Acoustic Properties of Norway Spruce Wood Modified with Staining Fungus (*Sydowia polyspora*)

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Effects of biological modification of Norway spruce wood with the wood-staining fungus *Sydowia polyspora* were evaluated relative to select physical and acoustical characteristics (PACHs), including the density (ρ), dynamic modulus of elasticity along the wood grain (E_L), specific modulus (E_{sp}), speed of sound along the wood grain (c_L), resonant frequency (f_r), acoustic constant (A), logarithmic decrement (ϑ), loss coefficient (η), acoustic conversion efficiency (ACE), sound quality factor (Q), and sound timbre. Incubation of the Norway spruce samples in *S. polyspora* lasted 12 w, 20 w, and 24 w. The results showed that the incubation time of spruce wood in *S. polyspora* did not have a statistically significant impact on most of the PACHs (ρ, E_L, c_L, f_r, and A). However, biological modification of the spruce wood with *S. polyspora* had significant effects on the ϑ, η, and ACE. Treatment of the spruce wood with *S. polyspora* also changed the sound timbre, but the effects varied for each frequency.

Keywords: Norway spruce wood; Biological modification; Sydowia polyspora; Physical and acoustical characteristics; Timbre of sound

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INTRODUCTION

The sound qualities of musical instruments made of wood, wood composites, or combinations thereof with metals, plastics, and other materials depend strongly on the wood properties. They are determined by the anatomical structure, chemical composition, and homogeneity of the wood, as well as its processing conditions. Some studies showed that in the case of a less homogeneous wood there are great differences between vibrating modes (Zorič *et al*. 2019). Such phenomena are very important for string instruments.

Stringed instruments and other musical instruments made in traditional workshops with skilled Italian artisans use only long-term stored and well-assorted pieces of wood to achieve the highest sound quality (Stoel *et al*. 2012).

Spruce wood has been long used for the making of high-quality musical instruments because of its anatomical structure and relatively high lignin content (Brémaud *et al*. 2012). For example, an increased proportion of amorphous lignin has a positive effect on resonant frequency and dynamic modulus of elasticity. Spruce wood from "Europe's Little Ice Age" between 1645 and 1715 (known as the Maunder Minimum) is ideal for the construction of musical instruments with exceptional sound quality (Esper *et al*. 2002; Wilson *et al*. 2007), as it has narrow annual rings (Burckle and Grissino-Mayer 2003), a relatively low density

(Stoel and Borman 2008), high modulus of elasticity, and high acoustic constant (ability to dissipate acoustic energy to the environment) (Spycher *et al*. 2008). Currently, the stocks of high-quality spruce wood with the required acoustical properties are decreasing (Gejdoš and Němec 2016). Consequently, new methods need to be explored to enhance the acoustical properties of spruce wood by targeted modifications *via* thermal and biological modes.

According to numerous studies, thermally modified spruce wood meets the requirements for the production of musical instruments (Pfriem *et al*. 2007; Korkut *et al*. 2008; Košúth *et al*. 2012; Puszyński and Warda 2014; Danihelová *et al*. 2015). The high-temperature treatment of wood (180 °C to 220 °C) causes a decrease in its density, which beneficially increases the sound radiation coefficient in connection with an increase in the sound speed in the wood (Schwarze and Schubert 2011). Zhu *et al.* (2016) studied how the high-temperature treatment at 170 °C, 190 °C, and 210 °C in N_2 gas (with the aim to limit thermo-oxidation processes) during 2, 3 and 4 hours affected the acoustic-vibration performance of *Picea jezoensis* wood. They found that the acoustic-vibration performance of *P. jezoensis* evidently improved when heated at 210 °C for 4 h.

The second approach to improving acoustical characteristics of spruce wood is targeted modification by fungi, accompanied by disruption and thinning of cell walls of tracheids and other types of wood cells. Oftentimes this is followed by a reduction in the density. However, these special fungi species should not substantially attack the structural polymers of wood (polysaccharides and lignin), since such attach would result in a more evident decrease in the mechanical properties of the solid material (Reinprecht 2016). Targeted incubation of spruce wood in the fungal mycelium *Physisporinus vitreus* can cause thinning of its cell walls and reduce differences in the density between the earlywood and latewood, with decreases in the wood density that improve its vibrational ability, as documented by several studies (Schwarze 2007; Schwarze *et al*. 2008; Spycher 2008; Schwarze and Schubert 2011; Lehringer *et al*. 2011). Gilani *et al*. (2015) found that the mechanical and vibrational properties of wood depend on the fungus species used, as well as the incubation period of the wood in the fungus. Spycher (2008) discovered that there is an optimum exposure time of wood to a fungal mycelium, where improvement of its acoustical properties is maximized, and if the exposure time is exceeded, the acoustical quality of the wood decreases.

Selection of the fungal species should be based on the requirements for the improvement of the wood quality for musical instruments. Consequently, after fungal modification, spruce wood should remain highly workable, its density should decrease moderately with minimum change in the dynamic modulus of elasticity along the wood grain (E_L) and acoustic constant (A), and the colouration of the modified wood should be acceptable in terms of aesthetics. Based on these requirements, the wood-staining fungus *Sydowia polyspora* was chosen. This fungus causes a change in the wood colour and slightly lowers the wood density, but in general, it does not alter the structural characteristics of wood, other than the disturbance of pit pairs and other cell wall thinnings, which increase the permeability of spruce wood to liquids and gases. In this regard, this fungus is reminiscent of the fungus *Trichoderma viride* or other wood-staining fungi used to improve the permeability of poorly permeable softwood species (Liese and Schmid 1961; Zink and Fengel 1988; Pánek and Reinprecht 2008).

The aim of this study was to propose a biological modification of Norway spruce wood (*Picea abies* Karst L.) with the wood-staining fungus *S. polyspora* to enhance select physical and acoustical characteristics (PACHs) (density (ρ), E_L, specific modulus (E_{sp}), speed of sound along the grain (c_L), A, logarithmic decrement (ϑ), resonant frequency (f_r), sound quality factor (Q), loss coefficient (η), and acoustic conversion efficiency (ACE)). At the same time, the impact of this wood modification on the sound was examined by the fast Fourier transform (FFT) method.

EXPERIMENTAL

Materials and Methods

The fungus *S. polyspora* BAM 31 (Bref. and Tavel E. Müll.), from Federal Institute for Materials Research and Testing, Berlin, Germany), (syn. *Hormonema dematioides* Lagerb. and Melin) was used in this experiment. This wood-staining fungus frequently grows on moist softwood, though it does not attack structural polymers. It causes grey-green colourisation of wood and feeds on reserve substances stored in the lumens of wood cells and pits in cell walls (Reinprecht 2016).

The proposal for biological modification of Norway spruce (*Picea abies* Karst. L.) wood was based on EN 152 (2012). For the purpose of this experiment, freshly felled spruce timber was cut into 96 test samples with the dimensions 10 mm × 10 mm × 400 mm (radial × tangential × axial). The samples were sorted into three sets of 32 pieces, of which 16 pieces were cut from the sapwood zone and the remaining 16 were obtained from the mature wood zone. Meanwhile, samples for the assessment of the initial moisture content of the wood before starting the biological modification process were prepared from the sapwood (moisture content of approximately 144%) and mature wood zones (moisture content of approximately 31%). The *S. polyspora* mycelia did not sufficiently grow through cells of the mature wood samples. Therefore, this study evaluated only the relevant characteristics of spruce sapwood samples.

Biological modification of the spruce samples started with their immersion in distilled water for 24 h. Then, they were sterilised for 35 min in an autoclave at a temperature of 121 °C and pressure of 125 kPa. Subsequently, the samples were transferred to an inoculation box, where they were sterilised again by a germicidal lamp. Finally, they were inoculated by immersion for 2 s to 3 s in a nutrient solution with the conidia of the wood-staining fungus *S. polyspora* (Fig. 1).

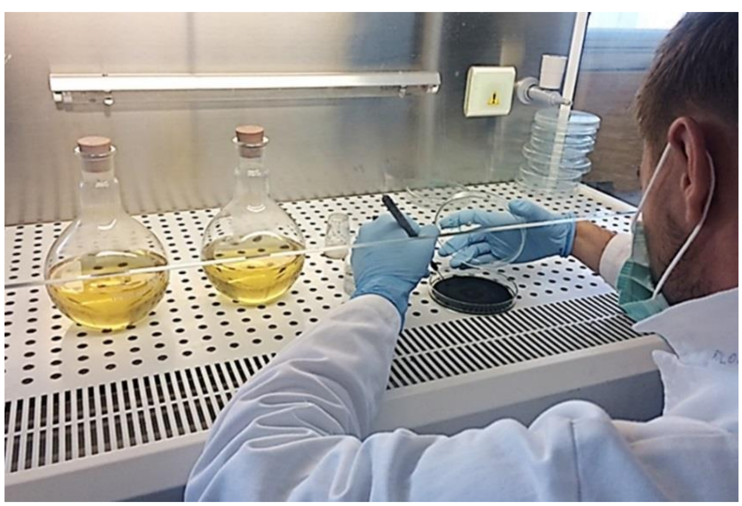

Fig. 1. Inoculation of samples with the fungus

The inoculated samples were stored in sterilised glass containers on stainless steel pads placed on a layer of Czapek-Dox medium with 10-mm gaps between them. The incubation of the Norway spruce samples in the fungus *S. polyspora* lasted 12 w, 20 w, and 24 w (Fig. 2).

Fig. 2. Samples after 24 w of incubation in *S. polyspora*

Upon completion of the biological modification, the spruce samples were placed for 24 h in a laboratory kiln heated to 60 °C, which suspended the growth of the fungal mycelium. Finally, they were air-conditioned in the environment with a relative humidity of 43% and temperature of 25 °C to reach an equilibrium wood moisture content of approximately 8%.

The PACHs of the Norway spruce sapwood were investigated before and after incubation. To obtain the relevant characteristics, the resonant dynamic method was used. A measurement resonant frequency amplitude (MEARFA) measuring device was used in the experiment (Fig. 3).

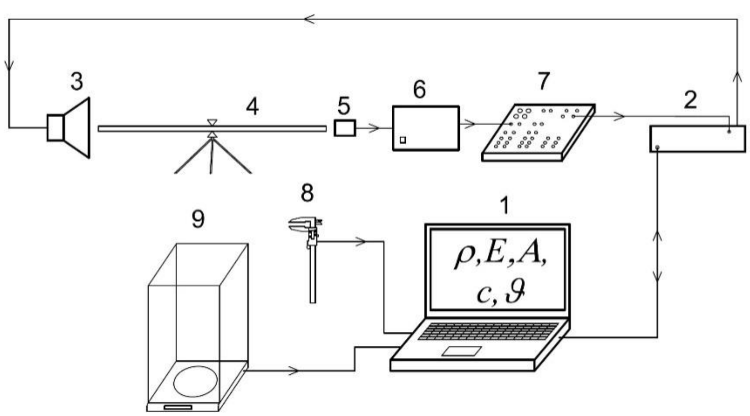

Fig. 3. MEARFA measuring device (Čulík *et al.* 2016): 1 – computer, 2 – sinusoidal signal generator and detector response, 3 – loudspeaker, 4 – sample, 5 – magnetodynamic detector, 6 – low-pass filter, 7 – preamplifier, 8 – digital gauge, and 9 – scales

Some PACHs of the wood (E_L, E_{sp}, A, c_L, and ϑ) were calculated based on the following formulas (Wegst 2006; Roohnia *et al*. 2011).

The E_L (Pa) of the samples in the shape of a bar was calculated with Eq. 1,

$$E_L = 4\ell^2 f_r^2 \rho \tag{1}$$

where ℓ (m) is the length of the samples, ρ (kg/m^3) is the wood density, and f_r (Hz) is the fundamental resonant frequency.

The E_{sp} (m^2/s^2) was calculated with Eq. 2:

$$E_{sp} = \frac{E_L}{\rho} \tag{2}$$

The A (m^4/kg·s), also known as the sound radiation coefficient (R), was calculated with Eq. 3:

$$A = \sqrt{\frac{E_L}{\rho^3}} \tag{3}$$

Equation 4 was used for calculating the c_L:

$$c_L = \sqrt{\frac{E_L}{\rho}} \tag{4}$$

The ϑ was calculated with Eq. 5,

$$\vartheta = \frac{\pi}{\sqrt{3}} \cdot \frac{f_2 - f_1}{f_r} \tag{5}$$

where f_1 and f_2 are the frequencies (Hz) at which the amplitude of the vibrations is half of the maximum amplitude at the f_r.

Given the importance of vibration damping in musical instruments, the internal friction is also relevant. This is an intrinsic material property, unlike other loss mechanisms, such as the radiation of acoustic energy. An indicator of the internal friction is the η. It was measured through the logarithmic decrement and calculated with Eq. 6:

$$\eta = \frac{\vartheta}{\pi} \tag{6}$$

Combining A (m^4/kg·s) and η, the ACE (m^4/kg·s) was calculated with Eq. 7:

$$ACE = \frac{A}{\eta} \tag{7}$$

The ACE is useful to show group effects, *e.g.*, the effect of internal friction and sound radiation together (Obataya *et al*. 2000; Abdolahian Sohi *et al*. 2011).

The η is related to the Q, which represents the mechanical gain of a structure at a resonant frequency. The Q is a descriptor of the wood sound quality because it provides information about the resonance sharpness. The Q was calculated with Eq. 8:

$$Q = \frac{1}{\eta} \tag{8}$$

The assessment of the sound quality of the Norway spruce samples before and after biological modification with the fungus *S. polyspora* (12 w, 20 w, and 24 w) was done by the FFT method. Fourier transformation of the function $f(t)$ fulfilling the Dirichlet conditions is given by Eq. 9,

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \tag{9}$$

where the amplitude spectrum $F(\omega)$ is obtained from the periodic signal $f(t)$ by the class of infinite waves $e^{-i\omega t}$, non-localised in time (Alessio 2016).

Through the FFT method, the periodic signal is divided into frequency components, *i.e.*, this method results in a frequency representation of the signal. The spectrum consists of a graph of the amplitudes (intensity) of sinusoidal components depending on the frequency. Thus, it is possible to determine the fundamental frequency component from the spectrum, as well as the frequencies of higher harmonic components. The ratios of higher harmonics to the fundamental frequency can be used to assess the sound timbre. In this experiment, the FFT analysis was performed using Adobe Audition 1.5 (Adobe Inc., San Jose, USA).

The experimental device, designed in our laboratory for measuring the acoustic signal radiated via the wood specimens, simulated the conditions resembling those in which a musician would play a xylophone. The test specimen was fastened in the nodes line of the 4th (2, 0) mode of vibration. The position of nodes was determined by excitation of the 4th mode of vibration before FFT analysis. The excitation system consists of a pendulum, *i.e.* a nylon cord (ℓ = 0.3 m) and a metal ball (d =14 mm, m = 12 g). The system was designed to excite a vibration in the wood bar by hitting of the bar at a distance of 10 cm from its end. The microphone was placed on a separate holder above the specimen.

Statistical analysis

The impact of biological modification of the Norway spruce wood by the wood-staining fungus *S. polyspora* on the selected PACHs (ρ, E_L, E_{sp}, c_L, A, f_r, ϑ, η, Q, and ACE) was evaluated with the program Statistica 7 (TIBCO Software Inc., Palo Alto, USA). A one-way analysis of variance (ANOVA) was used, as well as correlation analyses with the coefficient of determination (R^2) and Duncan's multiple range test to determine the significance of the variation at a 0.05 significance level (α).

RESULTS AND DISCUSSION

Physical and Acoustical Properties of the Biologically Modified Spruce Wood

Table 1 shows the mean values and standard deviations of the relevant PACHs, their linear correlations, and the dependence of particular properties on the incubation period of the sapwood spruce samples in the fungus *S. polyspora*, as expressed by the R^2.

The results and linear correlations with respect to the incubation period showed that its prolongation (0 w, 12 w, 20 w, and 24 w) had a statistically negligible impact (F_ρ = 0.54, p_ρ = 0.58) on the change in the wood density ρ. Similarly, the changes in the E_L, A, c_L, and f_r from prolonging the incubation period in the wood-staining fungus were statistically insignificant (F_{EL} = 1.85, p_{EL} = 0.16; F_A = 0.29, p_A = 0.35; F_{cL} = 1.99, p_{cL} = 0.14; F_{fr} = 2.09, p_{fr} = 0.13).

From the low R^2 values in the cases of the E_L, f_r, Q, c_L, and A (R^2 = 0.0004 to 0.02), it was apparent that only a small percentage of the changes in the respective characteristics were because of the fungal incubation duration.

Table 1. PACHs of the Spruce Sapwood Before and After Biological Modification with the Fungus *S. polyspora*

PACH		Norway Spruce Sapwood Modified with *S. polyspora* τ (w)				y = ax + b	R^2
		0	12	20	24		
ρ (kg/m^3)	MV	374	370	372	378	y = 0.1071x + 372	0.1102
	SD	20.4	18.5	17.3	13.5		
E_L (GPa)	MV	9.98	8.54	9.49	10.03	y = 0.0013x + 9.50	0.0004
	SD	2.41	2.55	2.75	2.58		
E_{sp} (10·m^2/s^2)	MV	26.68	23.08	25.51	26.53	y = - 0.0039x + 25.51	0.0006
	SD	0.31	0.32	0.28	0.30		
c_L (m/s)	MV	5 165	4 817	5 050	5 150	y = - 0.4286x + 5 052	0.0008
	SD	590	728	747	653		
A (m^4/kg·s)	MV	13.81	12.99	13.58	13.63	y = - 0.0048x + 13.57	0.0199
	SD	1.67	2.24	2.17	1.73		
f_r (Hz)	MV	6 457	6 006	6 313	6 439	y = - 0.4226x + 6 309	0.0005
	SD	746	908	933	816		
ϑ (-)	MV	0.026	0.027	0.031	0.032	y = 0.0003x + 0.0253	0.8864
	SD	0.012	0.009	0.008	0.004		
η (-)	MV	0.0083	0.0086	0.0099	0.0102	y = 8.10^{-5}x + 0.0081	0.8805
	SD	0.0003	0.00035	0.0038	0.0004		
Q	MV	120.5	116.3	101.0	98.0	y = - 0.9929x + 122.85	0.9455
	SD	5.8	4.1	3.8	2.6		
ACE (m^4/kg·s)	MV	1 664	1 510	1 372	1 336	y = - 14.06x + 1 667	0.9943
	SD	168	182	186	178		

In contrast, for the ϑ, the effect of the incubation period in the wood-staining fungus was clearly of greater significance (F_{ϑ} = 2.6, p_{ϑ} = 0.04), as was also confirmed by an R^2 value of 0.8864. The effect of prolonged incubation of spruce wood in the fungus *S. polyspora* was also significant in the cases of the η and ACE (F_{η} = 1.52, p_{η} = 0.03; F_{ACE} = 1.4, p_{ACE} = 0.01), which had high R^2 values of 0.88 and 0.99, respectively.

Biological modification of resonant spruce wood was studied by Schwarze *et al.* (2008), who used the wood-destroying fungi *Physisporinus vitreus* and *Xylaria longipes*. It was discovered that the gradual decomposition of hemicellulose caused a reduction in the ρ and increased the A and E_L, which started to decrease after 6 w, while the c_L and ϑ remained constant throughout the whole period of biological incubation. In the present experiment, the spruce wood modified with the wood-staining fungus *S. polyspora* for 12 w showed decreased values for almost all of the observed PACHs, except the η and ϑ, which increased (Table 1).

Impact of Biological Modification on the Sound Timbre

The first three harmonic frequencies and their ratios for select Norway spruce wood samples before and after incubation in *S. polyspora* for 12 w, 20 w, and 24 w are shown in Table 2.

Table 2. Frequencies of the First Three Harmonics of the Selected Spruce Sapwood Samples Before and After Incubation in *S. polyspora*

Marking	Incubation time (weeks)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	Ratio of the First Three Harmonics
$B_0$15	0	445	686	1033	1:1.54:2.32
B_{12}30	12	387	646	990	1:1.67:2.56
B_{20}35	20	420	653	947	1:1.56:2.25
B_{24}4	24	426	680	1190	1:1.60:2.80
$B_0$16	0	426	690	1162	1:1.62:2.73
B_{12}46	12	335	670	935	1:2.00:2.79
B_{20}37	20	387	605	920	1:1.56:2.38
B_{24}8	24	460	680	1150	1:1.48:2.50
$B_0$22	0	455	685	1120	1:1.51:2.46
B_{12}48	12	395	660	1030	1:1.67:2.61
B_{20}39	20	410	595	935	1:1.45:2.28
B_{24}10	24	365	590	920	1:1.62:2.52

Each sample has its specific set of eigen frequencies that depend on the size of the vibrating body, the wood species it is made of, and the excitation method. The timbre and intensity of the sound produced by the vibrating body result from the presence of eigen frequencies, also called harmonics, and their relative strengths (Wegst 2006). The ratios of the first three harmonic frequencies of the selected natural, non-modified samples were 1:1.54:2.32, 1:1.62:2.73, and 1:1.51:2.46. This result meant that the second and third harmonic frequencies of the bar tone decayed approximately 1.56 and 2.5 times faster than the fundamental of the bar tone, respectively. After biological modification of the spruce samples with *S. polyspora*, the second harmonic frequency decayed 1.8 times faster after 12 w, 1.53 times faster after 20 w, and 1.6 times faster after 24 w than the fundamental tone. Similarly, the third harmonic frequency of the bar tone decayed 2.7 times faster after 12 w, 2.3 times faster after 20 w, and 2.6 times faster after 24 w than the fundamental tone.

The results of the FFT (time course of the signal and sound spectrum) of select spruce wood samples before and after the incubation period in the fungus are presented in Figs. 4, 5, and 6.

Comparing the average ratios of the first three harmonics of the native spruce wood and spruce wood biologically modified by *S. polyspora*, it was clear that the ratio of the harmonics increased after 12 w of incubation, so the decay times of the second and third harmonics were shortened, which yielded brighter tones. After 20 w of incubation, the harmonic ratio decreased, *i.e.*, the decay times of the harmonics became longer, which yielded less bright tones (Moravec and Stepanek 2005; Elliott *et al.* 2013).

The modification of spruce wood with *S. polyspora* had only a minimum impact on the sound timbre. The effects of the modification were more pronounced for the sound intensity level and also influenced the fundamental resonant frequency (Figs. 4, 5, and 6).

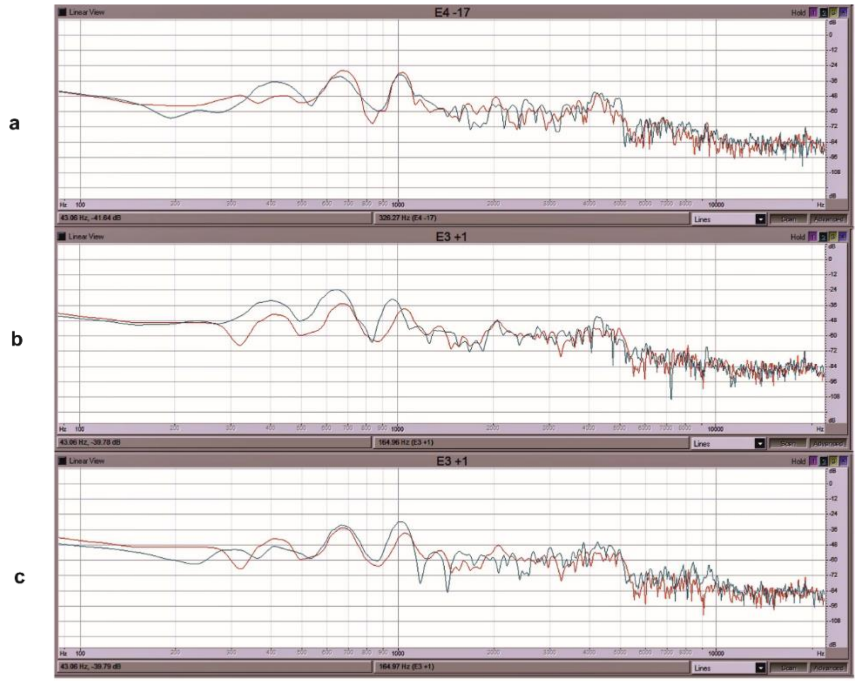

Fig. 4. Frequency spectra (x /Hz/; y /dB/) of the spruce sapwood before (B_015; blue curve) and after (red curve) 12 w (a; $B_{12}30$), 20 w (b; $B_{20}35$), and 24 w (c; $B_{24}4$) of incubation in *S. polyspora* measured in the near field

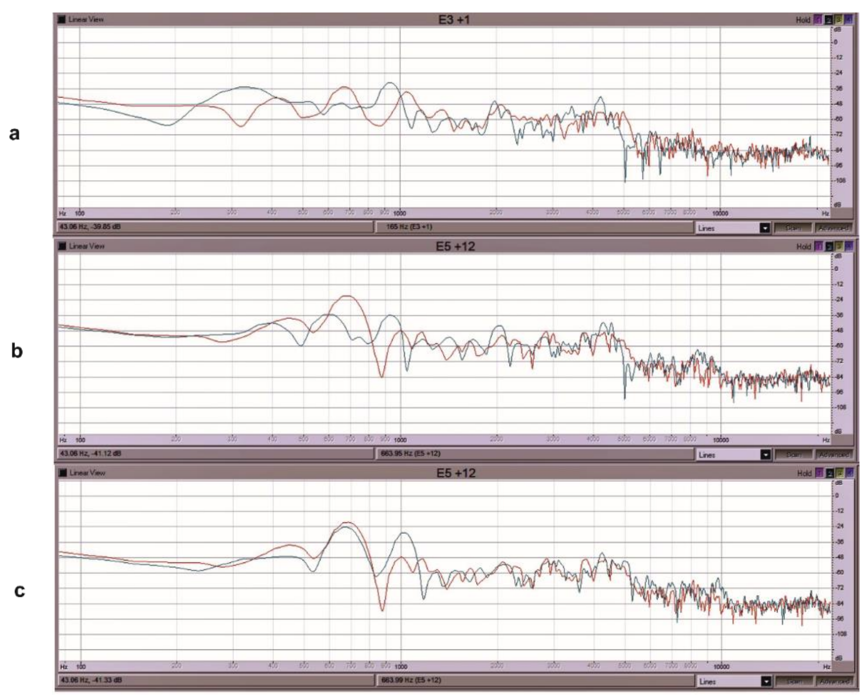

Fig. 5. Frequency spectra (x /Hz/; y /dB/) of the spruce sapwood before (B_016; blue curve) and after (red curve) 12 w (a; $B_{12}46$), 20 w (b; $B_{20}37$), and 24 w (c; $B_{24}8$) of incubation in *S. polyspora* measured in the near field

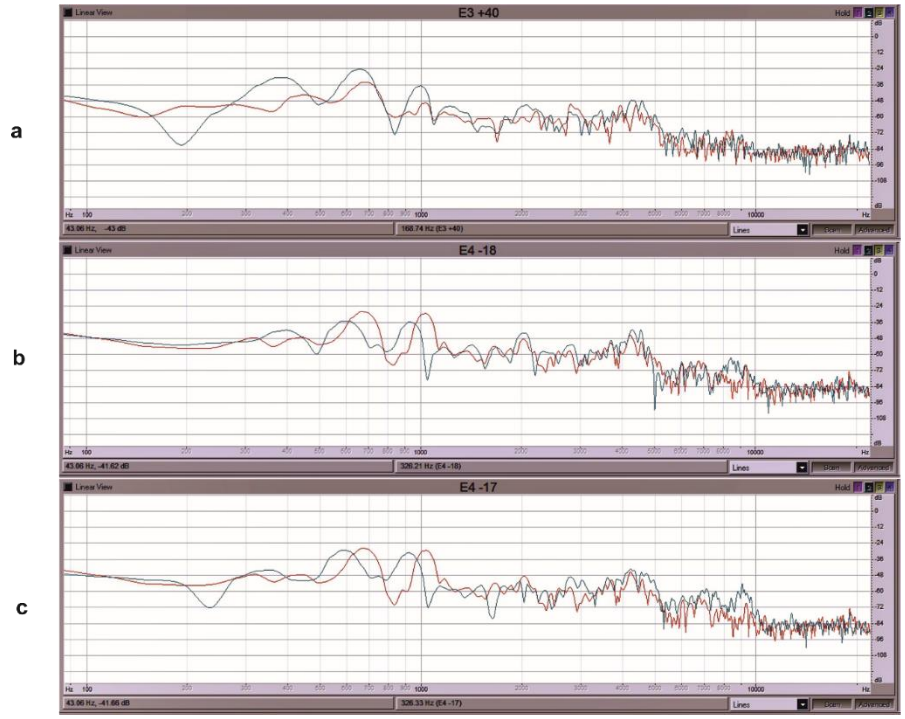

Fig. 6. Frequency spectra (x /Hz/; y /dB/) of the spruce sapwood before ($B_0$22; blue curve) and after (red curve) 12 w (a; B_{12}48), 20 w (b; B_{20}39), and 24 w (c; B_{24}10) of incubation in *S. polyspora* measured in the near field

After 12 w, 20 w, and also 24 w of incubation in *S. polyspora*, there was a tendency for an increase in the sound intensity level at a frequency of approximately 700 Hz and 1000 Hz.

At higher frequencies (approximately 2 kHz), the tendency was the opposite, *i.e.*, the sound pressure level decreased slightly compared with the unmodified samples. It was concluded that the lower frequencies were accentuated; thus, they sounded louder and clearer than the higher frequencies, which was in accordance with Bensa *et al*. (2000).

In summary, it should be noted that in addition to the objective evaluation of new wood materials based on the PACHs and FFT analysis, a subjective assessment of sound properties might be important, as it expresses the attitude of a musician or listener to the properties of a musical instrument creating sound.

CONCLUSIONS

1. Biological modification of the Norway spruce sapwood by the wood-staining fungus *S. polyspora* did not noticeably affect the PACHs, such as the ρ, E_L, A, and c_L.
2. Among the measured PACHs, it was evident that only the ϑ and η considerably increased and the ACE substantially decreased because action of the wood-staining fungus.

3. Biological modification of the Norway spruce sapwood also influenced the sound timbre, and changes were more reflected at frequencies below 2000 Hz.
4. The close relationships that were found between biological modification and sound properties of spruce wood can be used for creators of a musical instrument creating sound.
5. In that regard, the issue of biological modification of wood materials for the production of musical instruments remains current and open.

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