 for air-dried leaf samples with a size of 2.0 × 2.0 ㎠.

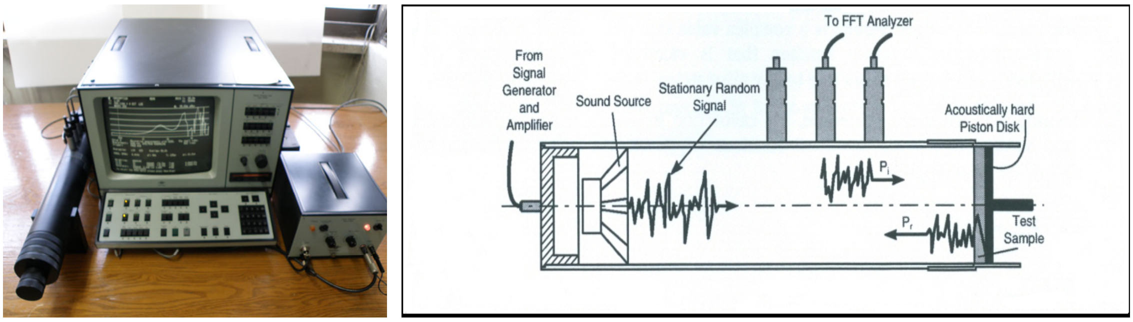


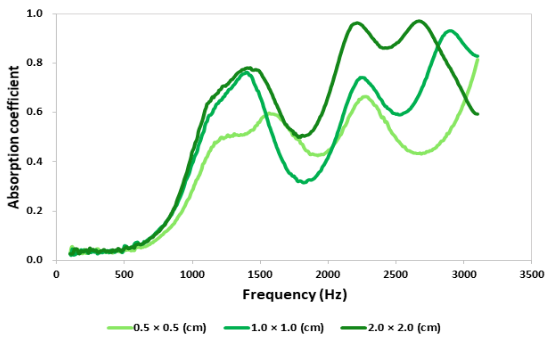
Fig. 2. Two-microphone impedance measurement tube (left side) for the transfer function method and cut-away diagram of the impedance measurement tube (right side).

However, although the SAC of the fresh leaf samples generally increased up to a thickness of 1.75 cm (SAC 0.566), at a thickness of 2.50 cm (SAC 0.532), the corresponding value decreased slightly. The effect of leaf layer thickness on sound absorption was relatively clearer in the 0.5 × 0.5 ㎠ and 2.0 × 2.0 ㎠ leaf size specimens than in the 1.0 × 1.0 ㎠ leaf size specimens. The SACs of most fresh leaf samples were generally higher than those of the dry leaf samples, except for the 2.50 cm leaf thickness samples with 0.5 × 0.5 ㎠ leaf size specimens and the 1.75 cm and 2.50 cm leaf thickness samples with 2.0 × 2.0 ㎠ leaf size specimens. These results may be attributed to the difference in density between the two moisture conditions for the leaf samples (Table 2). This is most likely due to the fact that the pressure density range of the fresh leaf sample group was 0.27-0.28 ρ (g/㎤), while that of the air-dried leaf sample group was relatively low at 0.10-0.11 ρ (g/㎤). In general, the higher the density per unit volume, the higher the SAC for the same material. McGrory et al. (2012) reported that the higher the density per unit volume of 28 polyesters, the higher the SAC. These results show a similar trend in terms of the relationship between leaf density characteristics and SAC in this study.

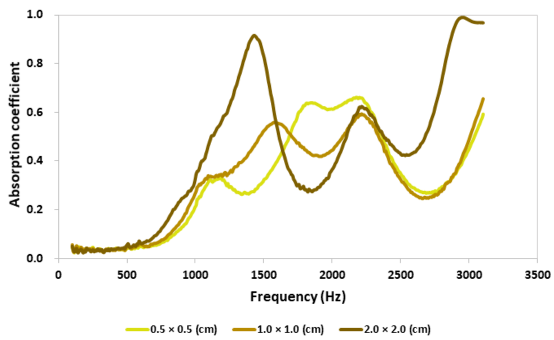
As mentioned above, under certain pressure and moisture content conditions, SAC generally tended to increase as the thickness of the leaf layer increased. As shown in Table 2, the overall mean SAC tended to increase with an increasing leaf specimen size. However the significant difference in SAC with increasing leaf specimen size gradually decreased as sample thickness increased. Jung et al. (2021) showed similar results in sound-absorbing tests on *Fatsia japonica* under the same experimental conditions, which showed somewhat different trends compared to those of *Dendropanax morbiferusa*. It is thought that the difference in the sound absorption response characteristics of leaves according to these evergreen broadleaf species is due to the unique leaf structure characteristic differences of each tree species.

3.2. Effect of leaf specimen unit size on the sound absorption coefficient

The sound-absorbing behavior of SAC for *Q. glauca* was found to be significantly affected not only by leaf layer thickness but also by leaf specimen size. In fact this finding was more pronounced in the air-dried leaf treatment group than in the fresh leaf treatment group (Table 2). The maximum SAC according to the leaf specimen unit size for each leaf moisture condition was commonly observed in the 0.5 × 0.5 ㎠ treatment groups. Among these leaf size treatment groups, the SAC was the highest at 0.617 under the 1.75 cm leaf layer thickness condition for the fresh leaf, and the highest SAC at 0.616 under the 2.50 cm leaf shown in Table 2, in the fresh leaf sample group, the minimum SAC value of 0.394 was observed for



(a) Fresh leaf



(b) Air-dried leaf

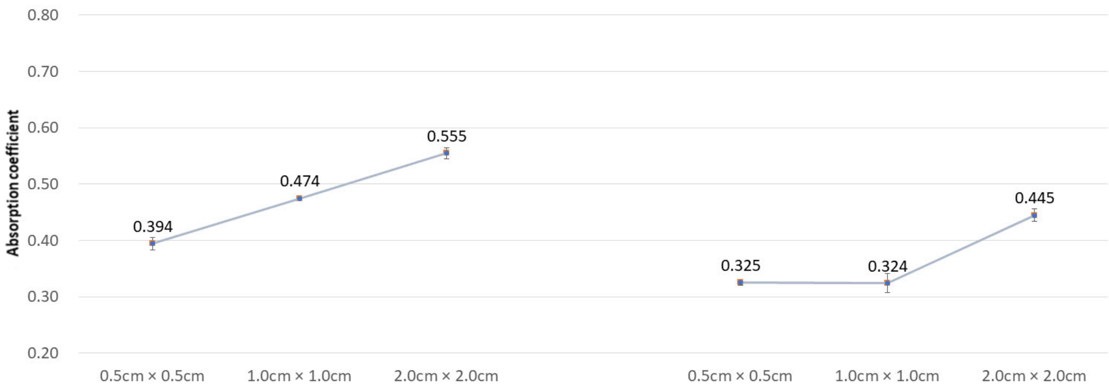
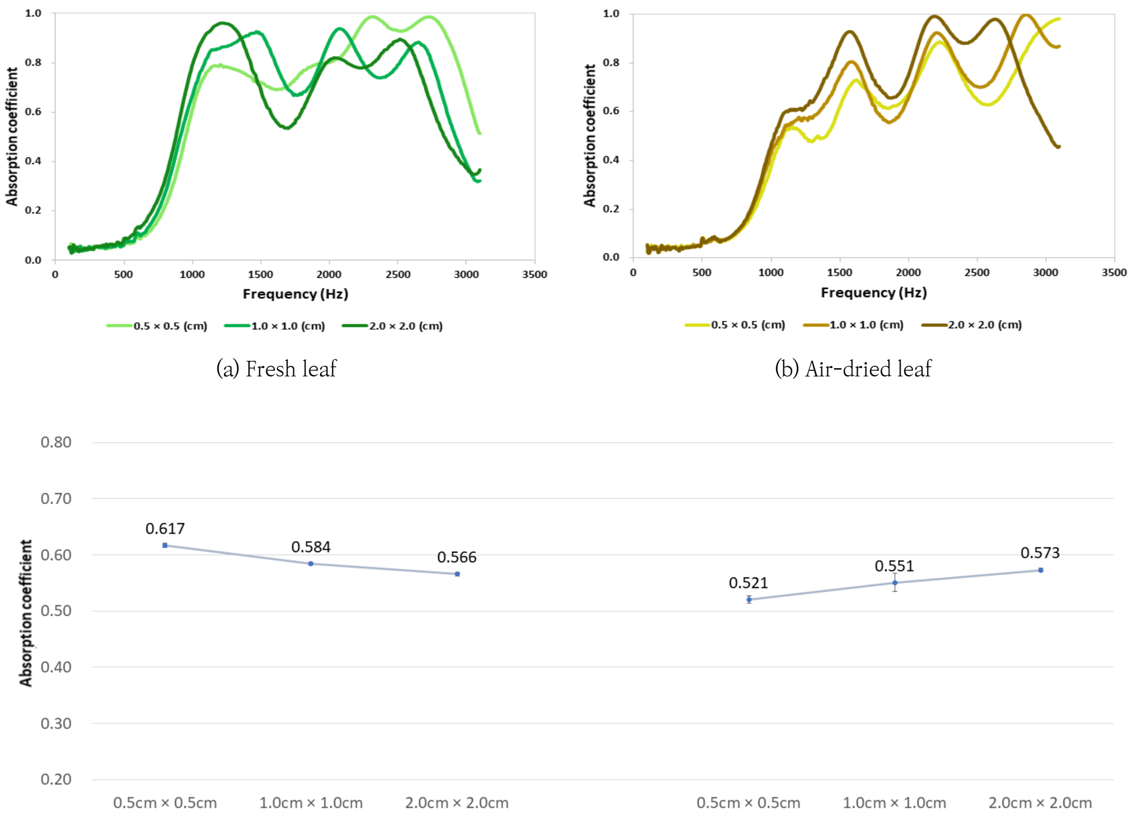


Fig. 3. Comparison of sound absorption performance by leaf specimen size of fresh and air-dried leaves with a leaf layer thickness of 1.00 cm.

0.5 cm × 0.5 ㎠ leaf size conditions with a leaf layer thickness of 1.00 cm, and the maximum SAC value of 0.617 was observed for the same leaf size and a leaf layer thickness of 1.75 cm. In the dry leaf sample group, the minimum SAC value of 0.324 was observed for 0.5 × 0.5 ㎠ leaf size with a leaf layer thickness of 1.00 cm, and varied under 2.50 cm leaf layer thickness conditions under the same leaf sample size conditions.

The results of the maximum SAC value in the thickest leaf layer sample in the dry leaf treatment group were consistent with the results that the relationship characteristics according to the thickness of the leaf layer were clearer in the air-dried leaf samples than in the fresh leaf samples, as mentioned above. Thus, the SAC for each leaf specimen size in the air-dried leaf samples showed a higher sound absorption effect when the leaf specimen size was smaller. The relationship between sample thickness and air gap has also been reported in previous studies on various materials (Hakamada et al., 2006; Taban et al., 2019). The smaller the unit size of the leaf specimen, the greater the porosity of the constructed sample. Jung et al. (2020, 2021) reported that differences in the porosity across unit sizes in leaf specimens of EBLT species, such as *Dendropanax morbiferus* and *Fatsia japonica* resulted in differences in the relationship characteristics of SACs.

Base on these findings, it can be seen that the sound absorption effect due to the increase in porosity was maximized as the thickness of the leaf layer increased under the same pressure conditions



(a) Fresh leaf (b) Air-dried leaf

Fig. 4. Comparison of sound absorption capacity by leaf specimen size of fresh and air-dried leaves with a leaf layer thickness of 1.75 cm.

and in the sample with a relatively small leaf specimen size.

Therefore, in the industrial use of leaves, which are by-products of *Q. glauca* forests, as sound-absorbing materials, the possibility of using air-dried leaves rather than fresh leaves is higher. It is thought that the more consistent test results on air-dried leaves in this study can provide useful information.

3.3. Sound absorption properties by frequency band

Fig. 3, 4, and 5 compare the acoustic response curves for each specimen size for leaf layer thicknesses of 1.00 cm, 1.75 cm, and 2.00 cm, respectively. According to these the SAC of fresh and air-dried leaves for *Q. glauca* ranged from 100 Hz to 3200 Hz. Fig. 5(a) and 5(b) show that the SAC of fresh and air-dried leaf samples in all conditions rapidly increased at 500 Hz, with the sound absorption effect of all leaf samples in the subsequent frequency band increasing by a larger difference than the sound absorption effect of the sponge. In addition, the SAC of the sponge for each frequency band peaked every 1,000 Hz and showed a constant pattern, indicating the characteristics of artificial materials, which differ from the sound- absorbing properties of natural leaf materials. As shown in Fig. 4(a), for a leaf layer thickness of 1.75 cm in a fresh leaf specimen with a size of 0.5 × 0.5 ㎠, the maximum SAC value was observed in the frequency range of 2,300 - 2,700 Hz. In the case of a leaf layer thickness of 2.50 cm

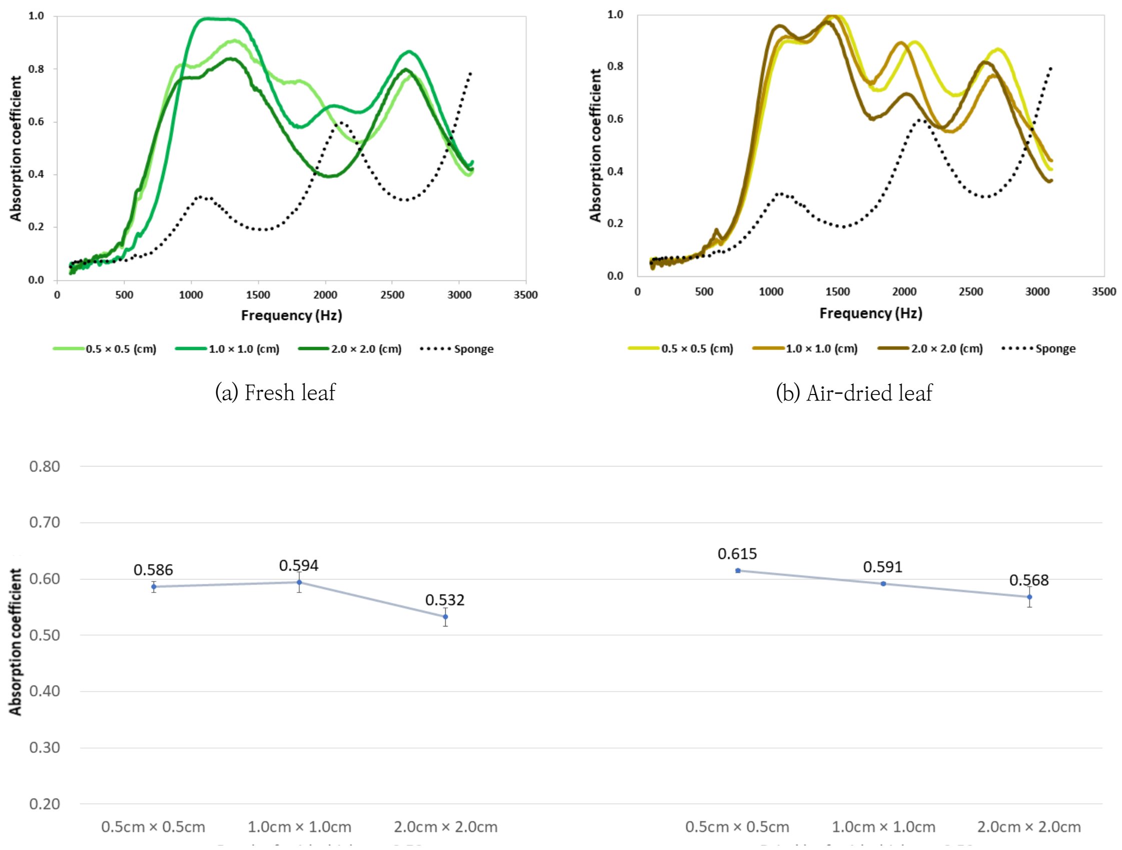


Fig. 5. Comparison of sound absorption capacity by leaf specimen size of fresh and air-dried leaves with a leaf layer thickness of 2.50 cm.

in air-dried leaf specimens of 0.5 × 0.5 ㎠ in size, the maximum SAC value was observed in the frequency range of 1,500 Hz, as shown in Fig. 5(b). Air-dried leaf treatment resulted in a higher sound-absorbing effect at a slightly higher frequency range, ranging from 2,000 Hz to 2,700 Hz for the 1.75 cm leaf layer thickness sample and from 1,000 Hz to 1,500 Hz for the 2.0 cm leaf layer thickness sample. In particular, in the air-dried leaf group, the SAC gradually increased as the frequency band increased after 500 Hz in the low-frequency band with a leaf layer thickness of 1.75 cm (Fig. 4(b)), whereas with a leaf layer thickness of 2.50 cm, it peaked between 1,000 and 1,500 Hz in the middle-frequency band before gradually increasing to 3,000 Hz(Fig. 5 (b)). The absorption coefficient gradually decreased as it moves to the high-frequency band. Based on these findings, the sound-absorbing effect was found to be generally high for a leaf layer thickness of 1.75 cm or more in the air-dried leaf samples. Furthermore, the sound attenuation effect was also found to be much higher in the frequency range above approximately 1,000 Hz. These results also showed similar sound absorption response characteristics by frequency band as those reported in a study by Jung et al. (2001) on two other evergreen broad-leaved tree species *D. morbiferus* and *F. japonica*. These results suggest that the difference in SAC according to the increase in frequency was more sensitive and consistent in *Q, glauca*. In another study on the

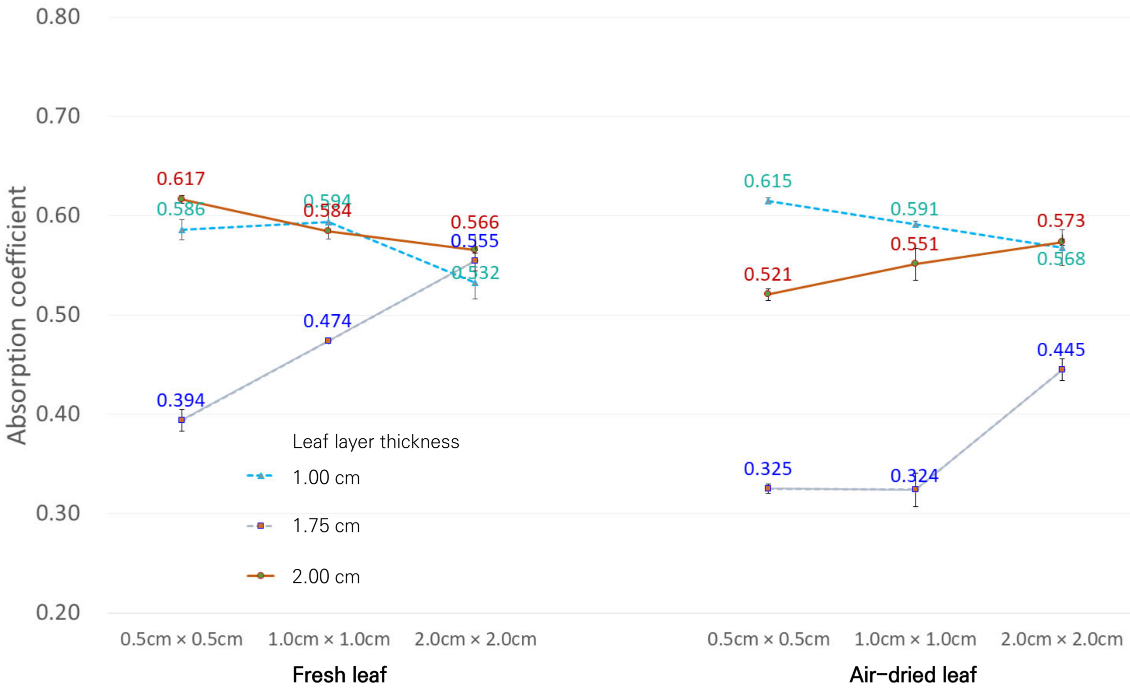


Fig. 6. Comparison of sound absorption performance by leaf specimen size between fresh and air-dried leaves composed of leaf layer thicknesses of 1.00 cm, 1.75 cm, and 2.50 cm.

sound-absorbing effect of warm-temperate tree species, Jung et al. (2021) found that the SAC continuously increased as the frequency increased *D. morbiferus* compared to *F. japonica*. Based on these results, the characteristics of the *F. japonica* leaf sample show a similar trend to *Q. glauca* in the present study. This difference in sound absorption characteristics is thought to be due to the difference in the structural characteristics of the leaves of these different warm-tropical evergreen broad-leaved tree species, and it has been reported that these characteristics secondarily cause differences in pore composition and resonance characteristics (Koizumi et al., 2002; Hakamada et al., 2006; Ismail et al, 2010; Taban et al., 2019). In a study on the effects of fiber type and size, material thickness, density, airflow resistance, and porosity on SAC (Hoda, 2009), the air gap was found to be involved in further increasing the SAC value at middle to high frequencies. The porosity of the same sound- absorbing material under the same pressure condition has been reported to be a factor of a great influence in the sound-absorbing characteristics according to the frequency band (Oldham et al., 2011).

4. Conclusions

The main purpose of this study was to compare and analyze the sound absorption effects of fresh and air-dried leaves of *Q. glauca*, a major evergreen tree in warm temperate and subtropical regions, to provide insights into the possibility of its application as a natural sound absorption material. To this end, the SACs of fresh and air-dried leaf samples of *Q. glauca*, an evergreen broad-leaved tree, were compared and analyzed under a total of 18 conditions. The sound absorption coefficients for all the obtained conditions were statistically analyzed using Duncan's multiple range test. The results are summarized as follows:

(1) The sound absorption capacity of air-dried leaf samples was generally lower than that of the fresh leaf samples. The sound-absorbing behavior of SAC for *Q. glauca* was found to be significantly affected not only by leaf layer thickness but also by leaf specimen size, which tended to be more pronounced in the air-dried leaf treatment group than in the fresh leaf treatment group

(2) The maximum SAC according to the leaf specimen unit size for each of the leaf moisture condition was observed in the 0.5 × 0.5 ㎠ treatment groups. Among these leaf size treatment groups, SAC was highest at 0.617 under the 1.75 cm leaf layer thickness condition for the fresh leaf, and highest at 0.616 under the 2.50 cm leaf layer thickness condition for the air-dried leaf.

(3) As a result of analyzing the sound absorption effect of each sample by frequency band, the maximum SAC was found in the frequency range of 2,300 Hz to 2,700 Hz wih a leaf thickness of 1.75 cm composed of a 0.5 × 0.5 ㎠ fresh leaf specimen. The maximum SAC was found in the frequency range of 1,400 Hz to 1,500 Hz in the case of a 2.50-cm-thick leaf layer composed of a 0.5 × 0.5 ㎠ air-dried leaf specimen.

With regards to the industrial use of leaves as a sound-absorbing material, the results presented in this study suggest that dry leaf materials are more advantageous than the fresh leaves in this respect. The sound attenuation effect of the dry leaf was found to be greater in thicker leaf layer samples composed of relatively small leaf specimens. Furthermore, the corresponding sound absorption effect was high, particularly in the middle- frequency range.

Acknowledgments

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