Pine Wood Extraction by Fermentation to Improve its Acoustical Efficiency

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Wood is a main material in the construction of musical instruments and speaker boxes, especially in developed countries. This study investigated the changes in acoustic properties of pine wood during the processes of fermentation, water washing, and organic washing solvent. The results indicated that both methods of water washing and ethanol-acetone mixture washing of the samples improved the values of density, modulus of elasticity, elastic stiffness, acoustic coefficient, vibration damping, and acoustic conversion efficiency. The effect of ethanol-acetone mixture washing was greater than water washing the samples. Additionally, results revealed that pretreatment before ethanol-acetone mixture washing had the most effect on vibration damping and acoustic conversion efficiency values. In general, the values obtained from ethanol-acetone mixture washing resulted in more improvement in acoustic properties compared to water washing, but the results showed that the pretreatment before water washing had a greater effect on the values of density, modulus of elasticity, elastic stiffness, and acoustic coefficient.

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INTRODUCTION

This research follows the authors' previous investigations on improving the acoustical quality of different wood species for use in the musical instruments industry. The authors will now discuss Silvestre pine, a softwood that has not been a common tone-wood due to its unsatisfactory acoustical characteristics, but that is promising if it could be treated to become an acceptable soundboard for the resonator boxes in stringed musical instruments. There are some different hypotheses to achieve this goal, but first the definitions of the most important acoustical parameters need to be introduced and illustrated here.

Wegst (2006) and Roohnia (2019) introduced the most important vibration and acoustic properties of wood in musical instruments. Density (d), elastic stiffness, especially parallel to the grain axis (EL), damping capacity ($\tan\gamma$), acoustic radiation coefficient (K), and acoustic conversion efficiency (ACE) were previously introduced in detail, but a summary is provided here as well.

According to Euler-Bernoulli's theory, the Young's modulus is evaluated as Eq. 1,

$$E_{\mathrm{L}} = \frac{48\pi^2 f^2 \rho L^4}{m_n^4 h^2} \tag{1}$$

where h is the height of the flexural beam and m_n is a scalar depending on the end support conditions and mode number, n. For a both ends free beam, it is equal to 4.73 for the 1st mode.

Higher elastic stiffness (specific modulus of elasticity) and/or higher sound radiation coefficient (acoustical coefficient) might be more efficient for use in the sounding boards of musical instruments and similar applications. Specific modulus and acoustical coefficients, which are parameters based on modulus of elasticity and density, are used in the musical instrument industry as criteria for selecting efficient woods. Important parameters are as follows,

$$S_{\mathrm{L}} = \frac{E_{\mathrm{L}}}{d} \tag{2}$$

$$K = \sqrt{\frac{E}{d^3}} \tag{3}$$

where S_{L} is the elastic stiffness (specific modulus of elasticity) (Pa.m^3/Kg), K is the acoustical coefficient (m^4/s.kg), E_{L} is the longitudinal modulus of elasticity (Pa), and d is the density of the air-dried wooden specimens (Kg/m^3).

The damping capacity of vibrating wood and wood products is the measurement of energy dissipation through internal friction. The damping capacity can be determined in several ways, *e.g.*, the logarithmic decrement method (Fig. 1) (Brémaud 2012; Roohania 2019). Considering n times of full oscillations, the logarithmic decrement is calculated through the successive decaying wave amplitudes (Xi), as:

$$tan\delta = \frac{1}{n\pi} ln \frac{X_i}{X_{i+1}} \tag{4}$$

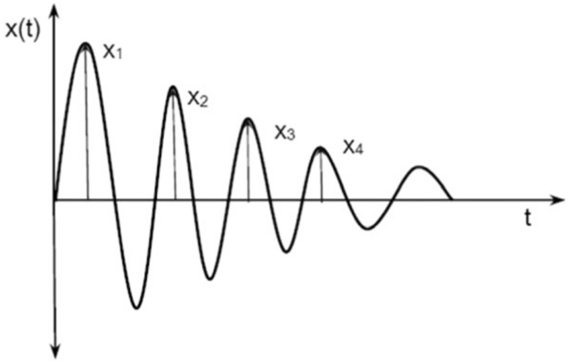

Fig. 1. Damping in logarithmic scale

Acoustic conversion efficiency resembles a combination of the radiation coefficient, K, and the damping capacity, tanδ, of the wood in resonator boxes:

$$ACE = \frac{K}{tan\delta} \tag{5}$$

Wegst (2006) showed the acceptable limits and ranges for these vibrational properties of wood to become suitable in different components of a musical instrument, *i.e.*, soundboards, backs, ribs, and so on.

This set of the equations shows that a treatment capable of increasing the elastic stiffness of wood while reducing density and damping capacity, would be considered a successful operation to improve the acoustic radiation and efficiency of the tonewood. Ignoring a few exceptions, the extraction of wood would be an example for such a treatment, decreasing the density, without changing the elastic stiffness of wood much. Ono and Norimoto (1984) demonstrated that wood with higher specific stiffness would show a lower damping capacity, though their correlation is not linear at all.

The authors strive to be a frontier laboratory in acoustics and vibration monitoring in different topics related to stringed musical instruments research. There are other followers in this topic too, especially in acoustical measurements and treatments on tonewood.

Roohnia *et al*. (2011a) studied the wood from Arizona cypress from pith to the bark. In this species, it was shown that the outer parts of the stem, close to the bark containing narrower growth rings, exhibited lower damping due to internal friction and higher sound radiation. They also tried the effects of extraction using distilled water on the damping capacity of Mulberry and Walnut wood (Roohnia *et al.* 2011b).

Soaking cycles in distilled water homogenized and decreased the damping capacities in both species. The usefulness of the ratios in longitudinal sound velocity to transverse were investigated as acoustic indicators in wood from mulberry and Arizona cypress by Roohnia *et al.* (2011a,b). They reported that the damping factor in cypress was affected by ring width and the white mulberry species were affected by the amount of extractives. Ghaznavi *et al.* (2013) studied the effects of different traditional varnishes on the acoustic quality of wood. They reported that all the varieties of the studied varnishes reduced the efficiency of wood in soundboards. Their results indicated that shellac lacquer caused the least negative impact on the acoustical properties of wood. They reported that to find a better lacquer to improve the acoustical qualities of wood, the new lacquer must have a lighter density, exhibit higher modulus of elasticity, and/or lower internal friction compared to raw unpolished wood. It seems impossible to find such a varnish now, but future technological improvements in this field might become likely. Roohnia and Kohantorabi (2015) studied the extraction treatments in *Acer velutinum*. Results showed that successive extraction with hot water and an ethanol/acetone mixture improved the acoustical quality of maple wood. The effect of extractives on acoustical properties of Persian silk wood (*Albizia julibrissin*) were studied by Farvardin *et al.* (2015). Their results showed that the extractive components soluble in hot water were positively useful to acoustical properties because removing these extractives reduced their acoustic efficiencies. A similar finding was previously reported for wood from Pernambuco. The water-soluble extractives from Pernambuco were effective in decreasing the damping capacities while impregnated to another piece of wood, *e.g.*, spruce soundboards (Matsunaga *et al.* 1999).

After these reference works, the extraction methodology was extended to *Pinus sylvestris* wood in this study. There was another experience utilized by the traditional luthiers in Iran. They believed that keeping wood in a sugar-fermented condition using bread yeasts would increase the acoustic quality of tonewood. Therefore, this concept was also investigated in the current study. The hypothesis is that sugar fermentation may release a small amount of ethanol that might loosen the extractives of wood to be better discharged though the next steps in the main extraction process. In addition, this idea was recently investigated by Zamaninsab *et al.* (2023) regarding the walnut species (as a hardwood species). Considering the different nature of extractives in hardwoods and softwoods, in this research, the effect of fermentation in removing the extractives of pine species (*Pinus sylvestris*) as a softwoods species was investigated. The goal was to determine whether this method has a positive effect on the acoustic properties of the *Pinus sylvestris* and whether this method can be used to improve the acoustic conditions of this species.

EXPERIMENTAL

Materials

Pinus sylvestris timber was collected from heartwood of the softwoods repertory at the authors' institutional acoustics laboratory. A total of 38 specimens were cut into quarter-sawn sticks in final dimensions of 2 × 13 × 150 mm^3 (tangential × radial × longitudinal). They were similar to ice cream sticks, but rectangular at their corners and edges. The specimens were divided into two groups with 19 individuals each. For the 1st group the extractive removal was initiated by a fermentation pretreatment, while the second group was directly subjected to the stepwise extraction using hot pure water and ethanol-acetone solvents.

Fermentation

Bread yeast is found on plants, grains, and fruits, and is occasionally used for baking. However, in general, it is not found in a pure form but comes from being propagated in a sourdough starter. One of the most famous bread yeasts belongs to the *Saccharomyces* genus, which is also known as *S. minor* (Zamaninasab *et al.* 2023). Bread or baker's yeast was used for fermentation pretreatment of the specimens. In this way, the yeast was dissolved in water, and the samples were immersed in it. Because they are a living organism, fungi require warmth, water, albumen or nitrogenous material, and sugars to remain alive. Thus, some edible sugar was added to pure hot water to help start the fermentation. Small ice cream sticks were dipped into the fermenting solvent and kept until the fermentation stopped (The amount of fermentation time was variable between 3 and 4 minutes for each of the samples). When the boiling fermentation stops, it indicates that there is no longer any food available for the yeasts, and the yeasts consumed the food from the additional sugar or wood extractives, simultaneously converting them into ethanol and carbon dioxide. Thus, the pretreatment operation of the samples was completed according to the experience of the traditional luthiers, and the samples were ready to continue the extraction operation.

Extraction

The specimens were put in a Soxhlet extractor in four separate courses. The 1st and the 2nd courses were scheduled for deionized water extraction of the pretreated specimens consecutively followed by ethanol-acetone mixture extraction (for 12 h each, *i.e.*, after reaching a colorless vivid solvent in Soxhlet tube (Farvardin *et al.* 2015; Roohnia and Kohantorabi 2015). The 3rd and 4th courses were repeated similar to the 1st and the 2nd courses but for the specimens without any fermentation pretreatments.

After each of the extraction courses, the specimens were subjected to an air-dried stabilization, beginning from wet condition, in a climatic chamber (21 ± 1 °C temperature and 65 ± 5% relative humidity) until the dimension stopped shrinking. The stabilized moisture contents were measured, and the extracted specimens were subjected to vibration and acoustic characterization.

Vibration and Acoustic Characterization

The contactless forced flexural vibration method was used to obtain the fundamental frequencies of the ice cream stick samples (Fig. 2). A specimen is hung on two thin silk supports at their nodal points to simulate a both the ends free bar. A tiny iron chip with negligible mass was glued to one end and an electric magnet scanned the frequency of its connection or disconnection while facing the iron chip to obtain the excited vibration sound of the specimen by a unidirectional microphone near the antinode of the vibration (Roohnia *et al.* 2011a). Determination of the fundamental flexural frequency of the specimen was made through the Fast Fourier transform in a setup, resembling the forced vibration method, which was reconstructed in accordance with a previous publication (Brémaud 2012), and its diverse programming, software, and accessories introduced as the Vibra-Force NDT system (Roohnia *et al.* 2011a).

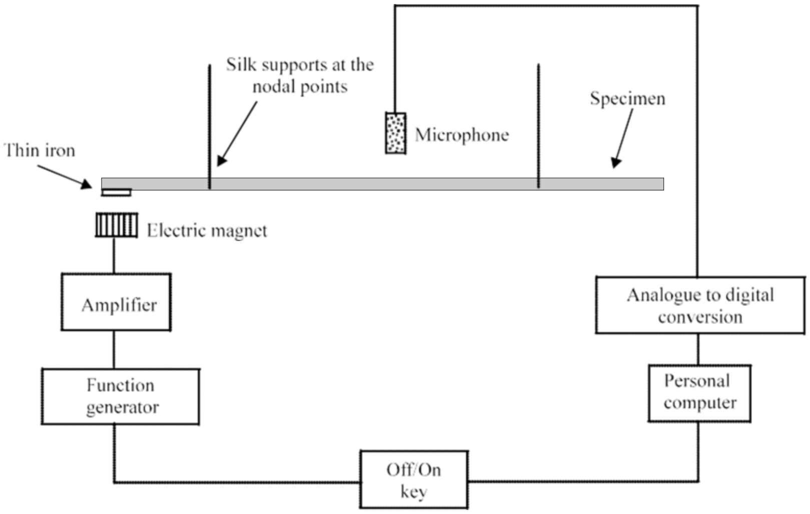

Fig. 2. A schematic view for the contactless forced vibration system

The elastic stiffness in the growth direction was evaluated through Euler-Bernoulli's elementary theory of the flexural vibration, considering the frequency of the 1st mode of vibration (Roohnia *et al.* 2011a). Then, the acoustic radiation coefficient, K, damping capacity, $\tan\delta$, and the acoustic conversion efficiencies, ACE, of the samples were determined through the above introduced equations. The smallest differences in moisture contents of the stabilized specimens were not neglected; they were corrected into 12% moisture content values in accordance with ISO13910 (2005) and Divos and Kiss (2010) in terms of their elastic stiffness and density variations.

Statistical Analysis

There were two separate sets of specimens, with 19 individuals, each. One set underwent a pretreatment of fermentation, whereas the second did not. Their extractives were consecutively washed out using pure water and then using a mixture of ethanol and acetone, as the solvents.

The obtained results of the above-mentioned acoustic characteristics were gathered into a table, while their differences were monitored through column and line plots. A comparison of each one of the mechanical properties obtained from each one of the test stages was also made by a statistical paired-sample T-test at 95% confidence level. The SPSS v.17.5 software (IBM Corp., Armonk, NY, USA) was applied in the statistical tests and Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA) was applied to draw the diagram. The obtained results were reported using the acoustic criteria provided by Wegst (2006).

RESULTS AND DISCUSSION

Table 1 shows the values of each factor of density, modulus of elasticity, elastic stiffness, acoustic coefficient, damping factor, and acoustic conversion efficiency in control samples and samples after water washing and ethanol-acetone mixture washing (without pretreatment and with pretreatment).

Table 1. Measured Quantitative Values of Acoustic Properties

Values		Control Samples	Water Washed Samples	Percentage of Changes Compared to the Control Test (%)	Ethanol-acetone Washed Samples	Percentage of Changes Compared to the Control Test (%)
Density (kg/m^3)	1*	640.67	633.77	-1.09	604.10	-6.05
	2*	660.86	636.30	-3.86	613.02	-7.80
Modulus of Elasticity(GPa)	1	6.10	6.17	+1.07	6.26	+2.44
	2	6.50	6.73	+3.40	6.84	+4.97
Elastic Stiffness (MPa.m^3/Kg)	1	9.44	9.49	+0.60	10.18	+7.32
	2	9.65	10.39	+7.10	10.89	+11.37
Acoustic Coefficient (m^4.s^{-1}.kg^{-1})	1	4.81	4.88	+1.41	5.29	+9.10
	2	4.72	5.11	+7.61	5.41	+12.80
Damping Factor	1	0.01507	0.01262	-19.43	0.01009	-49.32
	2	0.01573	0.01174	-33.95	0.01002	-57.04
Acoustic Conversion Efficiency (m^4.s^{-1}.kg^{-1})	1	330.92	399.81	+14.26	535.95	+38.26
	2	306.54	357.54	+17.23	546.18	+43.88

1: Without pretreatment
2: With pretreatment

Figure 3 compares the effect of soaking process and ethanol-acetone mixture washing in pre-treated and non-pre-treated samples in terms of density. Water washing without pretreatment had a negligible effect on density values (-1.09%). This decrease in value was not significant at the 95% confidence level. The fermentation pretreatment process caused a significant drop in the density values compared to the samples without pretreatment in the soaking process (-3.86% which is significant at the 95% confidence level). Extraction with ethanol-acetone mixture, unlike the soaking process without pretreatment, caused a significant decrease in density values in samples without pretreatment (-6.05% which is significant at the 95% confidence level). The implementation of a pre-treatment in ethanol-acetone mixture washed samples had an effect of less than 1% in the drop of density values compared to ethanol-acetone mixture washing without pre-treatment (-7.80% which was significant at the 95% confidence level).

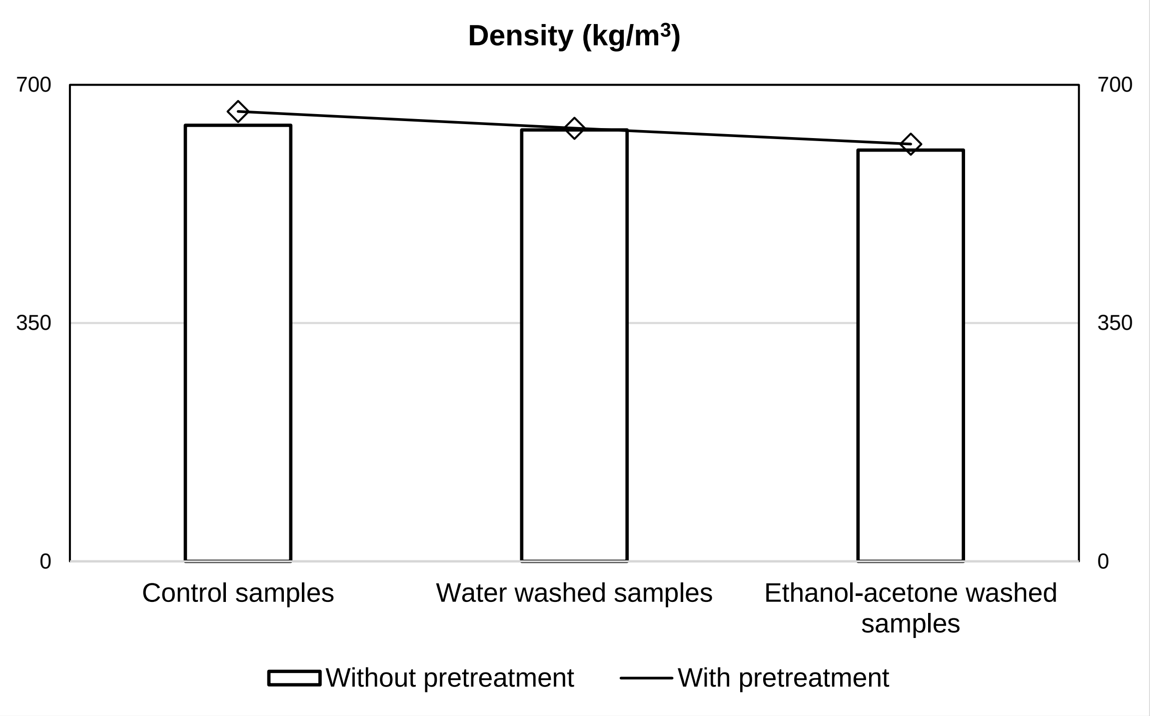

Fig. 3. Density changes in the process of consecutive extractions

According to past studies, the extractive materials of forest pine wood are more soluble in organic solvents (Keržič *et al.* 2023). Therefore, a greater decrease in density due to ethanol-acetone mixture washing than washing with pure water is a natural trend in this species. The role of the nature of extractives and solvents in the research conducted by Segolpayegani *et al.* (2012), Roohnia and Kohantorabi (2015), Mollaeikandelousy *et al.* (2016), and Zamaninasab *et al.* (2023), respectively, on white mulberry, *Acer velutinum*, *Acer platanoides*, and walnut wood has been reported. After water washing, the pre-treated samples showed a greater drop in density values than the untreated samples (the amount of this drop was more than 3 times compared to the untreated samples). This phenomenon is related to the higher consumption of sugar in the structure of extractive materials due to pretreatment (Zamaninasab *et al.* 2023).

Figures 4 to 6 show the effect of soaking process and ethanol-acetone mixture washing in pre-treated and non-pretreated samples on the modulus of elasticity, elastic stiffness, and acoustic coefficient. The soaking process without pretreatment caused a slight increase in modulus of elasticity values (+1.07%). This decrease in value was not significant at the 95% confidence level.

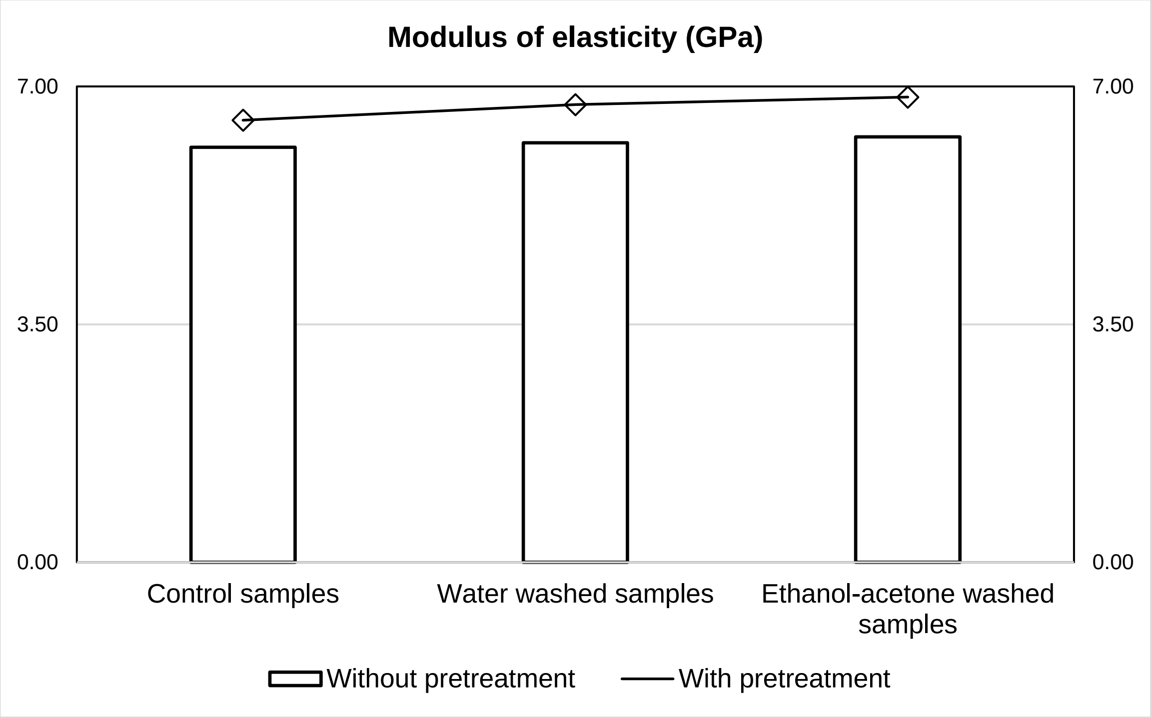

Fig. 4. Modulus of elasticity changes in the process of consecutive extractions

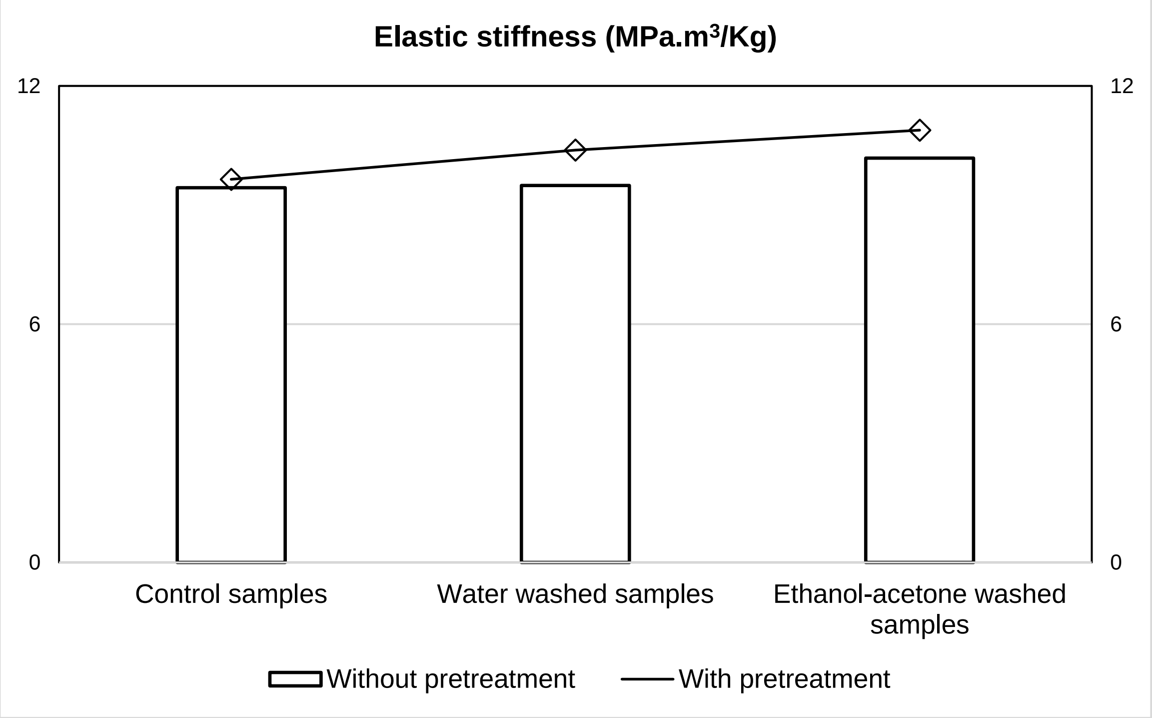

Fig. 5. Elastic stiffness changes in the process of consecutive extraction

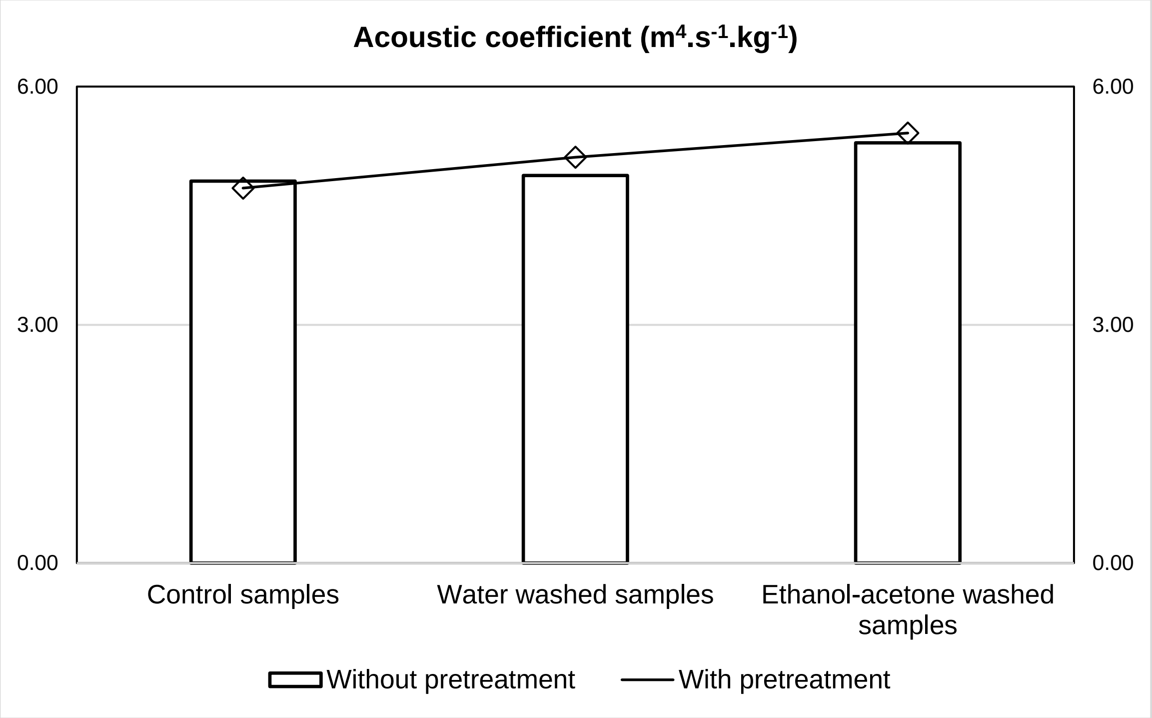

Fig. 6. Acoustic coefficient changes in the process of consecutive extractions

The effect of ethanol-acetone mixture washing of the samples with both non-pretreatment and with pre-treatment on the values of modulus of elasticity was significant at the 95% confidence level. Ethanol-acetone mixture washing of the samples without pretreatment also caused an increase in the values of the modulus of elasticity to the extent of more than 2 times that of the control samples (+2.44%). This amount of increase in modulus of elasticity values was more than the upward trend observed in the soaking process. The effect of fermentation pre-treatment before soaking process was much more than that of ethanol-acetone mixture washing. The process of changes in the values of elastic stiffness is also the same as the values of the modulus of elasticity. Thus, that water washing the samples without pretreatment had almost no effect on the values of this factor (+0.6% which was not significant at the 95% confidence level). While the implementation of pre-treatment caused an increase of more than 11 times the values obtained from elastic stiffness due to soaking process (+7.1% which is significant at the 95% confidence level).

Ethanol-acetone mixture washing without pretreatment caused a 7.32% increase of elastic stiffness compared to the control samples, which was significant at the 95% confidence level. Pre-treatment before ethanol-acetone mixture washing caused the highest percentage of changes in elastic stiffness factor (+11.37%, which was significant at the 95% confidence level). However, according to the results, the effect of pretreatment before ethanol-acetone mixture washing was far less effective than soaking process (1.6 times compared to samples without pretreatment). The changes obtained in the values of the acoustic coefficient due to soaking process and ethanol-acetone mixture washing were just like the changes obtained in the values of the modulus of elasticity and elastic stiffness (both groups without pre-treatment and with pre-treatment). Considering the non-structural role of extractive materials in most wood species, the upward trend observed in the values of elastic modulus, elastic stiffness, and acoustic coefficient due to the decrease in density is a predictable trend. Especially because results in some previous studies were similar to the current study (Segolpayegani *et al.* 2012; Roohnia and Kohantorabi 2015; Mollaeikandelousy *et al.* 2016). However, it should be noted that some studies indicated a decrease in modulus of elasticity and elastic stiffness due to the extraction (Matsugana *et al.* 1999; Zamaninasab *et al.* 2023). Therefore, in the implementation of similar treatments, it is important to consider the consequences of them on the values of modulus of elasticity and elastic stiffness.

Figure 7 shows the changes in vibration damping due to soaking process and ethanol-acetone mixture washing in pre-treated and untreated pre-treatment samples. Soaking process and ethanol-acetone mixture washing both without pretreatment and with pretreatment caused a significant decrease in damping factor values at the 95% confidence level.

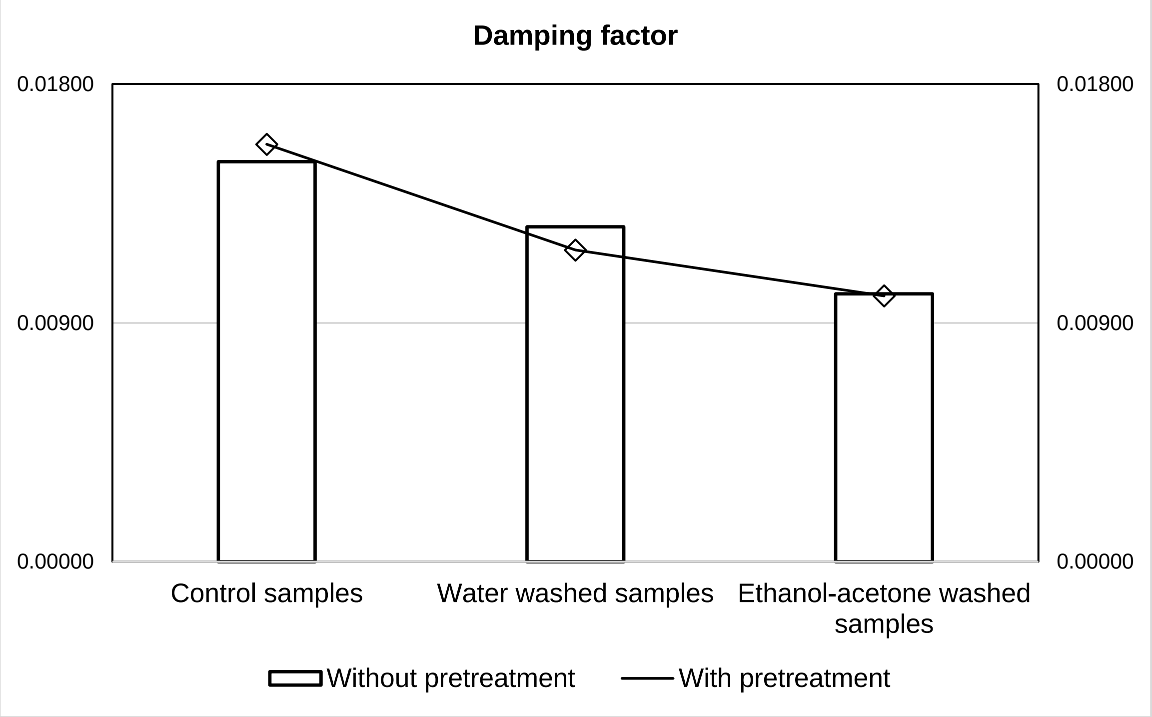

Fig. 7. Damping factor changes in the process of consecutive extractions

Both soaking process and ethanol-acetone mixture washing without pretreatment caused a significant drop in damping factor values in the samples. The results indicate a greater decrease in damping factor values in ethanol-acetone mixture washing (-49.3%) than in soaking process (-19.4%). In addition, the fermentation pre-treatment in both water washing (-34.0%) and ethanol-acetone mixture washing methods (-57.0%) caused a greater decrease in damping factor values. Damping factor is one of the most important characteristics of wood used in musical instruments. Based on the results of previous studies, a lower damping of wood results in a more suitable wood for use in sound reinforcement plates (Wegst 2006; Roohnia 2019). According to previous studies, the effect of extraction on the damping factor depends on the kind of wood species. In some species, the extraction process increased the values of damping factor (Matsunaga *et al.* 1999; Minato *et al.* 2010; Segolpayegani *et al.* 2012), and in other species, the extraction treatment process decreased vibration damping values (Roohnia *et al.* 2011a; Mollaeikandelousi *et al.* 2016; Miao *et al.* 2021; Zamaninasab *et al.* 2023). In contrast to the present research results, the results obtained from soaking process and ethanol-acetone mixture washing of the walnut species indicated that the implementation of the mentioned treatments without pretreatment did not significantly change the damping factor values. On the other hand, fermentation pretreatment significantly reduced vibration damping values in walnut wood (Zamaninasab *et al.* 2023). This issue is in addition to the importance of the nature of extractive materials of different species in choosing the type of treatment and pretreatment, it shows that the extractive materials of the *Pinus sylvestris* species can be extracted with easier conditions than the walnut species.

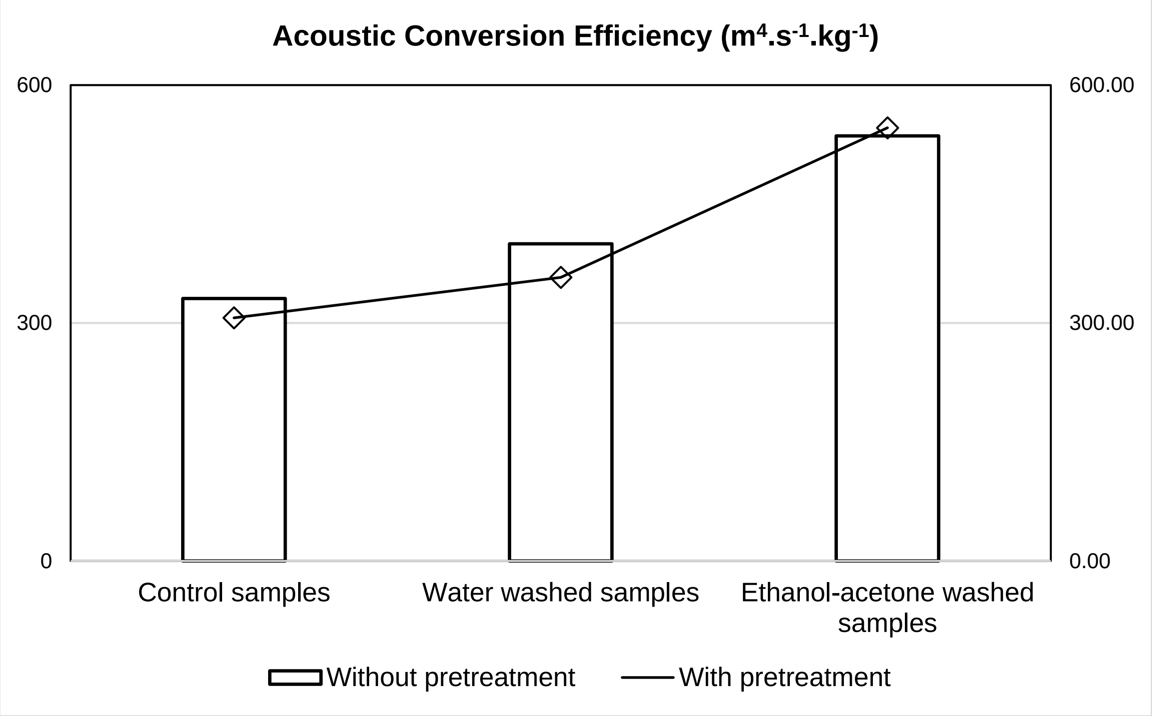

Fig. 8. ACE changes in the process of consecutive extractions

The acoustic conversion efficiency of the water-washed and ethanol-acetone mixture washed samples also exhibited a significant increase (Fig. 5). Soaking process and ethanol-acetone mixture washing both without pretreatment and with pretreatment caused a significant increase in acoustic conversion efficiency values at the 95% confidence level.

As shown in Table 1 and Fig. 8, the soaking process with 14.26 and ethanol-acetone mixture washing with 38.26 increased the ACE values. The implementation of fermentation pre-treatment also increased the acoustic conversion efficiency values in the soaking process to 17.2%, and in ethanol-acetone mixture washing it increased to its highest level, *i.e.*, 43.9, compared to the control samples. Acoustic conversion efficiency was introduced not only as the most important criterion in the selection of wood for using in musical instruments (Wegst 2006; Roohnia 2019); rather, it has been introduced as an accurate measure of the internal condition of wood in terms of the presence of defects such as knots and cracks (Kohantorabi *et al.* 2015, 2020). Previously, the increasing trend of the ACE factor was reported in *Acer velutinum*, *Acer platanoides*, and walnut wood species due to the soaking process and ethanol-acetone mixture washing (Roohnia *et al.* 2015; Mollaeikandelousy *et al.* 2016; Zamaninasab *et al.* 2023). The results of this research, while confirming the previous research, show that pre-treatment with bread yeast increases the upward trend of acoustic conversion efficiency values due to the proper extraction after soaking process and ethanol-acetone mixture washing (especially in ethanol-acetone mixture washing).

CONCLUSIONS

1. Although water washing caused a decrease in density, the fermentation pre-treatment before water washing caused a further decrease in density values.
2. Ethanol-acetone mixture washing decreased the density values. The decrease in density values in ethanol-acetone mixture washing was more than in water washing, but there was not much difference between the values of decrease in ethanol-acetone mixture washing in samples without pretreatment and with pretreatment.
3. The values modulus of elasticity, elastic stiffness, and acoustic coefficient increased due to water washing. The amount of this increase in the pre-treated samples was associated with a higher rise.
4. The values of modulus of elasticity, elastic stiffness, and acoustic coefficient showed an increase in the effect of ethanol-acetone mixture washing. The amount of this increase was higher than the values obtained from water washing, but there was not much difference between the increase of values obtained from ethanol-acetone mixture washing in the samples without pretreatment and with pretreatment.
5. The values of vibration damping were reduced due to water washing. The implementation of fermentation pretreatment caused a further decrease in the values.
6. Ethanol-acetone mixture washing caused a severe decrease in vibration damping values in the samples compared to water washing with water. The implementation of fermentation pretreatment intensified the downward trend of the obtained values.
7. The values obtained from the acoustic conversion efficiency exhibited a significant increase due to water washing. The implementation of pretreatment increased the upward trend in the values of acoustic conversion efficiency.
8. Ethanol-acetone mixture washing increased the values of acoustic conversion efficiency. The amount of this increase was significantly more than the values obtained from rinsing. Pretreatment increased the acoustic conversion efficiency.

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