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RESEARCH PAPER

# Effect of extraction on the acoustic vibrational properties of *Picea jezoensis* var. *microsperma* (Lindl.) W.C.Cheng & L.K.Fu

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## Abstract

• ***Key message*** **The specific dynamic elastic modulus, acoustic radiation, logarithmic decrement, sound transmission parameter, and acoustic conversion efficiency of spruce wood (Picea jezoensis var. microsperma (Lindl.) W.C.Cheng & L.K.Fu) were improved by extraction treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol. A larger improvement was achieved after extraction with benzoyl alcohol and dichloromethane extraction than by using ethanol and deionized water.**

• ***Context*** It is necessary to improve the acoustic vibrational properties of wood to solve the problem of resource shortage of wood with excellent acoustic vibrational properties for the soundboards of musical instruments and to improve the use value of wood.

• ***Aims*** The effects of extraction treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol on the acoustic vibrational properties of spruce wood were evaluated.

• ***Methods*** After the acoustic vibrational properties of untreated wood samples were measured using the free-free flexural vibration test method with a fast Fourier transform spectrum analyzer (FFT, CF-5220Z), extraction treatment of the wood samples was separately performed with deionized water, dichloromethane, benzyl alcohol, and ethanol for 15 days at room temperature and pressure, followed by drying. The acoustic vibrational properties of the treated wood samples were then measured, and the effect of extraction treatment on the acoustic vibrational properties was analyzed.

• ***Results*** The increase in the specific dynamic elastic modulus was highest (14.5%) after the benzyl alcohol treatment. The acoustic radiation clearly improved after the ethanol treatment (18.1%). The acoustic impedance of the wood treated by dichloromethane extraction decreased significantly (−4.35%), while the logarithmic decrement was significantly reduced (−52.0%) by benzyl alcohol treatment. From the viewpoint of energy utilization, with benzyl alcohol treatment, the acoustic conversion efficiency and transmission parameter increased by 124% and 125%, respectively.

• ***Conclusion*** The degree of improvement in the acoustic vibrational properties of wood differed depending on the solvent used. Greater improvement was observed after extraction with benzoyl alcohol and dichloromethane as compared to ethanol and deionized water.

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**Contribution of the co-authors** Conceptualization: Zhenbo LIU and Yixing LIU; Methodology: Yuanyuan MIAO, Rui LI and Zhenbo LIU; Formal Analysis: Yuanyuan MIAO, Rui LI and Xiaodong QIAN; Investigation: Zhenbo LIU, Yixing LIU and Yang YANG; Resources: Zhenbo LIU; Data curation: Yang YANG, Xianglong JIN and Bin LIN; Writing – original draft: all authors; Writing – review & editing: all authors; Supervision: Zhenbo LIU and Yixing LIU; Project Administration: Zhenbo LIU; Funding acquisition: Zhenbo LIU.

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**Keywords** Extraction · Spruce · Acoustical vibrational properties

## 1 Introduction

Spruce wood is an important material for making the soundboards of pianos and violins (Xu et al. 2014; Brémaud 2012). Spruce wood contains abundant compounds that have significant effects on the wood color, bioresistance, moisture content, and acoustic properties (Hillis 1962). Investigating the effects of different solvent extractions of wood on the acoustic vibrational properties can provide a basis for improving the acoustic properties of spruce wood.

Extraction is a common method used to improve the acoustic properties of wood, and the extraction solvent, time, temperature, and other factors affect the extraction results. Luxford (1931) pointed out that the effect of extraction on the strength of wood is related to the extract content, and the compressive strength along the grain is higher for higher extract content. Gilani et al. (2014) found that the specific modulus of elasticity of Norwegian spruce wood showed different degrees of hysteresis, and they found increased friction loss in the wood for high water content. The mechanical properties of wood, such as Young's modulus and strength, are closely related to the acoustic vibrational properties (Gan et al. 2019a, b). Furthermore, proper extraction treatment, such as hot water treatment, can reduce the hygroscopic properties and improve the dimensional stability and mechanical properties of wood. Hence, the sound stability of wood is improved, the acoustic properties parameters are optimized, and the acoustic properties are enhanced. Endo et al. (2016) investigated the effect of heating humidity on the physical properties by hydrothermally treating spruce wood, and they found that higher heating humidity resulted in greater weight loss. In addition, owing to the increased degradation of hemicellulose, the specific modulus of elasticity of the wood decreased. Minato et al. (2010) impregnated the crude extractives from muirapiranga (*Brosimun* sp.) into Sitka spruce wood (*Picea sitchensis* Bong. Carr.), and found that the internal friction (tan$\delta$) decreased. The main compounds of the extractives were xanthyletin and luvangetin. Traoré et al. (2010) extracted wood using ethanol–toluene and found that the extractive content was positively correlated with the density, dynamic elastic modulus, and specific modulus of elasticity of the wood and negatively correlated with the internal friction (tan$\delta$). Brémaud et al. (2011) investigated the effect of extraction on the acoustic vibrational characteristics of wood. They found that the acoustic vibrational properties of African Padauk (*Pterocarpus soyauxii* Taub.) improved after extraction with methanol because of the increased damping coefficient. Sha (2015) extracted Metasequoia wood (*Metasequoia glyptostroboides* Hu & Cheng) using 1% NaOH, phenyl alcohol, and hot water. The attenuation coefficient decreased with a reduction in the extract content. Roohnia et al. (2015) and Mollaeikandelousi et al. (2016) investigated the effects of different extraction treatments on the acoustic vibrational properties of maple (*Acer pseudoplatanus*), and they found that the acoustic properties improved after the extraction process. Compared with hot water extraction, acetone/ethanol is more beneficial for improving the acoustic properties of maple, and the combination method can result in a greater improvement in the acoustic properties. Wu et al. (2017) used different extractants to treat spruce wood. They found that the specific modulus of elasticity of wood increased from 3 to 6% after extraction with different extraction solvents, and the logarithmic decrement decreased by about 13%. Furthermore, different extracts had different effects on the acoustic vibrational properties of wood. Therefore, extraction treatment is an effective way to improve the vibrational properties of wood, and different extraction solvents have different effects.

In previous research, extraction processes have been complicated, and evaluation of the extraction effect on the acoustic vibrational properties of wood mainly focused on two indexes, namely the specific modulus of elasticity and logarithmic decrement. However, the acoustic vibrational performance of wood is a comprehensive property, and it is reflected by the acoustic radiation, acoustic impedance, acoustic conversion efficiency, and other indexes, in addition to the specific modulus of elasticity and logarithmic decrement. The logarithmic decrement, transmission parameter $\upsilon_L/\delta_L$, and acoustic conversion efficiency $\upsilon_L/(\delta_L \cdot \rho)$ evaluating the energy transfer efficiency and characterizing the vibration transmission (Ono and Norimoto 1983). Low density and a high elastic modulus are beneficial for the acoustic vibrational parameters (Lv et al. 2018), and there is a positive correlation between the crystallinity and the acoustic parameters such as the elastic modulus and specific elastic modulus (Andersson et al. 2003).

*Picea jezoensis* var. *microsperma* (Lindl.) W.C.Cheng & L.K.Fu is one of the most widely used tree species of spruce in the manufacture of piano soundboards. The main aim of this work was to investigate the effect of extraction treatment on the acoustic vibrational properties (density, dynamic modulus of elasticity, specific modulus of elasticity, acoustic radiation, acoustic impedance, acoustic conversion efficiency, and logarithmic decrement) of wood using four extraction solvents (deionized water, dichloromethane, benzyl alcohol, and absolute ethanol) at room temperature and pressure. The extraction effects of different solvents were compared and analyzed through the change in acoustic parameters, and the mechanism of the effect of extraction treatment on the acoustic properties of wood was analyzed through changes in the microstructure (scanning electron microscopy, SEM), crystallinity (X-ray diffraction, XRD), and internal functional groups of the wood (Fourier transform infrared spectroscopy, FTIR).

## 2 Material and methods

### 2.1 Materials

In this study, 20 pieces of *Picea jezoensis* var. *microsperma* (Lindl.) W.C. Cheng & L.K. Fu with dimensions of 300 mm (*L*) × 30 mm × (*R*) × 10 mm (*T*) were selected, and they contained no obvious defects, such as cracks, deformation, decay, or knots. They were harvested from Heilongjiang Province, China, and the trees were at least 120 years old. Before testing, the samples were stored in the natural environment for 1 year.

### 2.2 Main chemical reagents

An FX101-1 electric blast drying oven, a homemade constant temperature and pressure extractor, and a balance (accurate to 0.1 g) were used. The chemicals were deionized water, dichloromethane (AR), benzyl alcohol (AR), and ethanol (AR).

### 2.3 Acoustic vibrational properties

The 20 pieces of wood were divided into four groups, and each group was placed in a constant temperature and humidity chamber with humidity of 65% and temperature of 25 °C, and then adjusted to an equilibrium moisture content (according to the temperature and humidity of the wood, the equilibrium moisture content of the wood is 12% at temperature of 25 °C and humidity of 65%). The initial mass was measured as $M$, and the density $\rho$ was calculated. Based on Bernoulli–Euler beam transverse vibration, the natural frequency of the wood was tested using flexural vibration by a dual-channel fast Fourier transform (FFT) analyzer (CF-5220Z, Japan) (Kohantorabi et al. 2017; Miao et al. 2015), and the acoustic vibrational properties including the dynamic elastic modulus $E_L$, specific dynamic elastic modulus $E_L/\rho$, acoustic radiation $R$, logarithmic decrement $\delta_L$, stiffness modulus $G_{LR}$, acoustic impedance $Z$, $E_L/G_{LR}$, propagation velocity of bending vibration $\upsilon$, sound transmission parameter $\upsilon/\sigma$, and acoustic conversion efficiency $\upsilon/(\delta_L\rho)$ were calculated (Wegst 2006; Roohnia 2019; Miao et al. 2015). The $E_L$ and $\delta_L$ were calculated by Eqs. 1 and 2, and the other parameters were calculated based on $\rho$, $E_L$, and $\delta_L$.

$$E_L = \frac{48\pi^2 L^4 \rho f^2}{\beta_n^4 h^2} \tag{1}$$

where $L$ is the length of the sample (m), $\rho$ is the sample density (kg/m$^3$), $f$ is the resonance frequency (Hz), $\beta_n$ is the relative constant of the wood boundary conditions, and $h$ is the sample thickness (m).

$$\delta_L = \frac{1}{n}\sum_{i=1}^{n} ln\frac{A_i}{A_{i+1}} \times 100\% \tag{2}$$

where $n$ is the period number of vibration time-domain signal, and $A_i$ and $A_{i+1}$ are the amplitude of No. $i$, $i+1$ vibration period.

Then the samples were extracted with deionized water, dichloromethane, benzyl alcohol, and ethanol. The extraction time was 15 days. Finally, the samples were adjusted to the equilibrium moisture content, and then the same parameters were measured again.

### 2.4 Scanning electron microscopy (SEM)

The samples were analyzed with a QUANTA 200 electron microscope (FEI Company, Hillsboro, OR, USA) at ×500 and ×1000 magnification. The samples were coated with platinum prior to the observation to improve the surface conductivity and were observed at an acceleration voltage of 15 kV. The samples were mounted on the aluminum sample holder and placed in the specimen chamber in a vacuum condition of 0.06 mbar at room temperature.

### 2.5 X-ray diffraction (XRD)

The XRD patterns of the samples were obtained using a D/MAX 2200 X-ray diffractometer (Rigaku Corporation, Sendagaya, Japan). Prior to the measurement, the sample was placed on the supporter and compactly pressed. The XRD data were generated using a diffractometer with CuKα radiation ($\lambda = 1.542$ Å) at 40 kV and 30 mA over the angular range $2\theta = 5°$ to 45°, and a step size of 5°·min$^{-1}$. The degree of crystallinity or crystallinity index (*CI*, %) for each sample was evaluated by Eq. 3,

$$C_I = (I_{002} - I_{am})/I_{am} \times 100\% \tag{3}$$

where $I_{002}$ is the maximum diffractive strength of the 002 crystalline plane and $I_{\mathrm{am}}$ is the diffractive strength of the non-crystalline plane.

### 2.6 Fourier transform infrared (FTIR) spectroscopy

FTIR measurements were performed using a Nicolet 6700 FTIR spectrometer (Thermo Fisher Scientific Co., Ltd., Waltham, MA, USA) in the range 4000 to 400 $\mathrm{cm}^{-1}$ with a scanning rate of 32 scans per min. The resolution for the spectra was 4 $\mathrm{cm}^{-1}$.

## 2.7 Statistics and Analysis

Each sample was tested before and after treatment; in order to analyze the effect of extraction treatment on the acoustic vibrational properties of wood, the rate of change index was used. The relative change in each sample's vibrational properties was calculated by Eq. 4. Then the mean value of relative change and each acoustic parameter were calculated for each group of repeated samples. The standard deviation of each acoustic parameter was also calculated for each group of repeated samples.

$$X = (x' - x)/x \times 100\% \tag{4}$$

where $X$ is the rate of change, $x$ is the acoustic vibrational properties parameter of the untreated sample, and $x'$ is the acoustic properties parameter of the extracted sample.

The improvement between different extraction methods was compared by the relative change.

## 3 Results

The wood density $\rho$, elastic modulus $E_L$, specific elastic modulus $E_L/\rho$, stiffness modulus $G_{LR}$, and logarithmic decrement $\delta_L$ are directly related to the acoustic properties of wood (Roohnia 2019; Buksnowitz et al. 2007). The parameters of the spruce wood are given in Table 1.

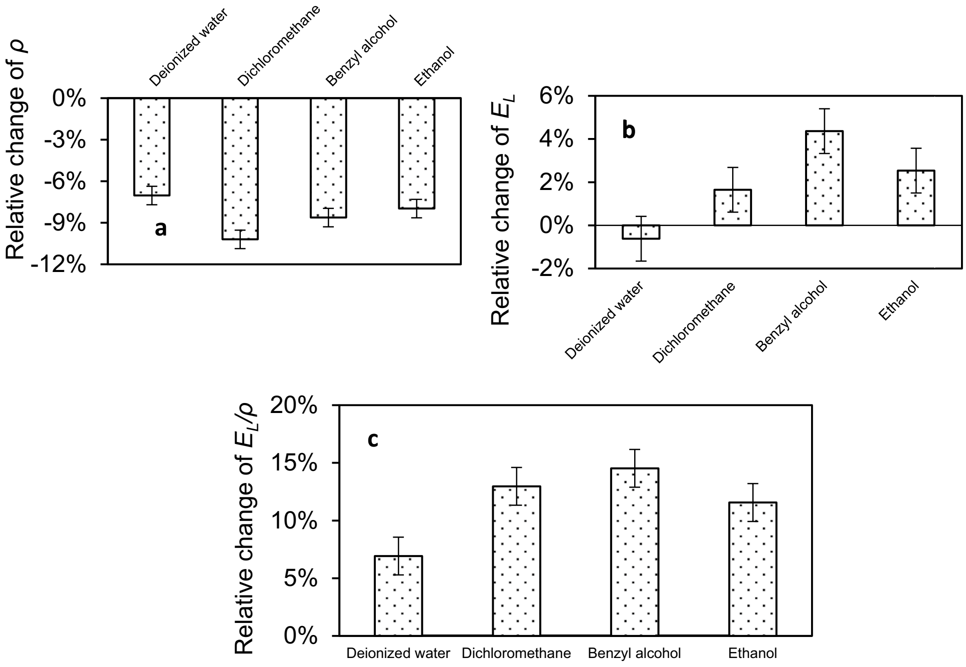
The density of the spruce wood decreased with extraction treatment. The elastic modulus of the spruce wood decreased with deionized water extraction, but some of the other parameters, such as $E_L/\rho$, $G_{LR}$, and $R$, showed an increasing trend (Table 1). Comparative analysis showed that the logarithmic decrement of the spruce specimen decreased from 0.65 to 0.31 with benzyl alcohol extraction. The acoustic radiation $R$, specific dynamic elastic modulus $E_L/\rho$, acoustic impedance $Z$, and $E_L/G_{LR}$ of the spruce wood specimen increased with benzyl alcohol extraction, but the sound transmission parameter $\upsilon/\sigma$ and acoustic conversion efficiency $\upsilon_L/(\delta_L\rho)$ changed from 9.26 and 2349.96 to 20.74 and 5761.36. This is because extraction with benzyl alcohol had a more negative effect on the logarithmic decrement, transmission parameter $\upsilon_L/\delta_L$, and acoustic conversion efficiency than on the other parameters. The high acoustic conversion efficiency and transmission parameter $\upsilon_L/\delta_L$ and low logarithmic decrement indicated that the conversion efficiency of vibration energy into sound energy is higher. (Bucur 2006).

**Table 1** Vibrational properties parameters of *P. jezoensis*

| Extraction methods | Deionized water | | | Dichloromethane | | | Benzyl alcohol | | | Ethanol | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameters | Before | After | Relative change | Before | After | Relative change | Before | After | Relative change | Before | After | Relative change |
| Density $\rho$(kg/m$^3$) | 398 | 370 | -7.04% | 451 | 405 | -10.2% | 394 | 360 | -8.63% | 401 | 369 | -7.98% |
| Dynamic modulus of elasticity $E_L$ (GPa) | 12.9 | 12.8 | -0.62% | 16.4 | 16.6 | 1.65% | 14.5 | 15.1 | 4.35% | 14.5 | 14.9 | 2.55% |
| Specific dynamic elastic modulus $E_L/\rho$ (GPa) | 32.4 | 34.6 | 6.92% | 36.3 | 41.0 | 13.0% | 36. 6 | 41.9 | 14.5% | 36.2 | 40.4 | 11.6% |
| Stiffness modulus $G_{LR}$ (GPa) | 0.68 | 0.70 | 2.94% | 0.76 | 0.78 | 2.63% | 0.61 | 0.63 | 3.28% | 0.63 | 0.64 | 1.59% |
| Ratio of $E_L$ to $G_{LR}$ $E_L/G_{LR}$ | 19.0 | 18.5 | -2.63% | 21.7 | 21.4 | -1.06% | 23.9 | 24.0 | 0.21% | 23.5 | 23.7 | 1.02% |
| Acoustic radiation $R$ (m$^4$/kg·s) | 14.4 | 16.1 | 11.2% | 13.4 | 15.1 | 12.7% | 15.4 | 18.1 | 17.4% | 15.1 | 17.4 | 14.9% |
| Acoustic impedance $Z$ (MPa·s/m) | 2.26 | 2.18 | -3.54% | 2.71 | 2.60 | -4.06% | 2.39 | 2.33 | -2.51% | 2.41 | 2.34 | -2.90% |
| Propagation velocity of bending vibration $\upsilon_L$ (m/s) | 5689 | 5882 | 3.39% | 6023 | 6409 | 6.41% | 6062 | 6479 | 6.88% | 6018 | 6352 | 5.55% |
| Logarithmic decrement $\delta_L$ (%) | 0.40 | 0.36 | -10.0% | 0.44 | 0.31 | -29.6% | 0.65 | 0.31 | -52.3% | 0.59 | 0.57 | -3.39% |
| Sound transmission parameter $\upsilon_L/\delta_L$ ($10^5$ m/s) | 14.1 | 16.4 | 16.5% | 13.8 | 20.6 | 48.9% | 9.26 | 20.7 | 124% | 10.2 | 11.2 | 9.19% |
| Acoustic conversion efficiency $\upsilon_L/(\delta_L{\cdot}\rho)$ | 3542 | 4441 | 25.4% | 3071 | 5088 | 65.7% | 2350 | 5761 | 145% | 2551 | 3027 | 18.7% |

1) The number of replicates: $n = 5$. 2) The column "Before" indicates the test results for untreated samples, and column "After" indicates the test results for treated samples. 3) The values of this column of "relative change" are calculated according to Eq. 4

**Fig. 1** Relative change in the density ($\rho$), dynamic elastic modulus ($E_L$) and specific dynamic elastic modulus ($E_L/\rho$) after treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol



## 3.1 Effects of different solvent extraction treatments on the wood density, elastic modulus, and specific dynamic elastic modulus

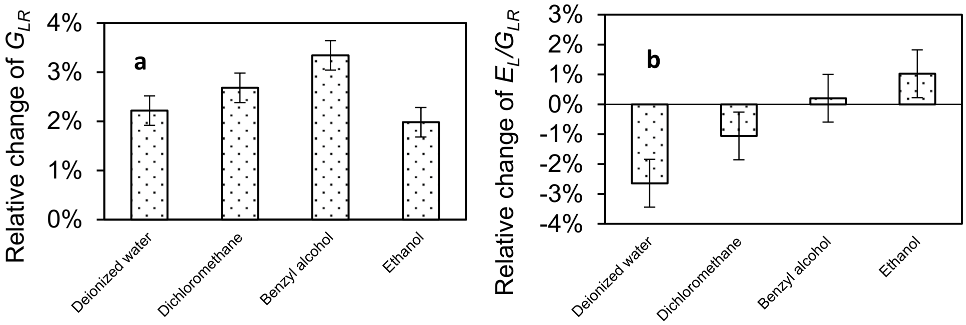
The density, elastic modulus, and specific elastic modulus before and after extraction treatment are shown in Fig. 1. When spruce wood was treated with deionized water, dichloromethane, benzyl alcohol, and ethanol, the density of the spruce wood decreased by 7.04%, 10.2%, 8.63%, and 7.98%, respectively (Fig. 1a). The density decreased the most with dichloromethane treatment (10.2%). The content and types of substances were different, so the density reduction ranges of each group were different. The elastic modulus of the spruce wood decreased by 0.62% with deionized water treatment. However, the elastic modulus improved with dichloromethane, benzyl alcohol, and ethanol extraction, and the largest change occurred for benzyl alcohol extraction (4.36%) (Fig. 1b). The specific elastic modulus was improved by the four solvent extraction treatments. The most significant improvement in the specific dynamic elastic modulus occurred with benzyl alcohol extraction (14.5%). The specific elastic modulus of the spruce wood after deionized water extraction was 6.92% higher than that of the natural wood (Fig. 1c).

## 3.2 Effects of different solvent extraction treatments on the stiffness modulus and $E_L/G_{LR}$ of spruce wood

The stiffness modulus $G_{LR}$ is directly related to the $E_L/G_{LR}$ value, and the $E_L/G_{LR}$ value is related to psychological factors such as the natural degree of tone, melody, and thickness of tone. Therefore, a material with a high $E_L/G_{LR}$ value is more suitable for use as a musical instrument (Zhu et al. 2017). The rates of change in $G_{LR}$ and $E_L/G_{LR}$ of the spruce wood are shown in Fig. 2.

The stiffness modulus of the spruce wood increased by extraction with deionized water, dichloromethane,

**Fig. 2** Relative change in the stiffness modulus ($G_{LR}$) and $E_L/G_{LR}$ values of spruce wood after treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol



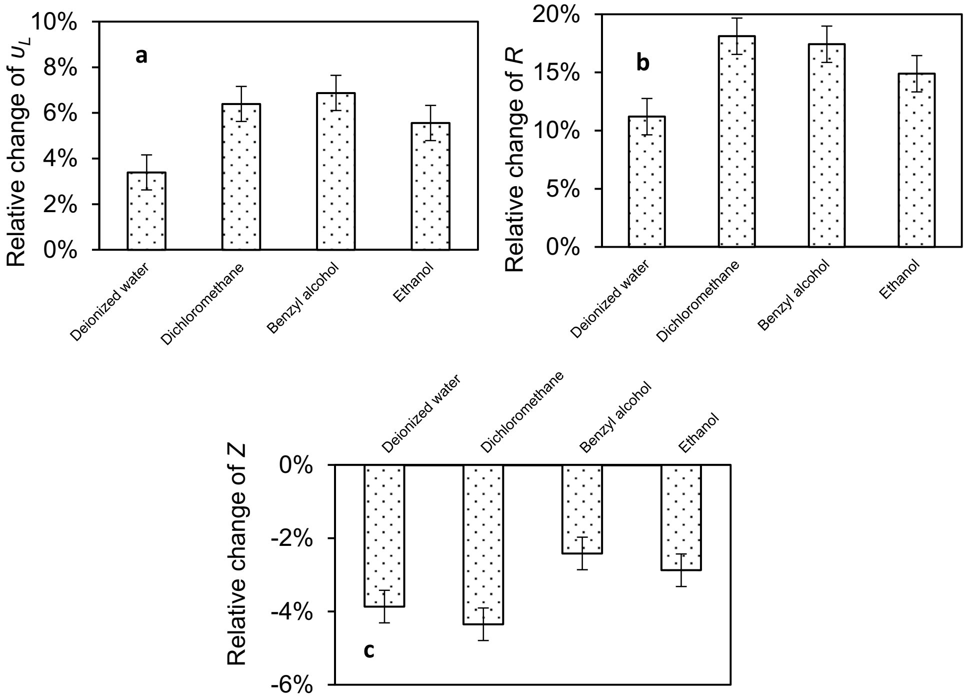


**Fig. 3** Relative change in the propagation velocity of bending vibration ($\upsilon_L$), acoustic radiation ($R$) and acoustic impedance ($Z$) of spruce wood after treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol

benzyl alcohol, and ethanol, and the largest increase of 3.34% occurred for benzyl alcohol extraction (Fig. 2a). After ethanol extraction treatment, the rate of change in $G_{LR}$ was 1.98%. The stiffness modulus of wood is directly related to the physical and mechanical properties. Extraction with these four solvents was not conducive to improving the stiffness modulus. The $E_L/G_{LR}$ values decreased by 2.44% and 1.06% with deionized water and dichloromethane extraction, respectively, but the $E_L/G_{LR}$ values increased by 0.20% and 1.02% with benzyl alcohol and ethanol extraction, respectively (Fig. 2b).

## 3.3 Effects of different solvent extraction treatments on the acoustic radiation, acoustic impedance, and propagation velocity of bending vibration

The capability of wood to radiate sound energy to the surrounding air when it vibrates is called the acoustic radiation ($R$), and is commonly used to evaluate the radiation quality of materials. $R=\frac{\upsilon_L}{\rho}=\sqrt{\frac{E_L}{\rho^3}}$, which shows that $R$ is proportional to the propagation velocity of the bending vibrations of wood and inversely proportional to the density. Materials with high acoustic radiation are often used as musical instrument resonance plates (Liu et al. 2008). The acoustic impedance $Z$ is the resistance of the sound reflected on the boundary of two media, which is related to the time response characteristics of the vibration. $Z=\rho\upsilon_L=\sqrt{\rho E_L}$, showing that $Z$ is proportional to the $\upsilon$, $\rho$, and the elastic modulus $E_L$. Hence, materials with low acoustic impedance are often used as wooden instrument soundboards (Bucur 2016). The relative change in R, Z, and υ for spruce wood is shown in Fig. 3.

The propagation velocity of the bending vibration of wood is one of the main indicators of wood sound transmission, which is directly related to the wood density, elastic modulus, acoustic radiation, and acoustic impedance (Kubojima et al. 2006). The propagation velocity of the bending vibration of the spruce wood improved with extraction treatment (Fig. 3a). The most significant improvement occurred for benzyl alcohol extraction (6.87%), while the increase for deionized water extraction was the smallest (3.39%).

After the four solvent extraction treatments, the density of the spruce wood was lower, while the sound transmission speed was higher. Thus, the acoustic radiation of the spruce wood improved (Fig. 3b). The greatest improvement was achieved with dichloromethane extraction (18.1%), while deionized water extraction treatment showed the smallest improvement (11.2%). According to Palm and Zacchi's research (Palm and Zacchi 2003), extraction of alcohols and terpenes has a great effect on the acoustic radiation of wood. The acoustic impedance can be used to evaluate the ability of the sound to reflect off the boundaries of two media to a medium with less impedance. The greater the difference in the acoustic impedance between the two media, the stronger the emission to a medium with less impedance (Hilde et al. 2014). The acoustic impedance showed the most significant change (−4.35%) for dichloromethane extraction and the smallest change for benzyl alcohol extraction (−0.24%) (Fig. 3c).

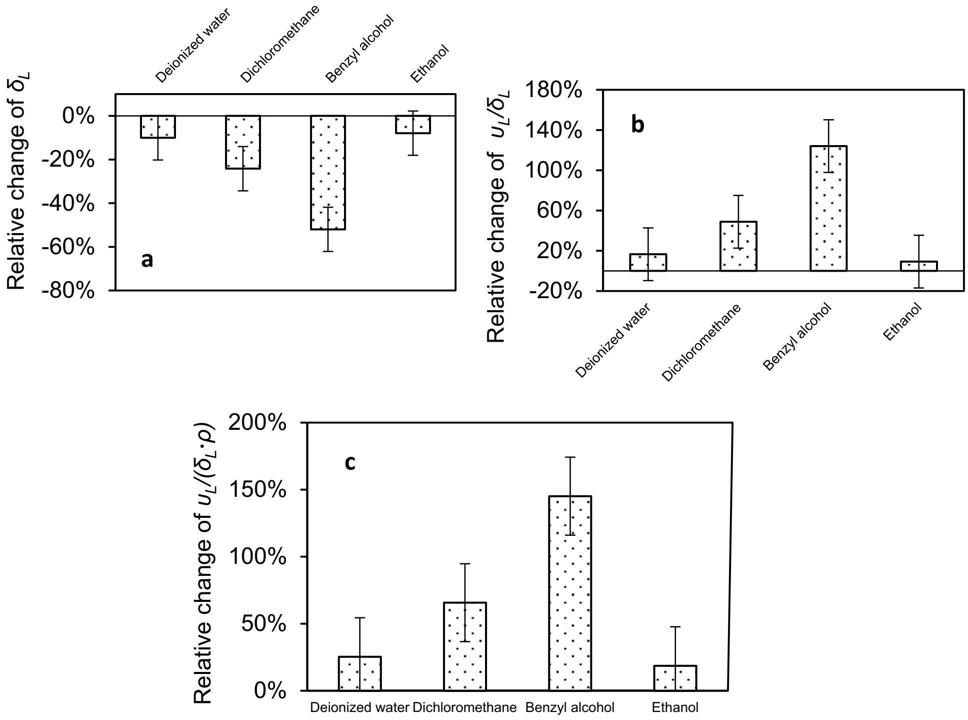


**Fig. 4** Relative change in the logarithmic decrement ($\delta_L$), sound transmission parameter ($\upsilon_L/\delta_L$), and acoustic conversion efficiency ($\upsilon_L/(\delta_L\cdot\rho)$) after treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol

### 3.4 Effects of different solvent extraction treatments on the logarithmic decrement, transmission parameter, and acoustic conversion efficiency

The relative changes in the logarithmic decrement, transmission parameter, and acoustic conversion are shown in Fig. 4. By reducing the logarithmic decrement, the energy conversion efficiency of the vibrational and acoustic properties of wood can be improved (Zhao et al. 2016). The logarithmic decrement values of the spruce wood were lower after extraction with the four solvents (Fig. 4a). The reduction was highest for benzyl alcohol extraction (52.0%) and lowest for ethanol extraction (7.90%). The transmission parameter is related to the transmission speed and the logarithmic decrement of wood, and this parameter is an important indicator characterizing the efficiency of energy transmission inside wood (Jang 2000). The transport parameter was improved with the four solvent extractions (Fig. 4b). The highest increase (124%) was obtained for benzyl alcohol extraction. The relative change in the other three solvent extractions was less than 50.0%, and the increase for ethanol treatment was the smallest (9.20%).

### 3.5 Micromorphological analysis

The microstructures of the untreated and extracted groups are shown in Fig. 5.

The cell cavities of the untreated materials were filled with extracts and showed gray coloration within the pits and resin channels. After the extraction process, the wall surface of the wood was smoother and the grain pattern was clear. After extraction, $\rho$ was higher and $E_L/\rho$ and $R$ were lower, which is conducive to improving the acoustic vibrational properties of wood. Figure 5 shows that the pits, resin channels, and wood rays were cleaner after extraction treatment using the organic solvents (dichloromethane and benzyl alcohol) than those of the sample using ethanol and deionized water. From the acoustic vibrational characteristics of wood, membranes or granules and inclusions were extracted, resulting in a decrease in $\rho$ and an increase in $E_L/\rho$ and $R$.

### 3.6 Analysis of the relative crystallinity

The effects of the four solvent extraction treatments on the crystallinity and the rates of changes in the crystallinity are shown in Fig. 6.

The relative crystallinity of spruce wood was analyzed after the four different solvent extraction treatments. The $2\theta$ value of the diffraction peak of the spruce specimens did not change with the four solvent extraction treatments, but the intensity of the diffraction peak changed, indicating that the crystalline structure of the wood fiber remained almost unchanged (Fig. 6a). Some amorphous substances in the wood were removed, resulting in an increase in the relative crystallinity (Qin et al. 2017). For extraction with deionized water, dichloromethane,

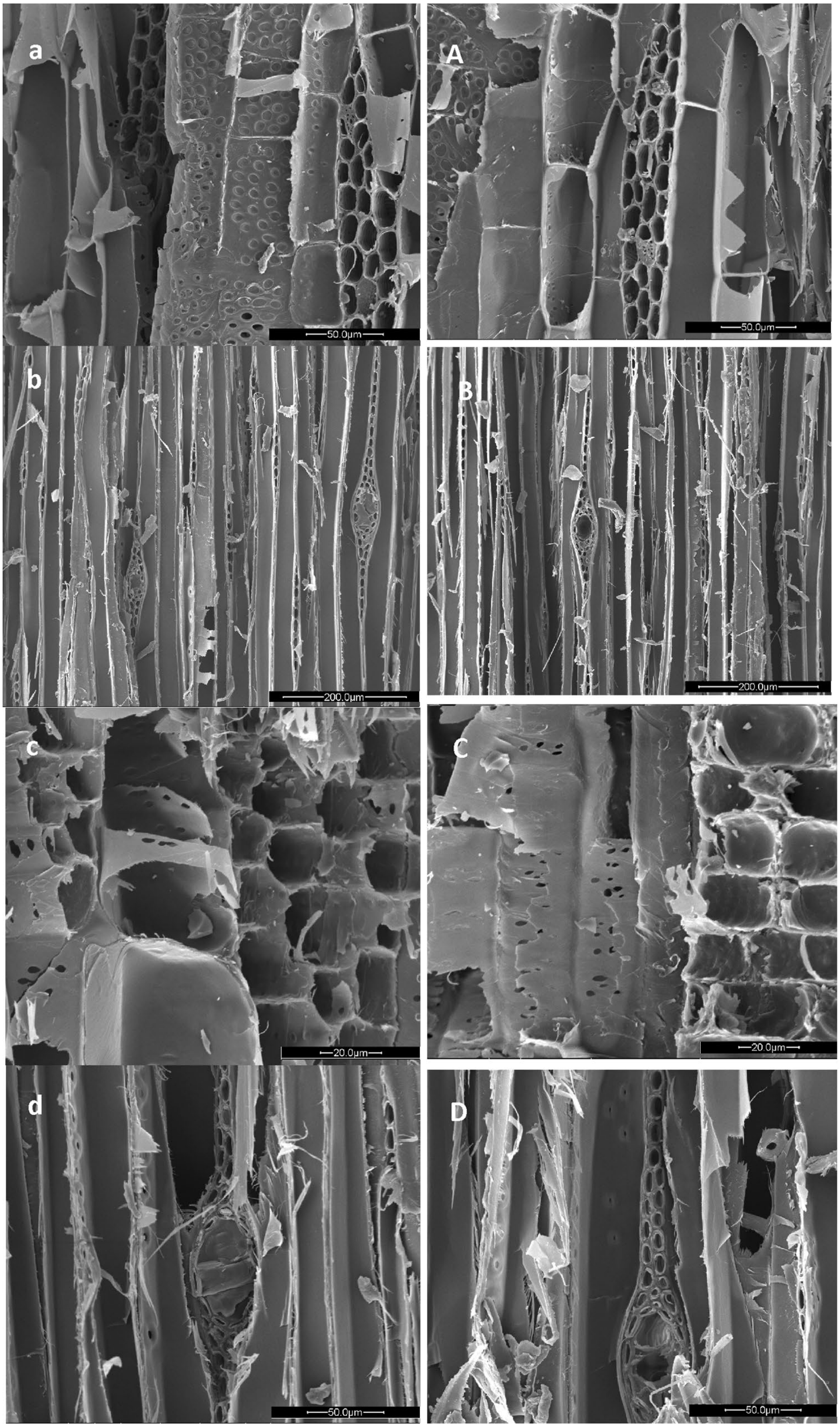


**Fig. 5** Scanning electron micrograph of untreated and extracted sample. **A**, **B**, **C**, **D**: treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol, respectively; **a**, **b**, **c**, **d**: Untreated

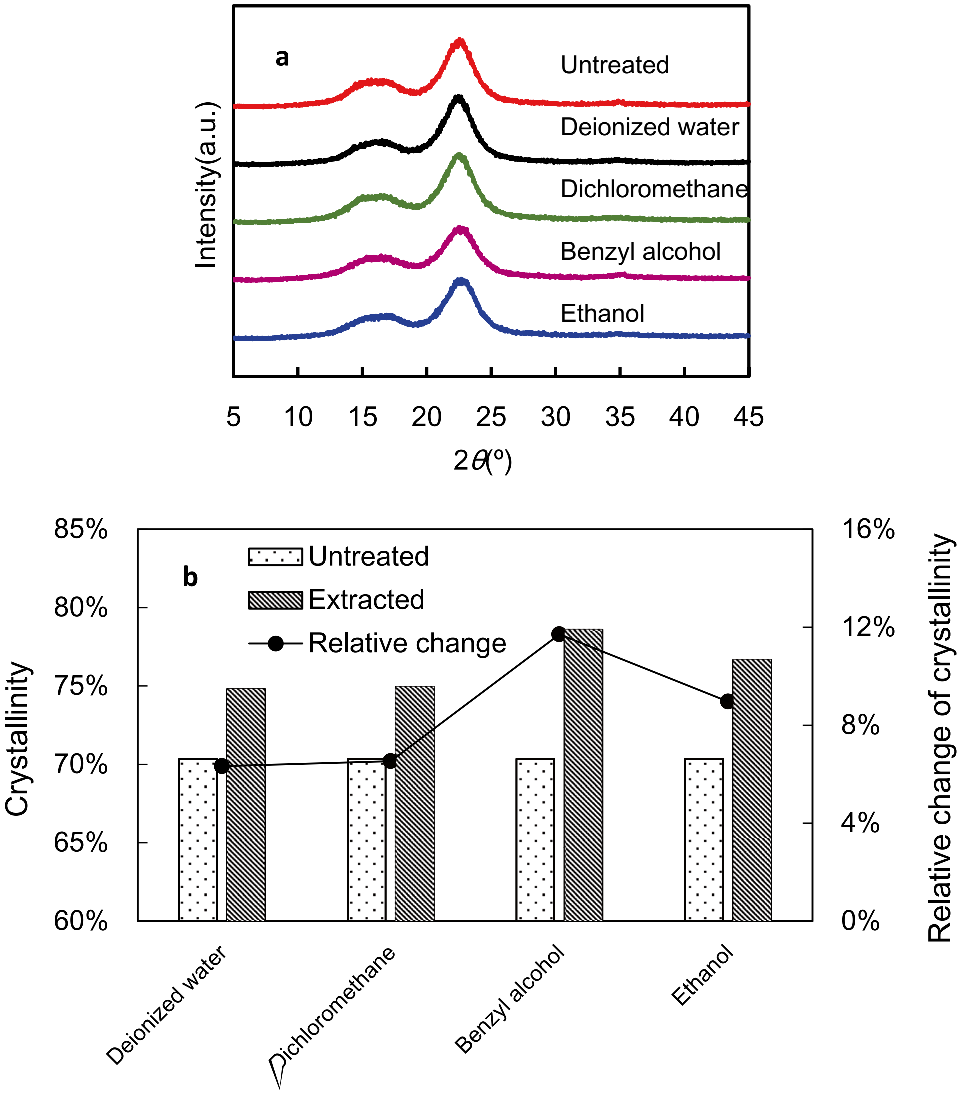


**Fig. 6** Crystallinity and relative change for spruce wood after treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol

benzyl alcohol, and ethanol, the relative crystallinity increased by 4.45%, 4.59%, 8.24%, and 6.31%, and the relative changes were 6.33%, 6.53%, 11.7%, and 8.96%, respectively (Fig. 6b).

### 3.7 Infrared analysis

The infrared spectra of the spruce wood before and after extraction treatment are shown in Fig. 7.

The peak positions and intensities of the infrared spectra did not change significantly with extraction treatment, and only the content of some water-absorbing groups, such as hydroxyl (–OH) and carboxyl (–COOH) groups, was slightly reduced. The wavenumbers were in the range 3650–3100 $\text{cm}^{-1}$ (Fig. 7), which represents the stretching vibration region of hydroxyl groups (Yu et al. 2002). The different extractions had different effects on the spruce wood. The hydroxyl vibration of the spruce wood was most reduced for extraction with benzyl alcohol, which was consistent with the changes in the crystallinity. The extractions mostly used alcoholic compounds. Extraction with these compounds reduced the free –OH groups inside the wood and weakened the infrared spectrum at 1000 $\text{cm}^{-1}$, the zone mainly including vibration of the C–O bonds of cellulose, hemicellulose, and lignin (Durmaz et al. 2016), and the wood samples treated with benzyl alcohol and dichloromethane were slightly smaller than those treated with ethanol and deionized water. Additionally, the free hydroxyl content of the untreated specimens was higher than that of the treated spruce specimens.

## 4 Discussion

The elastic modulus $E_L$ depends on the physical and mechanical properties of wood. Extraction with dichloromethane, benzyl alcohol, and ethanol were conducive to improving the elastic modulus of spruce wood, while the deionized

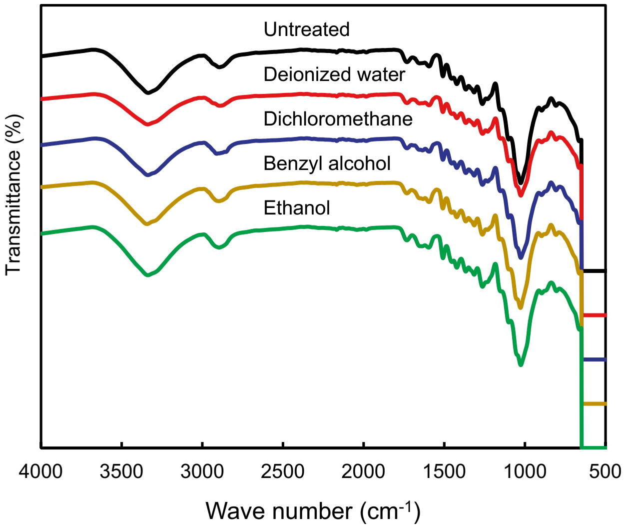


**Fig. 7** Infrared spectrum of spruce before and after treatment with deionized water, dichloromethane, benzyl alcohol, and ethanol

water solvents exhibited the opposite effect, and the relative changes in the elastic modulus and specific elastic modulus were highest after benzyl alcohol treatment. According to a previous study (Zhai et al. 2017), benzyl alcohol mainly dissolves the alcohols and terpenes in wood, so the content of these compounds is negatively correlated with the elastic modulus. Deionized water mainly dissolves the sugars, tannins, and inorganic salts in wood. Therefore, the content of these compounds is positive related with the elastic modulus. Because of the great reduction of the density after deionized water extraction, the treated wood also had a higher $E_L/\rho$ value.

According to previous studies (Leppänen et al. 2011), ethanol extracts mainly contain organic acids and resin compounds, while deionized water extracts mainly consist of sugars, tannins, and inorganic salts compounds. Therefore, it can be inferred that sugars, tannins, and inorganic salts are disadvantageous for improving the $E_L/G_{LR}$ value, and organic acids and resin compounds may promote improvement of the $E_L/G_{LR}$ value.

Analysis of the benzyl alcohol extracts showed that alcohols and terpenes had the lowest effect on reducing the acoustic impedance. The dichloromethane extracts mainly contained the same two types of compounds. These compounds had an adverse effect on the acoustic impedance and acoustic radiation of the spruce wood. Therefore, extraction of such compounds can effectively improve the vibration radiation ability of wood and improve the energy conversion efficiency of acoustic vibrations.

Acoustic conversion efficiency $\upsilon_L/(\delta_L\rho)$ is an important physical quantity for evaluating energy conversion efficiency (Yoshikawa 2007). The change trend of the spruce wood after extraction treatment was consistent with the sound transmission parameter $\upsilon/\sigma$, which exhibited the largest increase by benzyl alcohol extraction (145%) and the smallest increase by ethanol extraction treatment (18.7%) (Fig. 4c). The change trends in $\upsilon_L/(\delta_L\rho)$ and $\upsilon/\sigma$ were opposite that of the logarithmic decrement, so benzyl alcohol extraction was conducive to energy utilization of vibrations. The main benzyl alcohol extracts are terpenes and alcohols, and the two major compounds in wood have a negative effect on the energy consumption of wood. Furthermore, extraction of such compounds can effectively reduce the vibration energy loss in spruce wood and extend the duration of free vibration.

Different solvents extract different substances. The polar solvent (deionized water) primarily dissolves the gray matter and inorganic salt compounds of wood, which mainly occurs on the cell wall surface and in the intercellular layer. The organic solvents mainly extract tyloses, hemicellulose, and some amorphous substances from parenchymal cells. After solvent extraction of spruce wood, some substances were extracted from the cell wall and cavities so that the density of the wood decreased and the relative crystallinity increased. From the perspective of wood vibration energy transfer, the energy loss owing to internal friction is reduced when the tyloses of wood are extracted, and the acoustic conversion efficiency, transmission parameter, and logarithmic decrement are improved. Therefore, the extraction process is beneficial for improving the acoustic vibrational characteristics of spruce wood (Zhang and Xu 2019). Also, the increase in the relative crystallinity of wood will increase the elastic modulus of wood, thus increasing the specific dynamic elastic modulus $E_L/\rho$ and sound transmission speed of the wood, and improving the acoustic vibrational properties (Moryganov et al. 2018).

The decrease in the number of hydroxyl groups in spruce wood was beneficial for enhancing the moisture resistance property, and the acoustic properties also improved. At the same time, the decrease in the number of C–O bonds indicated that the amount of hemicellulose-like alcohols and terpenes in the wood decreased, resulting in a decrease in the density and an increase in the specific dynamic modulus. The extraction process reduced the free hydroxyl (–OH) content in the spruce wood, and hydrocarbons, esters, alcoholic inorganic salts, and other compounds were extracted, which decreased the density of the spruce wood and increased the elastic modulus, $E_L/G_{LR}$, and acoustic radiation. Because the extract content of the spruce wood decreased, internal friction loss was reduced and the sound transmission speed and efficiency increased, indicating that the extraction process improved the acoustic properties of the spruce wood specimens.

## 5 Conclusion

The acoustic properties of spruce wood improved with deionized water, dichloromethane, benzyl alcohol, and ethanol extraction. Compared with the untreated spruce wood, the specific elastic modulus values after deionized water, dichloromethane, benzyl alcohol, and ethanol extraction increased by 6.92%, 13.0%, 14.5%, and 11.6%, respectively, and the effect of extraction was in the order dichloromethane > benzyl alcohol > ethanol > deionized water. In terms of the acoustic radiation, 11.2%, 18.1%, 17.4%, and 14.9% enhancement was achieved by deionized water, dichloromethane, benzyl alcohol, and ethanol treatment, respectively, and the rates of change were in the order dichloromethane > benzyl alcohol > ethanol > deionized water. The logarithmic decrement and acoustic impedance of spruce wood decreased by deionized water, dichloromethane, benzyl alcohol, and ethanol extraction. After dichloromethane extraction, the spruce wood showed lower acoustic impedance (−4.35%). With regard to the tone of the material, the $E_L/G_{LR}$ value decreased after deionized water and dichloromethane extraction. However, the $E_L/G_{LR}$ values of wood were higher after extraction with benzyl alcohol and ethanol, demonstrating no obvious effect of the extraction treatment on the $E_L/G_{LR}$ value.

From the perspective of energy utilization, the transmission parameter and acoustic conversion efficiency of the four solvent-extracted spruce samples improved. After benzyl alcohol extraction, the transmission parameter and acoustic conversion efficiency values of spruce wood increased by 124% and 145%, respectively, revealing that benzyl alcohol extraction is beneficial for improving the utilization efficiency of the vibrational energy and prolonging the vibration time.

After extraction treatment, the infrared characteristic curve of spruce wood did not change significantly, but the intensity of the absorption peaks of the hydroxyl groups and hemicellulose was slightly weakened. In the SEM image, the duct walls and pits were clearer and cleaner after extraction, and the porous properties of the spruce wood were retained. XRD showed that the crystallinity of spruce wood increased by 4.45%, 4.59%, 8.24%, and 6.31% by deionized water, dichloromethane, benzyl alcohol, and ethanol extraction, respectively, and the relative crystallinity of the wood treated with benzyl alcohol increased the most (11.7%).

In summary, the extraction effect of the polar solvent (deionized water) on acoustic properties of spruce wood is not satisfactory. With regard to the rate of change, the effects of the different extraction solvents on the acoustic properties of wood were different. In the future, comprehensive extraction methods should be taken into consideration to improve the acoustic vibrational properties of wood.

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**Data availability** The data sets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Declaration

**Conflict of interest** Part of the research achievements was transferred to Canya Wood Industry Co. Ltd. The company gave permission for the paper to be published, and the authors declare that they have no conflicts of interest.

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