Tunable Acoustic Properties Using Different Coating Systems on Resonance Spruce Wood

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The study investigates the effect of the type of varnish and the number of layers on some acoustic properties of the resonance spruce in combination with the changes produced in some physical, morphological, and chemical properties of wood. In addition to color changes and surface chemistry, the surface roughness and morphology are modified by the thickness of the varnish film, 10 layers being optimal from this point of view, as well as the oil-based finish. The sound absorption coefficient increases with the number of varnish layers and varies with the sound frequency range, varnish type, and wood quality, all contributing to the acoustic tunability. For example, for a sound frequency of 1.5 kHz, it is observed that the oil-based varnish with 5 and 10 layers contributes to a full sound, while the alcohol varnish, due to a lower absorption coefficient for this frequency, can lead to some nasal sounds. Applying more than 10 layers of varnish does not improve the sound performance as it will soften the sound in an oil-based finish and make the sound too sharp in the case of alcohol–varnished wood.

1. Introduction

Studies on the acoustic quality of violins have highlighted the three determining factors: factors related to the wood material (species, the quality of the anatomical structure), the size of the violin correlated with the constructive form, and the applied varnishing system. The acoustic quality of the resonance wood has been the subject of numerous studies relating this quality with the physical, elastic, and acoustic properties of wood. Some studies classified the acoustic quality of wood according to its anatomical characteristics such as, for example, the proportion of early wood–late wood and the width of the annual rings.[1–4] With regard to the construction of the historical as well as of the nowadays violins precious information was gathered by means of various imaging methods that now constitute valuable 3D digital models and help luthiers and researchers to understand the technology of violin-making. The dynamics and acoustics of violins, with an emphasis on dynamic signature modes, have been highlighted in studies that shed light on properties such as resonance frequencies, the acoustic radiation of violins, and the frequency spectrum.[5–7] Some studies have compared the acoustic parameters of varnished and unvarnished violins as it has been proven that the applied varnish system changes the dynamic response of the instruments, at least until the evaporation of the solvent at the wood–varnish interface.[8–11] Some studies outlined the acoustic differences between the contemporary violins manufactured with the same shape, geometry, and wood material as the historical violins, which hypothetically could be attributed to the differences in the finishing system (varnish).[12–14] Although the varnish plays the role of protecting the wood (musical instrument) against environmental humidity fluctuations, but also an aesthetic role, the amorphous structure of the varnish produces changes at the vibrational and acoustic level. Thus, the research carried out by refs. [13–16] highlighted that both: the type of varnish (resin type) and especially the number of layers (film thickness) are responsible for the change in the acoustic quality of a violin, either ennobling or affecting the quality it had before being varnished. The argument of these researchers is related to the surface and mechanical changes that occur as a result of applying the varnish films, and on the other hand, the changes in the porosity and surface roughness of wood, as well as the increase in mass, stiffness and internal friction of the new system (varnish film and wood). According to refs. [12–15] the

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application of varnish leads to an instant decrease in the resonant frequency of the plate due to the increase in mass, but the stiffness effects develop gradually as a result of the rheological phenomena that occur during the process of hardening the varnish film, with effects different on the two main directions of the violin plates (longitudinal and radial). These processes continued even after the drying of the varnish was complete.

Interdisciplinary research on the chemical content of the varnishes of old violins performed in order to identify the chemical elements responsible for the acoustic quality has highlighted the existence of some mineral particles used as pore-filling material.[17] However, in the literature, there are controversies on the chemical fingerprints of old varnishes, especially regarding the preparation of recipes. Although some researchers consider that the varnish system is responsible for the acoustic quality of antique violins, Cai et al.[18] proposes the analysis of cellulose rearrangement patterns as a result of both wood aging and long-term exposure of musical instruments to vibrations. It is certain that, regardless of the varnish used, the film thickness (number of applied layers) and the wood–varnish interface lead to changes in the elastic and vibrational properties of the resonance wood used as a support. Wood varnishing is generating a new, asymmetrical layered system, influencing not only the longitudinal (E_L) and radial (E_R) modulus of elasticity but also the shear modulus in the longitudinal-radial plane (G_{LR}).[19–21]

To simplify calculations and comparisons with other materials, some researchers[5] introduced the equivalent elastic and acoustic values that depend on the wood's main directions and the quality class of the musical instruments. For violins, E_R and G_{LR} have a predominant influence on the acoustic sound propagation and the acoustic radiation in comparison with E_L. The equivalent quality factor shows that, for instruments in the guitar category, the damping properties along the longitudinal directions tend to predominate, while for instruments in the violin family, the damping properties in the radial direction are more important. Taking into account the typical elastic and damping properties of spruce boards, i.e., long and narrow boards, they are intrinsically more damped than short and wide boards. Although the soundboard is appreciated for the high speed of sound propagation in the longitudinal direction, the ability of wood to dampen sounds plays an important role in the acoustic quality of the musical instrument. In this respect, the influence of the thickness of the polyurethane finishing layers on the acoustic absorption coefficient of the resonance wood used in piano construction was highlighted by some authors.[22] They found that an increase in the varnish layer thickness leads to an increase in the acoustic absorption coefficient for frequencies higher than 2500 Hz, while, at frequencies between 1000–2000 Hz, the values of the absorption coefficient decrease. The wood species influences the values of the absorption coefficient. Similar studies on the acoustic absorption of wood from different wood species were also reported.[23-28] Thus, the wood–varnish system found in the construction of musical instruments presents distinct acoustic properties compared to the wood material itself. The asymmetry of the system structure as a result of applying the varnish film only on one surface (the face of the instrument), produces a difference in the acoustic behavior of the plate in contact with the sound waves. Knowing that the stiffness of the varnished boards is different from the stiffness of unvarnished ones, based on experimental research, some authors[29] developed a mathematical model for calculating the modulus of elasticity of the asymmetric varnishing system containing wood and lacquer film. In conclusion, most studies carried out on wood used for musical instruments have theoretically and experimentally approached the wood acoustic properties by determining the sound propagation speed, the resonance frequencies, the damping, and the quality factor.

To complement the previous studies, the research presented in this paper aims to characterize the performance of spruce resonance wood when covered with different varnishing systems, focusing on the reflection and sound absorption of the wood–lacquer system.

The novelty of the article consists of a comprehensive approach, in which the effect of the varnishing systems (varnish type, number of layers applied) on the selected acoustic parameters is analyzed in combination with the effect they produce on the physical, morphological, and the chemical properties of resonance spruce wood. The statistical analysis provides the correlation between those different factors. Knowing the acoustic characteristics, such as the sound absorption coefficient of the soundboard, is important in predicting the amount of sound absorbed by the violin's soundboard.

2. Experimental Section

2.1. Sample Preparation

A number of 36 spruce wood samples (*Picea abies L. Karst*) belonging to anatomical quality classes A (coded MA) and D (coded MD) with a moisture content of 6–8%, with dimensions of 240 × 80 × 4 mm^3 (L × R × T) were prepared from timber selected for violins (**Figure 1**). The classification of the samples into the two classes of anatomical quality was carried out based on the criteria presented in previous studies (width of annual rings, proportion of early wood, proportion of latewood).[2] The samples' surfaces were calibrated and sanded at a local musical instruments producer, by following the factory technology, common for preparing violin surfaces before varnishing. The average values of the initial mass, wood density (coded WD), and dimensions of the wood samples before varnishing are presented in Table S1 (Supporting Information). The characteristics of samples before varnishing were kept in control: their mass, density, surface color, surface roughness, chemical composition, and acoustic properties. Then, both quality samples (MA, MD) were subjected to varnishing on one side: 18 samples with oil-based varnish (coded LU), and the other 18 samples with alcohol varnish (coded LS). Three types of varnish applications were made for each varnishing material, differing in the number of layers applied: 5, 10, 15 and consequently differing in the resulting coating thickness (Figure 1). For each varnish thickness (number of layers NL), there were three replicates prepared. **Figure 2** shows a representation of the varnished samples with an indication of the thickness values of the layered structures: the spruce wood substrate (thickness $h_w = 4 \pm 0.2$ mm); the wood–varnish interface (thickness $h_{(w\text{-}v)} = 30 \pm 10$ µm) and the varnish film (thickness $h_v = 60 \div 100$ µm). The samples were obtained by applying successive varnish layers, drying, and sanding any intermediary layer with 320-grit paper.

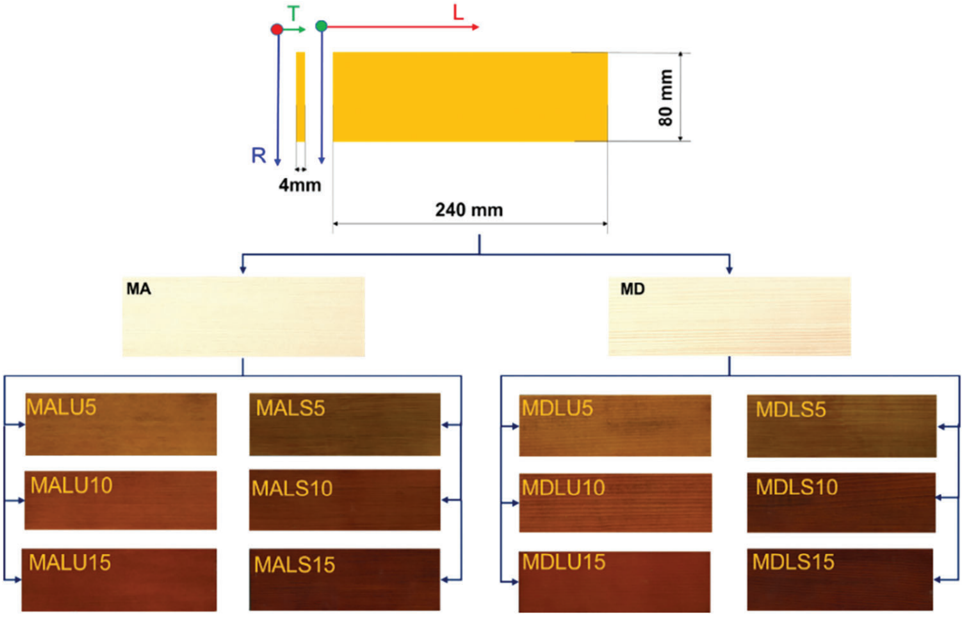


Figure 1. Types of prepared specimens.

According to ref. [15] the mass change of the spruce samples after applying the coating was evaluated as an areal mass loading (AM) induced by the varnish system (Equation 1):

$$\mathrm{AM} \;=\frac{m_{vs}-m_{w}}{b * l} \tag{(1)}$$

where AM is the areal mass loading induced by the varnish system (g m^{-2})[15]; m_{vs}—the final mass of the varnished wood, m_{w}—the initial mass of the wooden sample, b—the sample width; l—the sample length.

The application of varnish was carried out by a professional luthier, and the coating systems (oil-based varnish, alcohol varnish) were made according to the recipe of the violin maker.

2.2. Methods

2.2.1. Color Measurement

Color measurements in the CIE Lab system were performed with a Konica Minolta CR-400 chroma meter. Color coordinates, lightness (L^{*}), redness (a^{*}), and yellowness (b^{*}), were measured, on all wood samples, both initially and after each layer applied. The color measurements were made in three points (see Figure S1, Supporting Information), selected to be representative of the natural nonuniformity of the wood color.[30–32] Color differences denoted ΔE^{*} between the total color of the control samples and the color values measured, in the same locations, after varnishing were determined with Equation 2:

$$\Delta\ E^{*}=\sqrt{\left(\Delta L^{*}\right)^{2}+\left(\Delta a^{*}\right)^{2}+\left(\Delta b^{*}\right)^{2}} \tag{(2)}$$

where ΔL^{*} is the lightness difference between the lightness after varnishing and the initial lightness, Δa^{*} is the difference in the redness between the value after varnishing and the initial value, and Δb^{*} is the difference in yellowness between the value recorded after varnishing and the initial value.

2.2.2. Determination of Surface Energy

The evaluation of the surface energy (denoted SE) of the wood samples was carried out by the contact angle method. The value of the contact angle (denoted CA) depends on three factors: the morphology of the substrate expressed by the surface tension between the solid and gas medium (mN m^{-1}); the nature of the liquid expressed by the superficial liquid and gas tension (mN m^{-1}); the nature of liquid and substrate

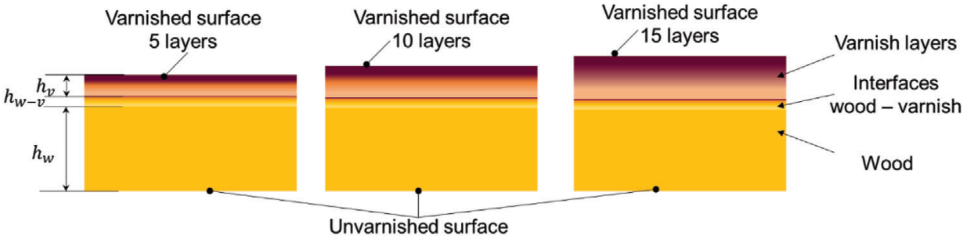


Figure 2. The coating system consists of the wood substrate, the wood–varnish interface, and the varnish film obtained by applying successive layers.

interactions expressed by the surface tension between the solid–liquid medium (mN m^{-1}).[32,33] The CA was determined with the System OCA-20 equipment, using successively distilled water and glycerin, for the drop, with a volume of 10 µL. Thus, the values of the contact angle for water (noted CAW) and for glycerin (CAG) were measured.[33,34] The measurements were performed at room temperature and under normal humidity conditions (T = 22.7 °C and RH = 65%). Three measurements per sample were made in the same areas, before and after varnishing. (Figure S1, Supporting Information).

2.2.3. Surface Quality Measurements

The surface quality of the samples before and after finishing was investigated using the MarSurf XT20 instrument, equipped with a stylus with a tip radius of 2 µm. The scanned profiles were further processed with the MARWIN XR20 software. The measurements were made on the same trace, before and after varnishing, the 30 mm profiles being scanned perpendicular to the fiber direction, with a lateral resolution of 5 µm (according to the scheme in Figure S1, Supporting Information). After removing the shape errors, a special filtering procedure was applied to the primary profile obtained, by using a robust Gaussian regression filter with a threshold value of 2.5 mm. This threshold separated the roughness profile from the waviness profile according to the procedure described in refs. [32,35–37] The mean values of the following parameters were calculated: R_a (the arithmetic mean deviation of the roughness profile) from ISO 4287:2009, R_k (the core roughness depth of the roughness profile), R_{pk} (the reduced peak height of the roughness profile) and R_{vk} (the reduced valley depth of the roughness profile) from ISO 13565-2:1998[36] and explained in detail in ref. [37]

2.2.4. Chemical Analysis with the Fourier Transformed Infrared Spectroscopy

Fourier transformed infrared spectroscopy (FTIR) was employed to analyze and compare the surface chemical features of the bare wood substrate and of the wood surfaces after coating with the two types of varnishes, applied in 5, 10, and 15 layers, respectively, resulting in three different thicknesses of the coating film. An Alpha Bruker spectrometer equipped with an attenuated total reflectance (ATR) unit was employed. The FTIR spectra were recorded in the range 4000–600 cm^{-1}, at a resolution of 4 cm^{-1}, 24 scans per spectrum, while a minimum of three spectra were recorded for each sample. OPUS 7.2 software was employed for the further processing of the recorded spectra obtaining the min–max normalized average spectra for all the investigated samples.[32,38-41]

2.2.5. Evaluation of Noise Insulation Characteristics

The analysis in the impedance tube was performed in relation to the standard procedure based on the two-microphone transfer function method (TFM) according to ISO 10534–2 and ASTM E1050–12 international standards.[42-44] Hereby, the TFM was used in order to evaluate the acoustic impedance and sound reflection coefficient at normal impedance. The general setup used for the evaluation of the sound absorption/reflection coefficient is schematically presented in Figure S2a (Supporting Information). The procedure consisted of cutting round shape samples, with 29 mm diameter, out from the varnished specimens according to the diagram in Figure S2b (Supporting Information). Each sample (1) was inserted into the sample holder of the impedance tube (2), type 4206, Brüel&Kjær (Nærum, Denmark), and acoustic signals with the frequency range 100 Hz–6.4 kHz were generated inside the tube using the loudspeaker (3); the signals provided by microphones (4) were acquired by a conditioner–DAQ board system (5), and finally were transmitted to a computer system (6)—see the schematic diagram in the Figure S2a,c (Supporting Information).[45–48] The samples were investigated on both: the unvarnished (denoted "a") and the varnished (denoted "b") sides, in order to identify the differences between sound absorption/reflection coefficients caused by the varnish layers (Figure S2a,c, Supporting Information).

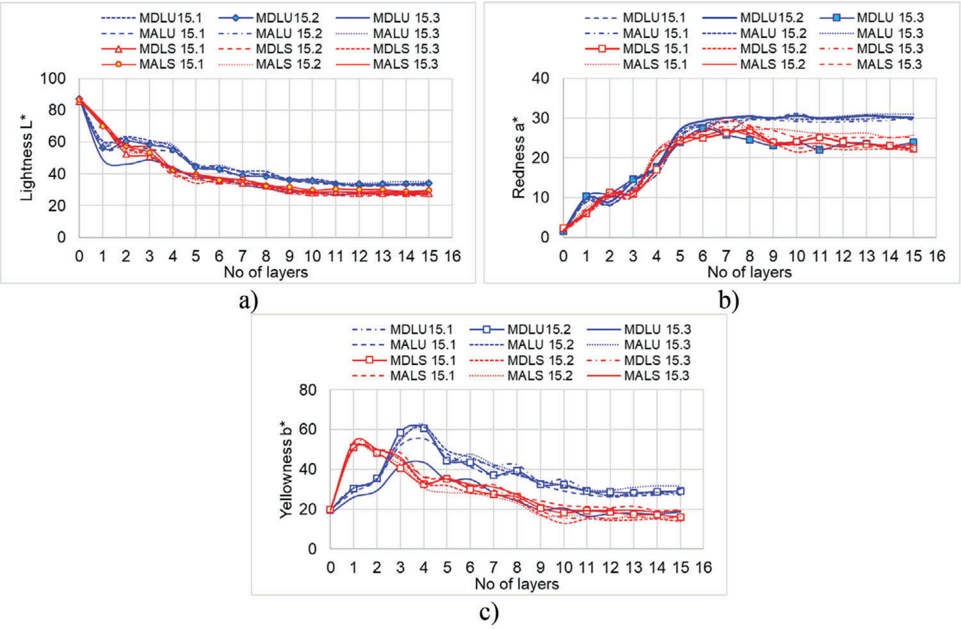
Based on experimental evaluation of the sound absorption coefficient (denoted SAC), the noise reduction coefficient (NRC) was calculated as the arithmetic average of the sound absorption coefficients at specific mid-range frequencies of the octave bands (250, 500, 1000, and 2000 Hz; see Equation 3).[23,49]

$$\mathrm{NRC} = \frac{\mathrm{SAC}_{250} + \mathrm{SAC}_{500} + \mathrm{SAC}_{1000} + \mathrm{SAC}_{2000}}{4} \tag{3}$$

In addition, the normal incidence sound reflection coefficient and the specific acoustic impedance were analyzed with respect to the frequency range of the impedance tube. The amount of reflection was provided by the sound reflection coefficient (usually denoted SRC), which depends on the material surface profile, the frequency of the traveling wave, and the incident angle which is the angle between the wavefront and the normal direction to the surface.[45-49] The impedance tube provided the conditions of normal incidence investigations (null angle), with the controlled frequency band of the incident waves.

2.2.6. Statistical Analysis

From a statistical point of view, due to a considerable amount of data, this was grouped as follows:, the wood characteristics studied in this paper were treated as alternative nominal variables (quality class), binary variables (varnished/unvarnished), nominal variables (wood varnishing systems), discrete quantitative variables (number of layers applied), and continuous quantitative variables (wood density, AM, color parameters, roughness parameters, contact angle, surface energy, NRC and absorption coefficient). The quantitative variables were first described with descriptive statistics (mean, minimum, maximum values, and coefficient of variation). In order to choose the most suitable test for identifying the differences between variables, the normality of the distribution of the variables was checked, with the Shapiro–Wilk test.[50] The effect of independent variables was studied with analysis of variance or nonparametric tests (Mann–Whitney, Kruskal–Wallis), as appropriate. The way of association of the variables was explored by means of principal component analysis (noted PCA). The significance and strength of associations



a) b) c)

Figure 3. Color changes during the varnishing process: a) lightness; b) redness; and c) yellowness.

between variables were examined using simple correlation.[51] Statistical data processing was performed with STATISTICA 8.0 (2007) software.

3. Results and Discussion

3.1. The Effect of Varnishing Systems on the Physical Parameters

3.1.1. Change in the Wood Color

The varnish and the number of varnish layers substantially changed the color of the samples. The alcohol varnish had a more pronounced effect on lightness, darkening the samples more than the oil-based varnish. After varnishing, the redness and yellowness changed substantially (p from the Kruskal–Wallis test < 0.001 for Δa^* and Δb^*). Both parameters a^* and b^* increased significantly more in oil-based varnish samples compared to samples finished with alcohol varnish. Thus, with each layer of varnish, the lightness decreased on average by 0.8% (**Figure 3**). The degree of red increased continuously until 10 layers were applied, after which it remained constant. The degree of yellowness decreased with the number of layers, on average by 1.4 units after each varnish film. The evolution of color changes during the varnishing process is shown in Figure 3, for each color parameter. The evolution of changes in color parameters is divided into three levels: between layers 1 and 5, the greatest change in all color parameters is observed; between layers 6 and 10 the second level is recorded, where the speed of change is considerably reduced, and between layers 11 and 15 a stabilization of the parameters is observed. Of course, this development depends on the formulation of the coating system, the pigments used, and the sanding between coats. The quality of the wood samples (MA, MD) did not influence the color parameters of the varnishing (p from the Mann–Whitney test = 0.60 for ΔL^*, 0.83 for Δa^*, 0.62 for Δb^*, 0.24 for ΔE^*).

The total color difference ΔE was higher for the LS varnish in comparison with LU varnish for both wood quality classes (MA, MD) and increased with the number of varnish layers. (Figure S3, Supporting Information).

3.1.2. Surface Morphology

In the case of the MA quality of the resonance spruce, which is characterized by narrow and dense annual rings, it was noted the presence of specific anatomical undulations corresponding to the succession of early wood and latewood zones. These undulations are generated by sanding zones with different densities. Having a high frequency, these undulations are not eliminated by filtering and remain captured in the roughness profiles. The presence of anatomical undulations is clearly visible after the roughness profiles (before and after finishing) were superimposed, for the MA material quality and both types of finishing (see Figure S4,Supporting Information). Even if the finishing covers the anatomical cavities and it reduces the raised fiber, the anatomical undulation is still visible. It can be noticed that in the case of the oil-based finish, LU, the increase in the number of layers produced a reduction in the surface roughness, reducing even the anatomical undulations (Figure S4a, Supporting Information). This is due to the fact that this type of finish fills the wood pores well and has a good surface covering power. In the case of finishing with solvent-based varnish, LS, the finish reduces the surface irregularities, but to a lesser extent than in the case of the LU finish. However, the anatomical undulation persists or becomes even more accentuated after varnishing, being sensed also by touch. The anatomical undulation retained in the roughness profiles depends on the initial undulation existing on

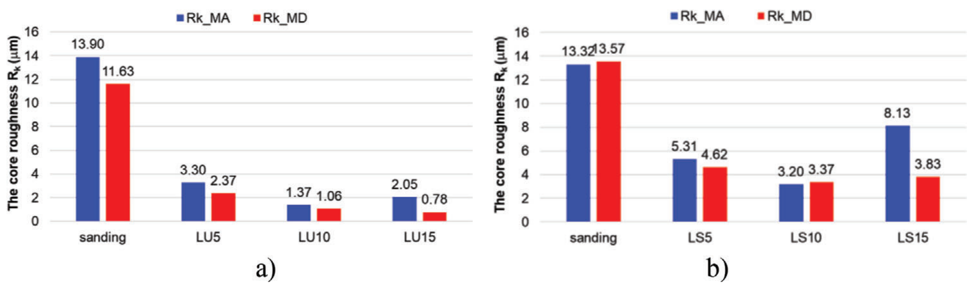


Figure 4. The core roughness R_k, for spruce qualities MA and MD: a) LU finished; b) LS finished.

the surface of the unfinished samples and influences the roughness values both before and after finishing. This explains why the MA quality surface finished with 15 layers of LS varnish appears wavier than in the case of samples with a lower number of layers (Figure S4b, Supporting Information). The core roughness, R_k, decreased after 5 layers of LU finishing, by 76% for MA and 80% for MD, and after 10 layers it decreased by ≈90% for both qualities of spruce wood (**Figure 4a**). After 5 layers of LS lacquer, R_k decreased by 60% for MA and by 65% for MD, and after 10 layers, R_k decreased by 75% for both spruce qualities (Figure 4b). The decrease in roughness after finishing with 5, respectively 10 layers compared to the unfinished support was significant following the single factor ANOVA test with a significance level $p < 0.05$. Also, by increasing the number of layers to 10 compared to 5, it produced a significant improvement in the central roughness R_k, for both types of finishing. Increasing the number of layers to 15 did not produce significant changes in the surface quality expressed by R_k, except for the case of LS finishing at MA quality, where the roughness actually increased, most likely due to the surface undulation caused by the early wood–latewood alternation. Moreover, with the increase in the number of layers to 15, the surfaces became more sensitive to scratches or the inclusion of dust particles, which did not improve the quality of the surfaces. The most responsive parameters to the presence of such defects on the surface were R_{pk} and R_{vk}, which marked a slight increase in the case of the 15-layer finish. Therefore, the best quality of the finished wood was recorded for a maximum number of 10 layers. R_{vk}, in the case of sanded wood and before finishing, is an expression of the depth of the cavities due to the cellular voids that exceed in size the traces produced by the abrasive grains in the wood (for example, tracheids from earlywood, resin canals). By applying the finish, a filling of these cavities is expected, which will reduce the values of the R_{vk} parameter. Similarly, R_{pk} is a measure of the peaks of isolated irregularities, such as fibers raised after sanding and covered by finishing. The ANOVA test indicated significant differences between the R_{vk} values of the two types of finishes, with significantly lower values in the case of oil-based varnish. This also confirms the fact that the oil-based varnish (LU) covers the cavities better than the solvent-based lacquer (LS), in the case of spruce and for both material qualities.

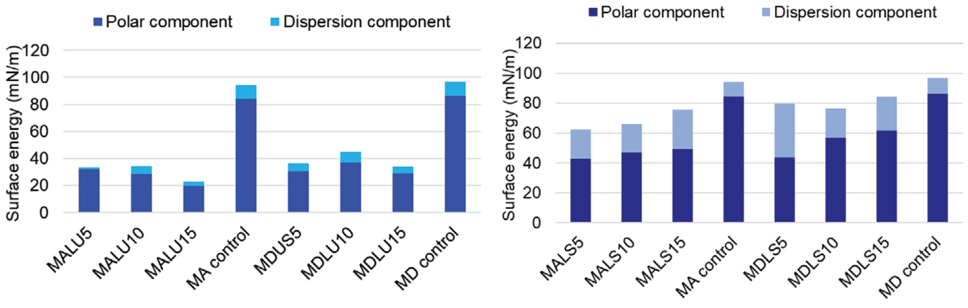
3.1.3. Surface Energy

In the first stage, the values of the contact angle were determined for the two fluids (distilled water and glycerin), whose variation is shown in (Figure S5, Supporting Information). It was observed that regardless of the fluid used, the contact angle was higher in the case of samples varnished with LU, for both wood quality classes. In contrast to the varnished samples, the control samples have a higher degree of crystallinity (**Figure 5**). So, the varnish film, regardless of the nature of the varnish, leads to a decrease in crystallinity, and the two components of the surface energy (polar and dispersive) give information about the polarity of the surface. The surface energy is closely related to the acoustic properties of the samples. The lower the surface energy, the lower the porosity of the surface and the lower the capacity of sound absorption, meaning that the surface becomes acoustically reflective.

3.2. The Influence of the Varnishing System on the Surface Chemical Features

The spectra from **Figure 8** show, in the IR range 3500–1700 cm^{-1} absorptions, some common functional groups/chemical bonds: H–bonded —OH groups (3500–3331 cm^{-1} O—H stretch); characteristic double absorption of methylene and methyl groups (aliphatic) at 2926–2858 cm^{-1} (for LU varnished samples); 2927–2858 cm^{-1} (for LS varnished samples); 2919–2860 (for unvarnished wood); unconjugated carbonyl groups (C═O stretch) assignable to aldehydes, ketones, esters or free acids at 1724 cm^{-1} (for LU varnished samples); 1708 cm^{-1} (for LS varnished samples); 1730 cm^{-1} (for unvarnished wood). For the wood substrate, the absorption at 1730 cm^{-1} is due mostly to the acetyl ester groups in the structure of hemicelluloses. The absorption at 1724 cm^{-1} in the spectra of LU film may be assigned to the unconjugated CO in ester groups from the structure of oils (glycerol–fatty acids), while the absorption at lower wavenumber 1708 cm^{-1} in the spectrum of LS film may indicate the presence of unconjugated CO mainly in free acid carboxyl groups. Also, FTIR spectra indicate a higher amount of —OH groups in the structure of LS compared to LU by the higher and better-highlighted absorption at 3360 cm^{-1}.

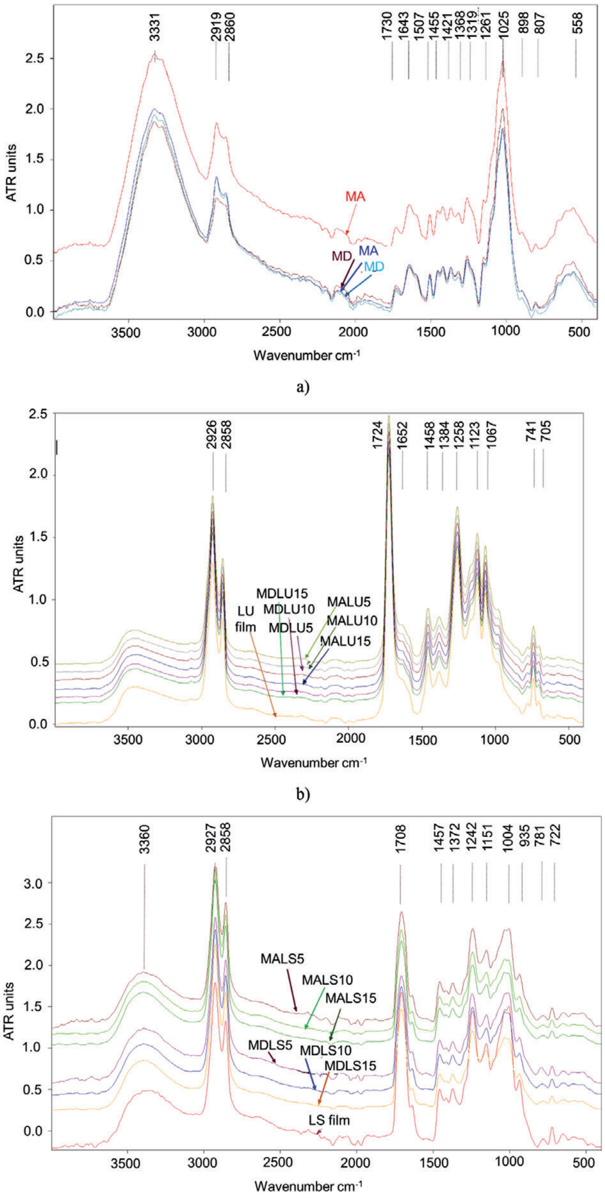
In the fingerprint region (1700–600 cm^{-1}), the FTIR spectra of the uncoated spruce wood are totally different from those of the wood samples coated with the two types of lacquers, regardless of the number of coating layers (5, 10, 15). Though some absorptions assigned to basic chemical bonds and/or structural features of organic chemical compounds, such as methylene or methyl groups, respectively C—O, C—O—C, O—H chemical bonds, with absorptions at 1455–1458 cm^{-1}, respectively 1240–1260 cm^{-1} and



a) b)

Figure 5. Comparisons of surface energy (average values): a) samples finished with oil-based varnish; b) samples finished with alcoholic varnish.

1100–1000 cm^{-1} may be present in all the spectra (**Figure** 6), there are notable differences in terms of the relative intensity of those bands and their actual position (wavenumber). Differences in the spectra of the unfinished wood and those of the varnished samples are clearly visible starting from the absorption at 1460 cm^{-1}, as centralized in Table S2 (Supporting Information). The wood characteristic absorptions in the fingerprint region, namely the lignin-related bands at 1507, 1600, 1319, 1261 cm^{-1} and those due to hollo cellulose (cellulose, hemicelluloses) at 1369, 1155–1151, 1025, and 898 cm^{-1} are clearly visible in the uncoated wood samples, but there were totally obscured in the spectra of the coated samples, for all the three thicknesses of the coating films. It can be concluded, that, for all coated samples, the recorded FTIR spectra represent, exclusively, the chemical components of the coating film.



a)

b)

c)

Figure 6. FTIR spectra of wood samples: a) unvarnished spruce wood; b) LU varnished; c) LS varnished.

3.3. The Effect of Varnishing Systems on the Acoustic Parameters

3.3.1. *Sound Absorption Coefficient*

Figures 7 and 8 show the average values of the acoustic absorption coefficients (SAC) measured on the unvarnished side (index “a”) and the varnished side (“b”) of samples. The anatomical structure of the unvarnished wood, respectively the wood quality class, influence the absorption characteristics. Thus, the absorption coefficient for the MA quality samples had peak values between 0.4 and 0.6 for the alcoholic varnish, LS, and 0.2–0.4 for the oil-based varnish, LU. (Figures 7a and 8a). Also, in comparison with the unvarnished side, for the MA category samples, the varnished side presents a distinct behavior with respect to the finishing system with notable differences, mainly when LS finishing was applied. For the LS samples, the maximum absorption appears in the range of 4–5 kHz, with $\text{SAC}_{\text{max}} = 0.45$ for the MALS10 sample and $\text{SAC}_{\text{max}} = 0.25$ for the MDLS10 sample respectively (Figures 7b and 8b). For MALU samples, the maximum absorption appears in the range of 3–4 kHz, with $\text{SAC}_{\text{max}} = 0.30$ for the MALU15 sample and, respectively, in the range of 2.0–3.5 kHz for MDLU samples, with $\text{SAC}_{\text{max}} = 0.30$–0.40. In the case of wood from the MD quality class, there were no significant differences between the sound absorption coefficients for the two analyzed surfaces (with and without varnish layers). Both LS and LU samples present local modulations of the absorption coefficient ≈2.3, 4.0, and 5.7 kHz frequency values.

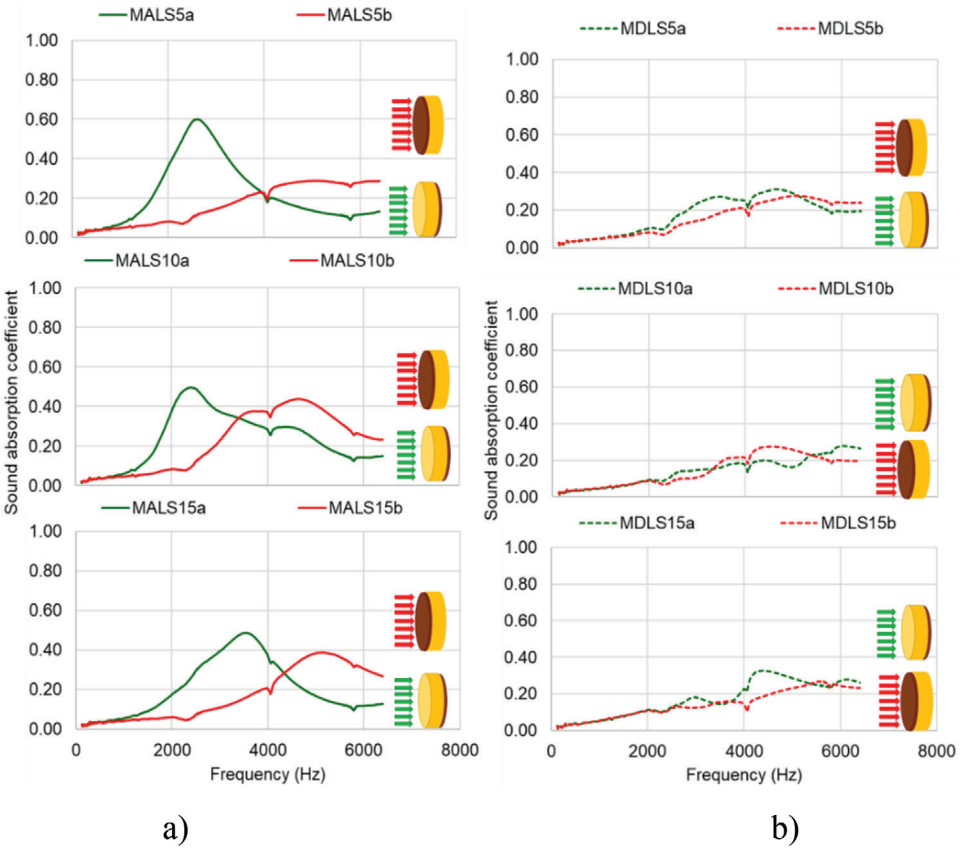


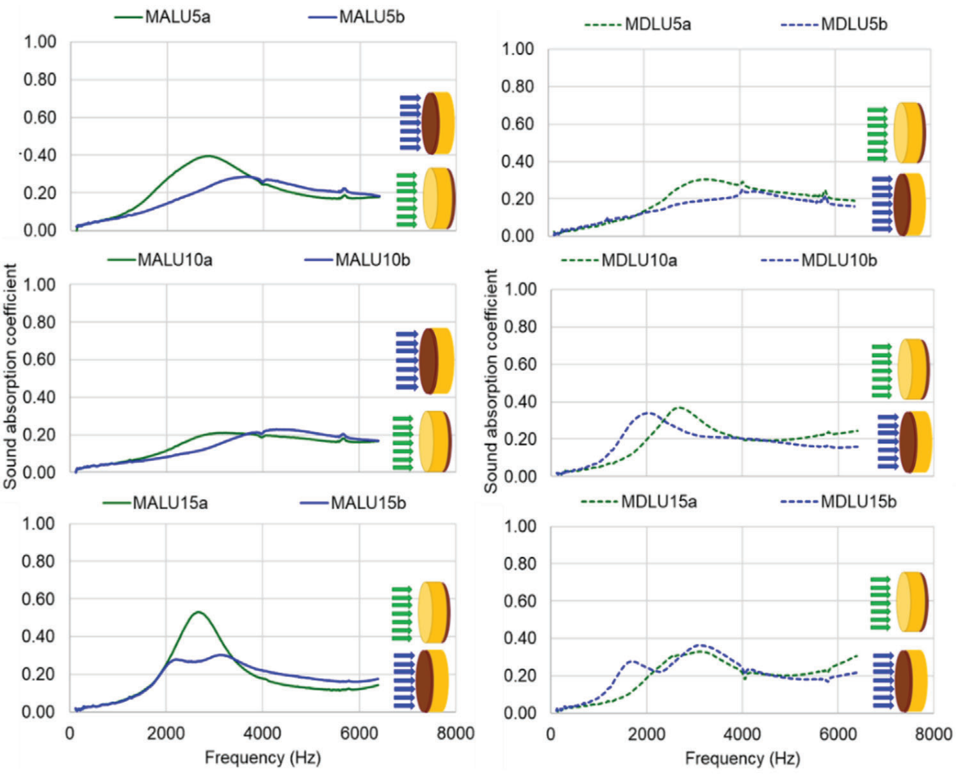
Figure 7. The sound absorption coefficient for LS varnished samples in relation to the sound frequency: a) spruce MA quality class; b) spruce MD quality class.

Correlating the results obtained in the acoustic impedance tube test with those highlighted by refs. [23,52] it can be concluded that the alcoholic varnish, LS, has a more pronounced effect on the acoustic parameters than the oil-based one. A thick layer of varnish (15 layers) does not improve the sound quality, regardless of the type of varnishing system, because it will either lead to a soft, dark sound, in the case of oil-based varnish, or too sharp, harsh sound, in the case of alcohol varnish. The acoustic behavior is related to the material mass, stiffness, and porosity. According to ref. [11] the impedance magnitude is determined by the square root of the material stiffness multiplied by its mass, both factors increasing as a result of the application of the lacquer films. In the samples varnished with alcohol varnish, LS, the mass is lower but the stiffness is increased as a result of the chemical recipe of the varnish, while in the samples varnished with oil-based varnish, the mass is higher, but the stiffness is lower.

Taking into account that the analysis was comparatively performed for varnished versus unvarnished sides of all samples, it was observed that the maximum absorption was recorded between 1–4 kHz for the unvarnished side of the MA quality class samples (with an absolute maximum ≈2 kHz). At the same time, for the varnished sides, the maximum absorption was recorded for frequencies greater than 2 kHz, even beyond 4 kHz, with an absolute maximum ≈2.5 kHz for the MD quality class samples, and ≈4.2 kHz for the MA quality class samples (Figure S6, Supporting Information).

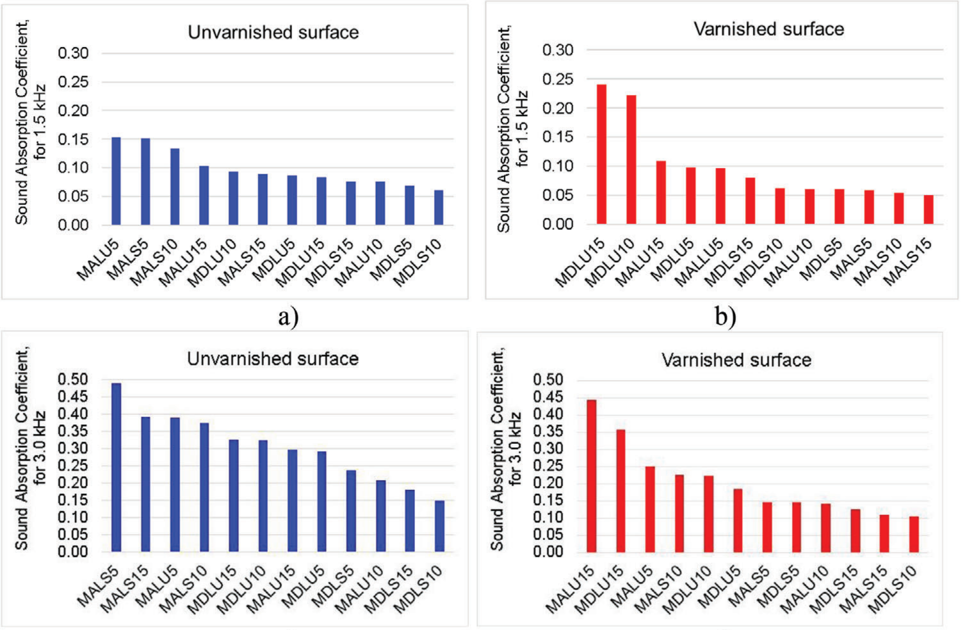
The undesirable qualities of a musical instrument (violins), respectively having a “shrill” or “hoarse” sound, seem to be associated with an excessive high-frequency content or too little low-frequency content and with little damping of some frequencies.[53] The authors have proposed a classification of the sound quality by five adjectives: bright, harsh, nasal, clear, or good sound, corresponding to five frequency intervals namely: 190–380, 380–760, 760–1520, 1520–3040, and 3040–6080 Hz. According to ref. [54] the frequency ranges of 1.300–4.200 kHz should be responsible for the brightness, the effective radiation, and the evenness of the tone, while the range of 4.200–6.400 kHz should be relatively low to create a clear sound (damped sounds). From here it follows that for a warm sound, the damping should be higher in the range of 1500–3040 kHz, an idea also supported by ref. [55]

From **Figure** 9a,b it follows that the samples varnished with oil-based varnish show the highest values of the sound damping coefficient for the frequency of 1.5 kHz. It appears that the oil-based varnish with 5 and 10 layers contributes to obtaining a full sound, while the alcoholic varnish can lead to obtaining some nasal sounds. For the frequency of 3 kHz, Figure 9c,d, it can be seen that again, the oil-based varnish with 15 layers has the highest sound absorption coefficient (0.35–0.45), followed by a group of samples with 5 and 10 layers of LU, with a SAC between



a) b)

Figure 8. The sound absorption coefficient for LU varnished samples in relation to the sound frequency: a) spruce MA quality class; b) spruce MD quality class.



a) b)

c) d)

Figure 9. Sound absorption coefficient for 1.5 kHz, unvarnished, (a) and varnished (b) samples and 3 kHz, unvarnished (c) and varnished (d).

Table 1. The descriptive statistics of the studied properties.

Dependent variable	No. of samples	Minim	Mean	Maxim	Coefficient of variation [%]	Normality[a]
WD [g cm^{-3}]	36	0.370	0.436	0.517	8.99	Yes
AM [g m^{-2}]	36	55.36	138.24	243.49	41.83	No
L^* [%]	198	20.69	62.42	88.39	43.12	No
a^*	198	1.05	11.95	31.79	97.93	No
b^*	198	12.54	24.31	92.74	40.43	No
Ra	72	0.24	2.78	5.34	56.11	No
Rk	72	0.63	8.19	18.31	64.79	No
Rpk	72	0.30	3.72	8.85	48.31	No
Rvk	72	0.63	5.17	11.02	46.93	No
CAW (deg)	90	24.75	70.68	100.60	26.61	No
CAG (deg)	90	31.25	72.42	99.40	25.30	No
SE [mN m^{-1}]	90	16.21	64.80	328.28	80.78	No
PC [mN m^{-1}]	90	0.01	47.99	245.56	97.97	No
DC [mN m^{-1}]	90	0	16.38	94.57	143.02	No
NRC	94	0.03	0.07	0.24	60.03	No

[a] The normality hypothesis cannot be rejected (YES) respectively cannot be accepted (NO)

0.20–0.25. The last category of samples, with the SAC coefficient between 0.15–0.1was specific to samples varnished with alcoholic varnish with 5, 10, and 15 layers.

3.3.2. Sound Reflection Coefficient

The variation of the sound reflection coefficient with the sound frequency for the unvarnished and varnished samples shows a similar graphical trend in relation to the sound frequency (Figure S7, Supporting Information). However, the reflection coefficient recorded greater values in the case of the varnished surfaces (0.75–1.00) in comparison with the unvarnished ones. It is worth mentioning that for the spruce samples of the MA quality class, when the sound absorption coefficient acquires a maximum value ≈2.3 kHz, the sound reflection coefficient indicates the lowest values, down to 0.6, at the same frequency. In addition, it can be noticed that for the MD quality class, there was no difference in terms of sound absorption/reflection coefficients between the varnished and unvarnished sides.

3.3.3. Noise Reduction Coefficient

NRC represents an important indicator of noise absorption for a certain material (established by ASTM C423 Regulation). This parameter was evaluated for both, the varnished and the unvarnished sides of all samples. The results are presented in Table S3 (Supporting Information). The alcohol varnish considerably reduced both the magnitude and the amplitude of the NRC variation. In contrast, the oil-based varnish applied to the soundboard does not change the NRC. The absorption coefficient decreases significantly ($p = 0.0008$) after varnishing with alcohol varnish and decreases insignificantly ($p = 0.08$) when varnishing with oil-based varnish. The number of layers has no contribution to the reduction of the NRC, but it affects the absorption coefficient, the size of which increases with the number of added layers, especially when it reaches 15 layers.

3.4. Statistical Panoramic Overview

The statistical analysis of the studied parameters highlighted the fact that the type of varnishing system and the number of layers are the most influential independent variables, along with the wood density, which varies with the wood quality class (MA or MD). Between the two quality classes of wood, the differences in the physical properties (color, morphology, and surface energy) become insignificant after applying the varnish films. **Table 1** shows the range of variation of the studied properties.

The statistical significance from the ANOVA F test, the Mann–Whitney test, or the Kruskal–Wallis test can be found in **Table 2**. Thus, the samples treated with oil-based varnish have a significantly higher areal mass loading (AM) induced by the varnish system (by 50 g m^{-2}) than the samples treated with alcohol varnish. Obviously, the AM increases directly proportional to the number of layers of varnish applied—on average by 10–14 g m^{-2} for each layer of added varnish. If the quality of wood class does not influence the color of the finish, however, the type of varnishing system has different effects on the color: the oil-based varnish had a lightness 50% higher than the alcoholic varnish, and the redness and yellowness changed substantially with the number of varnish layers (p from Kruskal–Wallis test < 0.001 for Δa^* and Δb^*). Both the degree of redness (a^*) and the degree of yellowness (b^*) increased significantly, more in the oil-based samples compared to the alcohol-based samples. Both the type of varnish and the number of layers substantially changed the samples color.

Thus, with each layer of varnish the lightness decreased by 0.8%, on average. The degree of red increased continuously until the application of 10 layers, after which it remained constant. The degree of yellowness decreased with the number of layers,

Table 2. The results of the statistical tests (p-value), checking the differences between groups.

Dependent variable	Wood quality class	Unvarnished/ varnished	Type of the varnish system	No. of layers
WD [g cm^{-3}]	0.17[a)]	0.59[a)]	0.59[a)]	0.23[a)]
AM [g m^{-2}]	0.68[b)]	–	0.40[b)]	<0.001[c)]
L^* (%)	0.83[b)]	<0.001[b)]	0.33[b)]	<0.001[c)]
a^*	0.20[b)]	<0.001[b)]	<0.001[b)]	<0.001[c)]
b^*	0.10[b)]	<0.001[b)]	<0.001[b)]	<0.001[c)]
Ra	0.48[b)]	<0.001[b)]	<0.001[b)]	0.10[c)]
Rk	0.30[b)]	<0.001[b)]	<0.001[b)]	0.06[c)]
Rpk	0.73[b)]	0.004[b)]	0.002[b)]	0.02[c)]
Rvk	0.51[b)]	<0.001[b)]	<0.001[b)]	0.48[c)]
CAW (deg)	0.56[b)]	<0.001[b)]	<0.001[b)]	0.31[c)]
CAG (deg)	0.97[b)]	<0.001[b)]	<0.001[b)]	0.91[c)]
SE [mN m^{-1}]	0.68[b)]	<0.001[b)]	<0.001[b)]	0.75[c)]
PC [mN m^{-1}]	0.29[b)]	0.004[b)]	0.01[b)]	0.07[c)]
DC [mN m^{-1}]	0.63[b)]	0.46[b)]	<0.001[b)]	0.67[c)]
NRC	0.85[b)]	0.06[b)]	<0.001[b)]	0.31[c)]

[a)] *p* from ANOVA F test; [b)] *p* from Mann–Whitney test; [c)] *p* from Kruskal-Wallis test, (for a 0.05 level of significance)

on average by 1.4 units after each varnish film. The effect of varnishing manifested on all parameters related to the surface morphology (R_a, R_k, R_{pk}, and R_{vk}), the reduction being greater in the case of the oil-based varnish than the alcoholic varnish, but without statistical confirmation (*p* from Kruskal–Wallis test = 0.06, 0.07, 0.10, and 0.13 respectively).

The number of layers applied had a significant influence on R_{pk} (Table 2), whose magnitude decreased with an increase in their number, especially from 5 to 10 layers. In contrast, the number of layers did not significantly affect the values of R_a, R_k, and R_{vk} (Table 2). The varnishing system produced a more pronounced decrease in surface energy in the case of oil-based varnish and almost insignificant in the case of alcoholic varnish. The dispersive component was not significantly affected by the varnish; it increased slightly and insignificantly with the alcohol varnish but decreased slightly with the oil varnish. The number of layers applied had no statistically detectable effect on these physical parameters (Table 2). The sound absorption in samples varnished with the alcohol varnish was significantly reduced compared to the oil-based varnish, an observation highlighted statistically by the size and amplitude of the NRC and the absorption coefficient (SAC) ($p = 0.0008$). The acoustic absorption coefficient increased with the increase in the number of layers, regardless of the type of varnish.

Based on the Factor Analysis, four principal components were selected, the first two, together, explaining 53% of the total variance. The first main component is the roughness parameters, which vary with the varnish system, together with the contact angle and the degree of redness. The second component is described by the lightness and the degree of yellowness and, at the antipode, by the number of varnish layers (**Figure 10**). It is observed that the roughness parameters vary with the dispersive component of the surface energy. The coating system is closely related to the contact angle and NRC. The color components (*L*, *a*, *b*) projected on different axes, suggest a different behavior in relation to the other properties examined.

4. Conclusion

The study investigated the effect of the varnish type and the number of layers on some acoustic properties of the resonance spruce analyzed in combination with the changes produced in some physical, morphological, and chemical wood properties.

The alcohol varnish has darkened the wood color more than the oil-based varnish and the most important color changes occurred up to 10 layers. No important color change and no surface quality improvement occur if more than 10 layers of lacquer are applied. The surface chemical analysis of the varnished samples confirmed a complete varnish surface coverage, the oil-based lacquer proving a superior surface quality in comparison with the alcoholic varnish.

The application of varnish has increased the sound reflection coefficient and it was significantly higher in the case of samples varnished with alcohol varnish compared to those covered with oil-based varnish. The sound absorption coefficient increased with the number of varnish layers and varied with the range of sound frequencies, with the type of varnish, and with the wood quality, all contributing to the acoustic tunability.

For example, for a sound frequency of 1.5 kHz, it appeared that the oil-based varnish with 5 and 10 layers contributes to obtaining a full sound, while the alcoholic varnish can lead to some

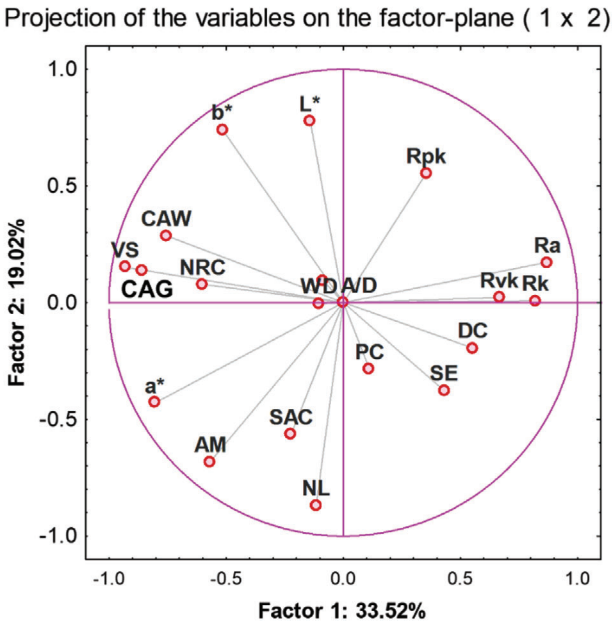


Figure 10. Physical and acoustical parameters in the 1,2 plane of the PCA legend: a^*: color redness, A/D quality class of wood, AM: areal mass loading, b^*: color yellowness, CAE: contact angle in water, CAW: contact angle in ethylene glycol, DC: dispersion component of SE, L^*: color lightness, NL: no of layers, PC: polar component of SE, *Ra*: the arithmetic mean deviation of the roughness profile, *Rk*: the core roughness depth of the roughness profile, *Rpk*: the reduced peak height of the roughness profile, *Rvk*: the reduced valley depth of the roughness profile, SAC: sound absorbtion coefficient, SE: surface energy, VS: varnish system, WD: wood density.

nasal sounds. Applying 15 layers of lacquer does not improve the sound performance, because it will soften the sound when finishing with oil-based varnish and will generate a too sharp sound in case of alcoholic varnish. A maximum number of 10 layers seems to be a reasonable choice.

There are some limitations that keep us away from establishing which type of varnish is more advantageous from the point of view of the acoustic quality of the violins as a result of the fact that the investigations presented in this study were carried out on rectangular plates of constant thickness, and not on violin plates, the studies will continue with the analysis of the sound propagation speeds in the longitudinal and radial direction, as well as with the analysis of the viscous–elastic behavior of the varnished samples.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Author Contributions

S.M.D. performed the conceptualization, formal analysis, and investigation, worked with the software, gathered resources, acquired funds, wrote and prepared the original draft, and administered the project. C.M. performed the conceptualization, supervision, validation, and data curation, and also wrote, reviewed, and edited the final manuscript. G.V.G. developed the methodology, performed validation, and investigation, and gathered resources. G.L. developed the methodology, worked with software, performed formal analysis, investigation, data curation, and supervision, and wrote, reviewed, and edited the final manuscript. T. C. developed the methodology, worked with software, formal analysis, investigation, and data curation, and wrote, reviewed, and edited the final manuscript. G.V. developed the methodology, worked with software, and performed formal analysis, investigation, and data curation. N.S.M. developed the methodology, worked with software, performed validation, and data curation, and wrote, reviewed, and edited the final manuscript. R.I.C. developed the methodology, performed validation and supervision, gathered resources, and wrote, reviewed, and edited the final manuscript. B.V. developed the methodology, performed supervision, and wrote, reviewed, and edited the final manuscript. D.F. developed the methodology, worked with software, performed formal analysis, and wrote, reviewed, and edited the final manuscript. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

chemical changes, color changes, noise reduction coefficient, resonance spruce wood, sound absorption coefficient, surface energy, surface roughness, varnishing system

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