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The Effects of Wood Material Selection on Sound Absorption Performance in Industrial Noise Insulation

Utjecaj odabira drvnog materijala na učinkovitost apsorpcije zvuka industrijske zvučne izolacije

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ABSTRACT • *This study investigates the sound insulation performance of various wood-based materials used to mitigate industrial noise generated by an air compressor in a furniture workshop. LA_{eq} measurements were conducted at eight different locations within the facility, including classrooms, faculty offices, corridors, and near the noise source. Fourteen wood-based scenarios involving solid wood and engineered panels of varying thicknesses were tested. Statistical analysis using the Kruskal–Wallis test revealed significant differences in noise reduction across scenarios ($p < 0.05$), and Dunn’s post-hoc test identified the most effective materials. Hierarchical clustering grouped scenarios into five clusters, enabling systematic comparison of similar acoustic performances. Among all tested materials, 6 mm MDF-laminate demonstrated the highest cumulative noise reduction (17.23 %), outperforming even thicker materials like 18 mm MDF. Notably, certain materials were found to contribute to elevated noise levels in proximity to the compressor, which may be attributed to their inherent acoustic reflectivity and vibrational response characteristics, rather than their capacity for sound absorption. Correlation analysis further revealed that sound reduction effectiveness varied across spatial contexts, with positive correlations decreasing and negative ones increasing after insulation, indicating heterogeneous acoustic effects. In conclusion, thinner MDF-laminate panels offer effective, space-efficient, and economical solutions for industrial noise control. These findings underscore the importance of material selection and spatial analysis in assessing acoustic performance and suggest promising directions for sustainable soundproofing applications in industrial environments.*

KEYWORDS: *acoustic performance; industrial noise; LA_{eq} measurement; sound insulation; wood-based materials*

SAŽETAK • *U ovoj je studiji istraživana učinkovitost zvučne izolacije različitih drvnih materijala koji se upotrebljavaju za ublažavanje industrijske buke što je stvara kompresor zraka u stolarskoj radionici. Mjerenja razine zvuka LA_{eq} provedena su na osam različitih lokacija unutar objekta, uključujući učionice, urede, hodnike i prostor oko izvora buke. Ispitano je 14 varijanti zvučnih izolacija na bazi drva koje obuhvaćaju masivno drvo i drvene plo-*

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če različitih debljina. Statistička analiza primjenom Kruskal-Wallisova testa otkrila je znatne razlike u smanjenju buke među varijantama ($p < 0,05$), a Dunnovim post-hoc testom identificirani su najučinkovitiji materijali za tu namjenu. Hijerarhijskim grupiranjem varijante su svrstane u pet klastera kako bi se omogućila sustavna usporedba sličnih akustičnih svojstava. Od svih ispitnih materijala MDF debljine 6 mm, obložen laminatom, pokazao je su najveće kumulativno smanjenje buke (17,23 %), nadmašivši čak i deblje materijale poput MDF-a debljine 18 mm. Zabilježena je i pojava da određeni materijali pridonose povišenim razinama buke u blizini kompresora, što se može pripisati njihovoj inherentnoj akustičnoj reflektivnosti i obilježjima vibracijskog odziva, a ne njihovoj sposobnosti apsorpcije zvuka. Analiza korelacija dodatno je otkrila da se učinkovitost smanjenja buke razlikuje ovisno o prostornim kontekstima. Utvrđene su pozitivne korelacije koje se smanjuju i negativne korelacije koje se povećavaju nakon izolacije, što upućuje na heterogene akustične učinke. Zaključno, tanje MDF ploče obložene laminatom pridonose djelotvornim, prostorno učinkovitim i ekonomičnim rješenjima za industrijsku kontrolu buke. Ti rezultati naglašavaju važnost odabira materijala i prostorne analize u procjeni akustične učinkovitosti te sugeriraju obećavajuće smjerove za održivu primjenu zvučne izolacije u industrijskim okruženjima.

KLJUČNE RIJEČI: akustična učinkovitost; industrijska buka; LA_{eq} mjerenje; zvučna izolacija; drveni materijali

1 INTRODUCTION

1. UVOD

With the rapid advancement of technology today, the use of machinery in industrial and manufacturing sectors has significantly increased. This trend introduces new risks in terms of occupational health and safety (Çakiroğlu *et al.*, 2025). Noise, in particular, is a major environmental factor that negatively affects both the physical and psychological health of workers. From a health perspective, noise can lead not only to hearing loss but also to various psychological and behavioral disorders such as restlessness, insomnia, irritability, lack of concentration, stress, anxiety, and decreased cognitive performance (Işık *et al.*, 2022; Andrews, 1982; Feldman and Grimes, 1985). Furthermore, noise is known to damage the nervous system, cause communication difficulties, and reduce work productivity. Studies have shown that noise exposure may cause vascular damage through stress mechanisms, and this effect has also been observed in human trials (Eriksson *et al.*, 2018).

In industrial settings, noise primarily originates from machinery used during the production process. In this context, equipment such as compressors – along with pumps, manifolds, ventilation ducts, fans, and cooling systems – generate significant levels of noise (Andrews and Kornas, 1982). Particularly in wood processing facilities, the machines in use can produce disturbing sound levels for both workers and the surrounding environment. In a study conducted by Şahin *et al.* (2017), noise levels of 22 different machines across 56 facilities engaged in furniture and door manufacturing were analyzed. According to the findings, the highest noise level during production was recorded at (95.17 ± 4.50) dBA for the planing machine. Among idle machines, the highest average noise level was identified as (88.09 ± 0.36) dBA for surface finishing machines. Similarly, in another study by Ülker (2018), noise measurements were carried out at 21 different

locations during both active production and downtime in a furniture manufacturing plant using high-tech machines such as CNC equipment.

One of the most effective methods for noise reduction is the use of physical barriers. These barriers enclose noise sources, thereby limiting the propagation of sound energy into the surrounding environment and preventing reverberation. The use of composite materials in noise control emerges as an effective strategy for enhancing sound insulation performance. For instance, in a study conducted by Owoyemi *et al.* (2016), it was demonstrated that sound-absorbing panels significantly reduced noise levels by 4 – 6 dB through high sound energy absorption, resulting in an overall noise reduction of approximately 20 – 30 %. In composite materials, the type of filler used, particle size, surface characteristics, and pore structure significantly affect performance criteria such as mechanical strength, vibration isolation, and noise attenuation (Barrera and Tardiff, 2022; Jong *et al.*, 2014; Masek *et al.*, 2021).

In a study conducted by Mago *et al.* (2022), it was demonstrated that biochar-based composites derived from bamboo waste can be used as effectively as commercial fillers for vibration and noise control. When evaluated in conjunction with green processing technologies, such environmentally sustainable materials can offer significant benefits in production processes, both in terms of environmental impact and occupational health (Gowri *et al.*, 2023; Wang *et al.*, 2023).

Noise-induced hearing loss is one of the most frequently encountered occupational health problems today. In Europe, noise is the leading cause of hearing loss, affecting 34.4 million people in 2019 alone, with an annual economic impact exceeding €185 billion due to productivity loss (Shield, 2022). Various studies on industrial workers have demonstrated a direct relationship between exposure to high noise levels and occupational accidents and injuries (Ali, 2011; Eleftherou, 2002; Palmer *et al.*, 2008). Daily exposure to noise levels above 90 dB increases the risk of hearing loss,

Table 1 Examples of noise exposure levels in occupational and non-occupational environments**Tablica 1.** Primjeri razina izloženosti buci u radnim i neradnim okruženjima

Safe sound level / Sigurna razina zvuka	
Breathing / <i>Disanje</i>	10 dB
Ticking watch / <i>Otkucavanje sata</i>	20 dB
Average room noise / <i>Prosječna buka u sobi</i>	30-50 dB
Normal conversation / background music <i>Normalni razgovor / glazba u pozadini</i>	60 dB
Levels at which long-term exposure can lead to hearing loss <i>Razine pri kojima dugotrajna izloženost buci može rezultirati gubitkom sluha</i>	
Landscaping equipment <i>oprema za uređenje okoliša</i>	75 dB
Vacuum / inside an airplane <i>usisavač / unutrašnjost zrakoplova</i>	75-80 dB
City traffic / noisy restaurant <i>gradski promet / bučni restoran</i>	80-85 dB
Subway / shouted conversation <i>podzemna željeznica / glasni razgovor</i>	85 dB
Pro sports events, car horn at 16 ft <i>profesionalni sportski događaji, automobilska sirena na udaljenosti do 5 m</i>	90-100 dB
Motorcycle, stereo <i>motocikl, stereouređaj</i>	95-100 dB
Chainsaw, leaf blower, snowmobile <i>motorna pila, puhač lišća, motorne saonice</i>	106-115 dB
Levels that may lead to sudden and permanent hearing loss from a single close exposure <i>Razine koje mogu dovesti do iznenadnoga i trajnoga gubitka sluha zbog samo jednog bliskog izlaganja buci</i>	
Music concert, ambulance siren <i>glazbeni koncert, sirena hitne pomoći</i>	120 dB
Jet engine taking off <i>polijetanje mlaznog zrakoplova</i>	130 dB
Gun shot / <i>pucanj</i>	140-160 dB

making the implementation of protective measures essential in such conditions.

According to data obtained from the National Institute for Occupational Safety and Health (NIOSH) and hearing health resources in the United States, Table 1 presents examples of noise exposure levels in both occupational and non-occupational environments (NIOSH, 2024). This table covers a wide spectrum, ranging from safe levels such as breathing sounds to levels capable of causing sudden and permanent hearing loss, such as jet engine noise.

In the scope of this study, the potential of absorbing noise generated by the screw-type air compressor located in the furniture workshop at the Seyitler campus of Artvin Çoruh University was evaluated using different wood-based materials. Specifically, the focus was on the portion of the noise transmitted into the classroom and office spaces of the workshop building. In this context, LA_{eq} measurements were conducted at eight different locations to comparatively assess the noise reduction performance of various wood species and panel materials. The primary objective of this study is to evaluate and compare the sound absorption effectiveness of different wood species and panel materials in mitigating compressor-generated noise in a

furniture workshop, with a focus on minimizing noise transmission to adjacent educational and office spaces.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

In this study, the potential of absorbing noise generated by the air compressor located in the furniture workshop was evaluated using different wood species. The sound insulation performance of various wood types and panel materials was comparatively analyzed. The materials used in the study include 30 mm particleboard with melamine coating, 8 mm MDF Laminate, 18 mm laminated particleboard, 16 mm spruce plywood, 30 mm Solid sapelli Wood Panel, 18 mm solid beech wood beech panel, 10 mm poplar plywood, 18 mm solid pine panel, 12 mm MDF covered with sapelli veneer, 4 mm double-sided MDF Laminate, and 8 mm double-sided MDF Laminate.

The production section of the furniture workshop consists of a single-story space with a high ceiling, while the administrative section is a two-story structure. A top-view layout of the workshop and the noise measurement points are presented in Figure 1. The first floor contains the production area, the air compressor

Table 2 Locations and characteristics of noise measurement points**Tablica 2.** Lokacije i obilježja mjernih mjesta buke

Point No <i>Broj mjernog mjesta</i>	Floor <i>Kat</i>	Point description <i>Opis točke</i>
P1	Second Floor <i>drugi kat</i>	Faculty office <i>fakultetski ured</i>
P2	Second Floor <i>drugi kat</i>	Faculty office <i>fakultetski ured</i>
P3	Second Floor <i>drugi kat</i>	Corridor <i>hodnik</i>
P4	Second Floor <i>drugi kat</i>	Meeting room <i>soba za sastanke</i>
P5	First Floor <i>prvi kat</i>	Classroom <i>učionica</i>
P6	First Floor <i>prvi kat</i>	Laser CNC room <i>soba s CNC laserom</i>
P7	First Floor <i>prvi kat</i>	Compressor room <i>soba s kompresorom</i>
P8	First Floor <i>prvi kat</i>	Above the compressor unit <i>prostor iznad kompresorske jedinice</i>

room, changing rooms, and one classroom. The upper floor includes three faculty offices, a meeting room, a kitchen, and restrooms. Noise measurements were conducted at eight locations (Points P) representing different areas of the workshop. Detailed information regarding the measurement points is provided in Table 2.

2.1 Noise measurements

2.1.1. Mjerenje buke

In accordance with the hierarchy of control measures commonly employed in occupational health and safety – including hazard elimination, substitution, isolation, and the use of personal protective equipment –

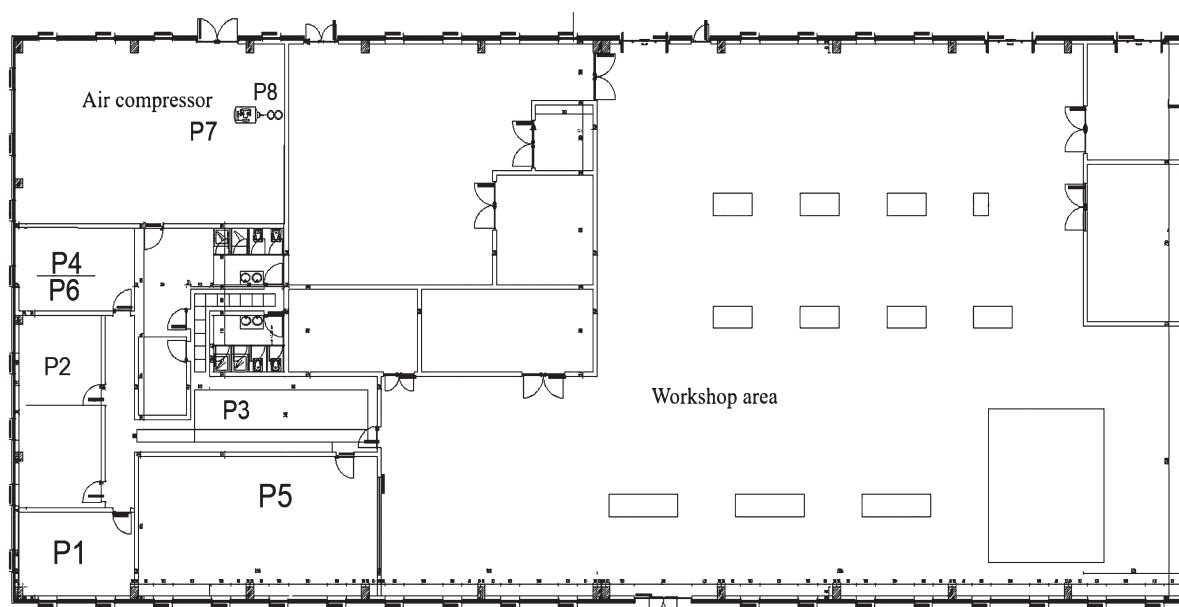
this study applied the isolation method. Wood-based insulation materials were used to create a physical barrier between the noise source (compressor) and the surrounding occupied areas to reduce noise exposure (Technical Guide for Noise Control, n.d.).

The technical specifications of the air compressor, which is the primary source of noise, are as follows: 7.5 bar pressure, 110 m³/min flow rate, 6.4 PSI, and a motor power of 37/50 kW/HP.

The measurements were conducted using the CESVA SC310, a Class 1 integrating-averaging sound level meter in compliance with international standards. The SC310 provides high precision through full conformity with IEC 61672 and EN 61672 standards, and it also meets additional regulatory requirements such as IEC 60651, IEC 60804, EN 60651, and EN 60804. Furthermore, the device complies with American standards ANSI S1.4 and ANSI S1.43. The SC310 is capable of performing real-time one-third octave and full octave band spectrum analyses using Class 1 filters in accordance with IEC 61260, EN 61260, and ANSI S1.11 standards (CESVA, 2024).

In this study, noise measurements were carried out in accordance with the “Task-Based Measurement” method defined in the TS EN ISO 9612:2009 standard. This method involves analyzing noise levels in the work environment based on specific tasks or scenarios, with separate measurements performed for each scenario (TS EN ISO 9612, 2009). Figure 2A presents the noise absorbance method, while Figure 2B illustrates the measurement procedure.

During the measurement process, the noise reduction performance of enclosing the identified compressor noise source with different wood materials was evaluated. In this context, various scenarios were cre-

**Figure 1** Workshop floor plan and measurement points**Slika 1.** Tlocrt radionice i mjerna mjesta

ated by placing different types of solid wood and engineered wood panels over the compressor, and sound absorption was analyzed for each scenario (Figure 2A). Noise measurements were performed at eight distinct locations, with data collected over a 5-minute period at each point. This method provides a scientific approach for comparatively assessing the noise reduction effects of different materials and for optimizing noise levels in the working environment.

In this study, A-weighted Equivalent Continuous Sound Level (LA_{eq}) values were measured and analyzed for each scenario. LA_{eq} is an acoustic parameter that represents the energy-based average of fluctuating sound levels over a specific time period and is commonly used to assess environmental noise exposure. This value, calculated with A-weighting, takes into account the human ear varying sensitivity to different sound frequencies (Brambilla *et al.*, 2023; Barbaresco *et al.*, 2019). Mathematically, it is expressed as follows:

$$LA_{eq} = 10 \log \left(\frac{1}{N} \sum_{i=1}^n n_i 10^{\frac{Lp_i}{10}} \right) \quad (1)$$

In this expression, $Lp(t)$ represents the sound pressure level at time t (in dB); n_i denotes the number of sound level measurements taken within a specific time interval; and N indicates the total number of samples.

In the study, different scenarios were analyzed to evaluate their effects on noise levels. Each scenario was structured based on specific variables and examined systematically. The details of these scenarios are summarized in Table 3.

Table 3 Experimental scenarios investigating the effects of different wood materials on noise absorption

Tablica 3. Eksperimentalne varijante kojima se istražuju učinci različitih drvnih materijala na apsorpciju buke

Scenario Varijanta	Description / Opis
S1	Quiet environment <i>tiha okolina</i>
S2	Compressor only (No barrier) <i>samo kompresor (bez pregrade)</i>
S3	Standard layout <i>standardni raspored</i>
S4	30 mm particleboard <i>iverica debljine 30 mm</i>
S5	18 mm Double-sided MDF lam <i>MDF od 18 mm obostrano obložen laminatom</i>
S6	18 mm Double-sided particleboard <i>iverica od 18 mm obostrano obložena melaminom</i>
S7	16 mm Spruce plywood <i>furnirska ploča debljine 16 mm od smrekovine</i>
S8	30 mm Solid sapelli wood panel <i>ploča od drva sapeli debljine 30 mm</i>
S9	18 mm Solid beech wood panel <i>ploča od bukovine debljine 18 mm</i>
S10	10 mm Poplar plywood <i>furnirska ploča od topolovine debljine 10 mm</i>
S11	18 mm Solid yellow pine <i>ploča od borovine debljine 18 mm</i>
S12	12 mm MDF with solid sapelli veneer <i>MDF od 12 mm obložen furnirom drva sapeli</i>
S13	4 mm Double-sided MDF laminate <i>MDF od 4 mm obostrano obložen laminatom</i>
S14	8 mm Double-sided MDF laminate <i>MDF od 8 mm obostrano obložen laminatom</i>



a)



b)

Figure 2 A) modular insulation panel mounted on the compressor, (B) noise measurement setup at point P2
Slika 2. A) Modularna izolacijska ploča montirana na kompresor, B) postav za mjerenje buke u točki P2

2.2 Wood materials

2.2. Drvni materijali

Figure 3 illustrates the variety of solid wood species and engineered wood-based panel materials used as insulation components in the experimental scenarios of this study. These materials were selected to represent a range of structural and acoustic properties, including differences in density, thickness, and surface characteristics, which are critical factors influencing sound absorption performance. The figure provides a visual reference for the tested materials, including laminated particleboards, MDF laminates, plywood types, and various solid wood panels.

2.3 Statistical evaluations

2.3. Statističke analize

In this study, the effects of different wood species and experimental scenarios on noise reduction were evaluated using statistical methods based on experi-

mental data. During the analysis process, non-parametric tests were preferred to ensure reliable results in cases where the data did not exhibit a normal distribution.

To determine differences in noise reduction, the Kruskal-Wallis test was applied to examine the relationship between different wood species and experimental scenarios. The Kruskal-Wallis test is a non-parametric method used to evaluate median differences among independent groups, particularly effective for multi-group comparisons when the assumption of normal distribution is not satisfied (Ostertagová *et al.*, 2014). This test assesses whether the group medians are equal, and if the p -value is below the significance threshold of 0.05, it is accepted that a statistically significant difference exists between the groups. The hypotheses used for the Kruskal-Wallis test are as follows:

H_0 (Null Hypothesis): There is no statistically significant difference in noise reduction performance among the wood species.

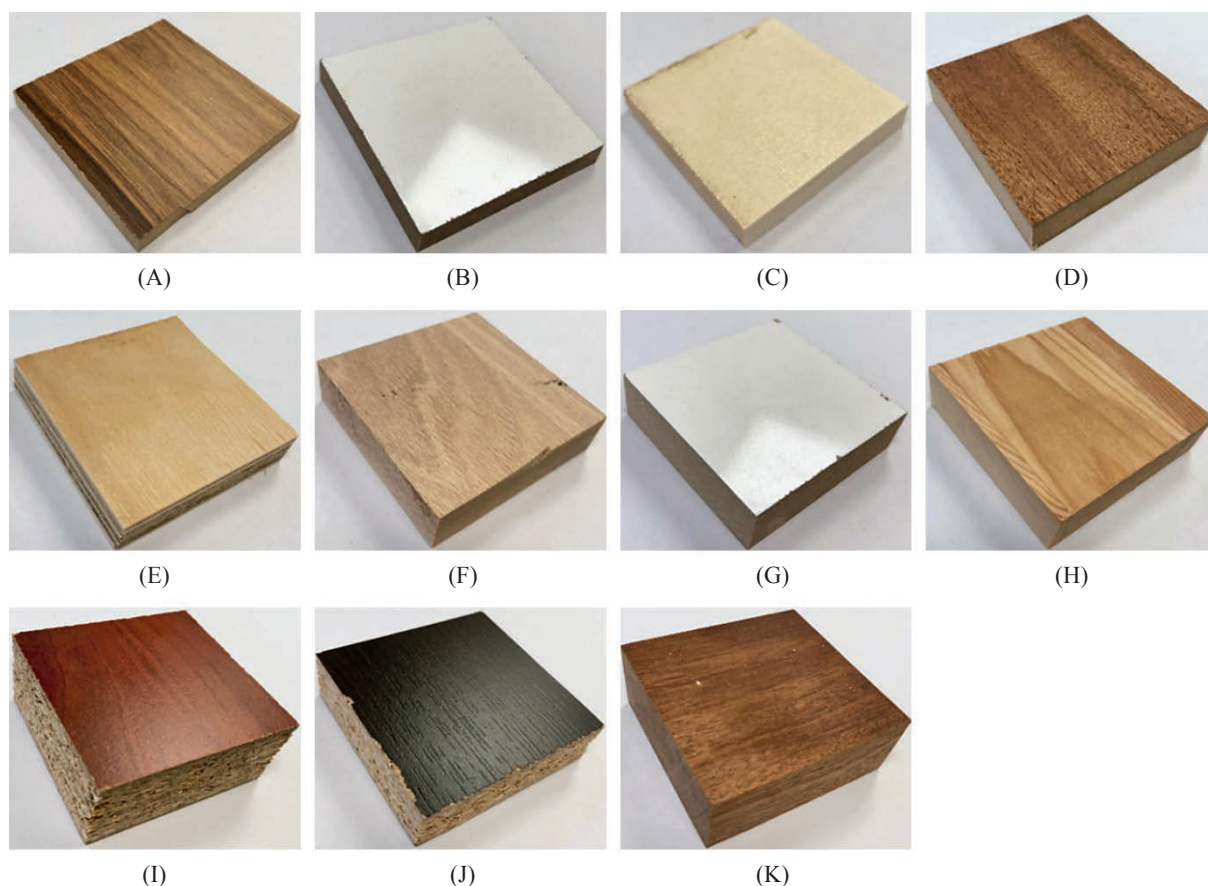


Figure 3 Types of solid wood and wood-based panel materials used in the study: (A) 6 mm MDF laminate, (B) 8 mm MDF laminate, (C) 10 mm poplar plywood, (D) 12 mm MDF covered with Sapelli veneer, (E) 16 mm spruce plywood, (F) 18 mm solid beech wood panel, (G) 18 mm double-sided MDF laminate, (H) 18 mm solid yellow pine wood panel, (I) 30 mm melamine-coated particleboard, (J) 18 mm double-sided melamine-coated particleboard, (K) 30 mm Solid sapelli wood panel

Slika 3. Vrste masivnog drva i drvnih ploča ispitivanih u studiji: A) MDF od 6 mm obložen laminatom; B) MDF od 8 mm obložen laminatom; C) furnirska ploča od topolovine debljine 10 mm; D) MDF od 12 mm obložen furnirom drva sapeli; E) furnirska ploča od smrekovine debljine 16 mm; F) 18 mm debela ploča od bukovine; G) MDF od 18 mm obostrano obložen laminatom; H) ploča od borovine debljine 18 mm; I) iverica od 30 mm obložena melaminom; J) iverica od 18 mm obostrano obložena melaminom; K) ploča od drva sapeli debljine 30 mm

H_1 (Alternative Hypothesis): At least one wood species exhibits a noise reduction performance that is significantly different from the others.

If the Kruskal-Wallis test revealed a statistically significant difference among the groups, a Dunn post-hoc test was applied to determine which specific group comparisons accounted for this difference (Al-Shamari, 2021; Kamrath, 2023). The Dunn test is a complementary post-hoc analysis to the Kruskal-Wallis test and enables pairwise comparisons between groups to identify statistically significant differences.

The hierarchical clustering method was employed to identify patterns within the dataset and to form groupings based on different experimental scenarios. Cluster analysis grouped observations with similar characteristics and resulted in five distinct clusters, thereby revealing a meaningful structure among the scenarios. Using these clusters, the effects of different wood species on noise reduction were systematically evaluated. The data within each cluster were analyzed to compare the sound insulation performance of the associated wood types and to examine the statistical differences in noise reduction across the scenarios.

In the hierarchical clustering process, Ward's method was employed, with Euclidean distance selected as the distance metric. Euclidean distance is used to calculate the straight-line distance between data points in a two-dimensional or multi-dimensional space and is expressed by the following formula (Murtagh and Legendre, 2014):

$$d(i, j) = \sqrt{\sum_{k=1}^p (x_{ik} - x_{jk})^2} \quad (2)$$

Where, $d(i, j)$ denotes the Euclidean distance between two data points i and j ; x_{ik} and x_{jk} represent the coordinates of points i and j in the k th dimension, respectively; and p indicates the total number of dimensions in the dataset.

Hierarchical clustering is a classification method that organizes data into nested hierarchical structures based on similarity or distance metrics between data points. It aims to construct a hierarchy by iteratively grouping the most similar data points or clusters (Murtagh & Contreras, 2017). The Ward's method used in this study is an agglomerative hierarchical clustering technique based on the minimum variance or error sum of squares (ESS) criterion. At each step, this method merges the clusters that result in the smallest increase in within-cluster variance, thereby aiming to maintain internal homogeneity within the resulting groups. The ESS is calculated using the following formula (Murtagh and Legendre, 2014):

$$ESS = \sum_{i \in C} \|x_i - \underline{x}_c\|^2 \quad (3)$$

Where x_i denotes each data point within the cluster, \underline{x}_c represents the centroid (mean) of the cluster, and $\|x_i - \underline{x}_c\|^2$ indicates the squared Euclidean distance between each point and the cluster centroid. This formula serves as the core of Ward's method and aims to minimize the within-cluster error sum of squares.

Ward's method uses a formulation that takes into account both the distances between cluster centroids and the sizes of the clusters. Within the Lance-Williams update formula, specific coefficients are assigned for Ward's method to ensure optimal performance of the clustering process (Ran *et al.*, 2023). During the formation of new clusters, Ward's method applies the following Lance-Williams update formula (Murtagh and Legendre, 2014):

$$d(i \cup j, k) = \alpha_i d(i, k) + \alpha_j d(j, k) + \beta d(i, j) + \gamma |d(i, k) - d(j, k)| \quad (4)$$

In this formula, the coefficients used for Ward's method are defined as follows (Murtagh and Legendre, 2014):

$$\alpha_i = \frac{|C_i| + |C_k|}{|C_i| + |C_j| + |C_k|}, \alpha_j = \frac{|C_j| + |C_k|}{|C_i| + |C_j| + |C_k|} \quad (5)$$

$$\beta = \frac{-|C_k|}{|C_i| + |C_j| + |C_k|}, \gamma = 0$$

Where, $d(i, j)$ denotes the distance between clusters i and j ; C_i , C_j , and C_k represent the sizes (i.e., number of elements) of the respective clusters; and $d(i \cup j, k)$ indicates the updated distance between the newly merged cluster i and cluster k .

This method is considered a reliable clustering technique, particularly because it is designed to minimize differences between groups, ensuring internal homogeneity within clusters and optimizing inter-cluster distances. Finally, Ward's Minimum Variance Criterion is calculated using the following formula (Murtagh and Legendre, 2014):

$$D(C_i, C_j) = \frac{|C_i| |C_j|}{|C_i| + |C_j|} \|\underline{x}_{c_i} - \underline{x}_{c_j}\|^2 \quad (6)$$

Where, $D(C_i, C_j)$ represents the total increase in within-cluster error resulting from the merging of clusters; \underline{x}_{c_i} and \underline{x}_{c_j} denote the centroids of the respective clusters; $|C_i|$ and $|C_j|$ indicate the number of elements in each cluster; and $\|\underline{x}_{c_i} - \underline{x}_{c_j}\|^2$ represents the squared Euclidean distance between the cluster centroids.

As a result, the groups identified through hierarchical clustering enabled a more detailed evaluation of the differences in noise reduction across various wood species and experimental scenarios. All statistical procedures were performed using MATLAB R2024a.

3 RESULTS

3. REZULTATI

This study investigates the effects of different wood species on compressor-generated noise through A-weighted equivalent continuous sound level (LA_{eq}) measurements conducted at eight distinct measurement points (P1 – P8).

In addition, a 1/3 octave band analysis was performed to identify the dominant frequency characteristics of the noise source. According to the results, the compressor generated a dominant frequency of approximately 125 Hz under the reference condition without any wood-based insulation material applied.

In this study, the Kruskal-Wallis test was initially conducted to evaluate whether there were statistically significant differences in noise reduction levels among the different scenarios (i.e., wood species). Upon identifying significant differences, the Dunn post-hoc test was applied to determine which specific pairs of scenarios contributed to these differences.

Accordingly, hierarchical clustering analysis was performed to group the statistically distinct scenarios. Clustering conducted for each measurement point revealed the internal structure of the data based on observed patterns and allowed for the joint evaluation of scenarios exhibiting similar acoustic performance.

During the clustering process, Ward's method (minimum variance criterion) was used, and Euclidean distance was selected as the distance metric. In this way, the cluster structures and relationships of the statistically significant scenarios were systematically evaluated, and the contributions of different wood species to sound insulation were analyzed both statistically and structurally.

This study investigates the effects of different wood species on compressor-generated noise through A-weighted equivalent continuous sound level (LA_{eq}) measurements conducted at eight distinct measurement points (P1–P8). Kruskal-Wallis tests applied to the measurement data indicated statistically significant differences among the scenarios at all points ($p < 0.05$). The observed dBA values across all scenarios and locations are presented graphically in Figure 4.

Following the identification of significance, Dunn post-hoc tests were conducted to determine which wood species were more effective in absorbing noise. The percentage changes in dB levels based on scenarios at each of the eight measurement points are shown in Figure 4 (LA_{eq}).

In the study, the effect of different wood species on average noise levels was evaluated using the LA_{eq} parameter across eight distinct measurement points (P1–P8). The findings indicate that statistically significant differences were observed among the scenarios at

all measurement points. When the scenarios associated with different wood types were compared to the reference scenario (S3) at each location, significant reductions in noise levels were generally recorded.

At measurement point P1, Scenario S14 achieved the highest noise reduction with a rate of -25.99% , while the lowest reduction was observed in Scenario S6 at -10.02% . This finding highlights the notable differences in sound insulation performance among the wood species. A similar trend was observed at point P2, where Scenarios S11, S4, and S13 exhibited prominent reductions in LA_{eq} levels, with -13.06% , -12.77% , and -11.92% , respectively. The measurements at point P3 showed that all scenarios resulted in lower LA_{eq} values compared to the reference scenario (S3); here, the most substantial improvement was again observed in Scenario S14, with a reduction of -20.03% .

At measurement point P4, Scenarios S13, S11, and S14 demonstrated notable average noise reductions of -18.04% , -17.34% , and -15.68% , respectively. At point P5, all scenarios showed statistically significant reductions in comparison to the reference condition, with Scenario S13 yielding the best result at -25.09% . At point P6, Scenarios S13 and S14 exhibited effective sound insulation performance, whereas Scenario S7 presented a negative outcome with a 9.01% increase in noise level. This finding indicates that not all scenarios performed equally across all measurement points.

At measurement point P7, Scenario S14 demonstrated a positive effect with a -13.89% reduction in LA_{eq} . Finally, the data obtained at point P8 indicated that Scenarios S4 (-35.21%) and S5 (-29.54%) achieved the highest reductions in LA_{eq} levels. These findings reveal that the mentioned scenarios were particularly effective in mitigating continuous noise sources.

In the overall evaluation, Scenarios S13 and S14 emerged as the most effective solutions for controlling average sound levels, providing high levels of noise reduction across the majority of measurement points. It can be concluded that the botanical structures of these materials optimized the absorption of compressor-generated noise and should be considered among the preferred configurations in terms of acoustic performance.

The statistical analyses presented above revealed that different wood species have significant effects on noise reduction. The overall differences identified through the Kruskal–Wallis test were further examined using the Dunn post-hoc test, which specified which pairs of scenarios differed significantly.

Based on these findings, hierarchical clustering analysis was conducted to better identify patterns in sound insulation performance across the scenarios. All measurements were grouped into five clusters using

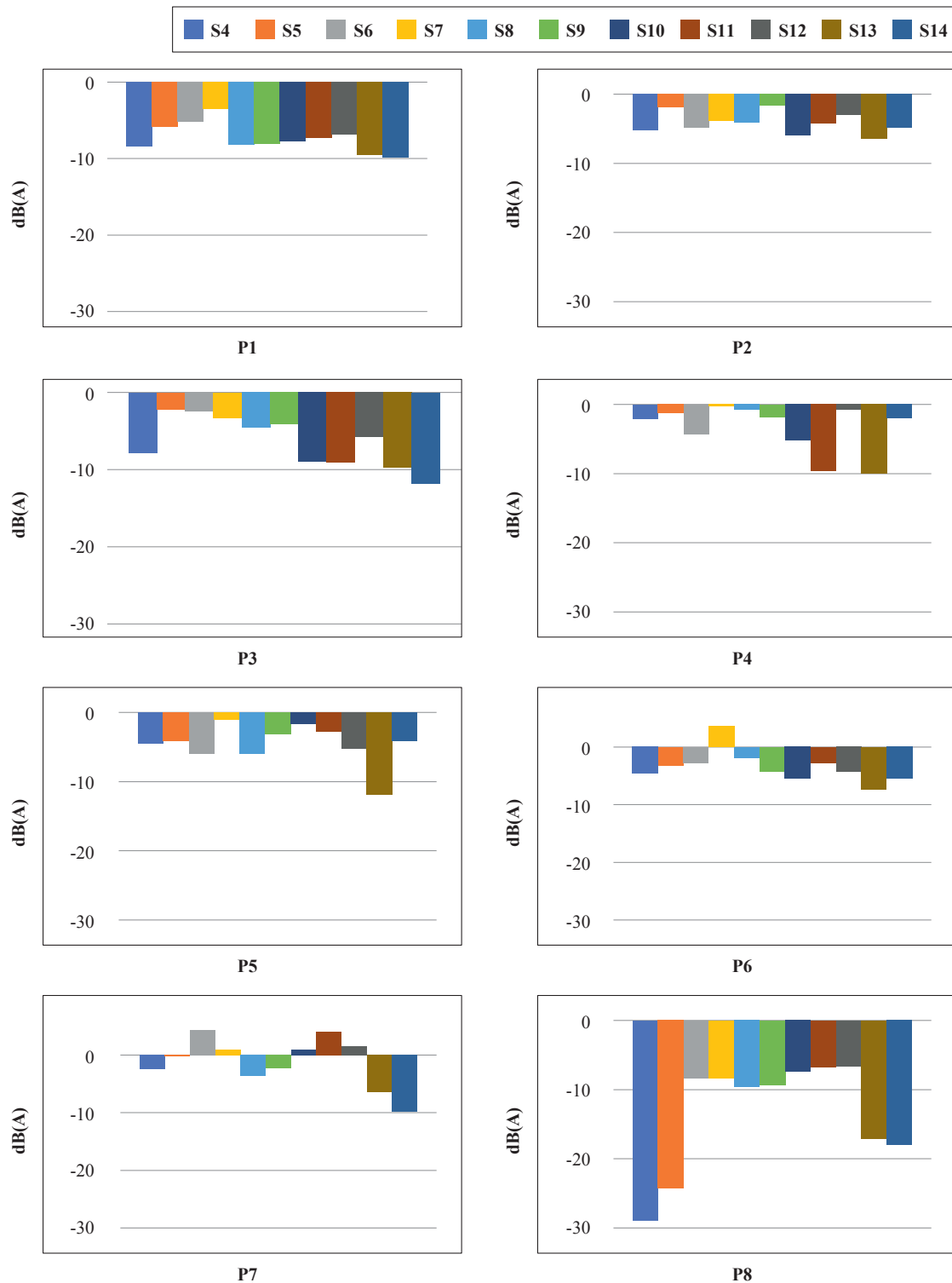


Figure 4 Percentage changes in LA_{eq} values (in dBA) observed for each scenario across all measurement points
Slika 4. Postotne promjene vrijednosti LA_{eq} (u dBA) uočene za svaku varijantu na svim mjernim mjestima

Ward's method and Euclidean distance, allowing for a systematic comparison of the wood species.

The LA_{eq} analyses conducted for each measurement point revealed the comparative sound insulation performance of the wood materials classified using the hierarchical clustering method. At point P1, the scenarios with the lowest average noise levels – S14 (38.8 dBA), S13 (42.9 dBA), and S4 (42.2 dBA) – demon-

strated the best sound insulation. Similarly, at point P2, materials such as S4 (47.7 dBA), S10 (48.8 dBA), and S14 (49.8 dBA) stood out in terms of acoustic performance. At point P3, S14 (47.6 dBA) and S13 (49.7 dBA) were the most prominent, while S5 (57.3 dBA) showed relatively weak insulation performance. At measurement point P4, Scenarios S13 (45.2 dBA), S14 (46.5 dBA), and S11 (45.6 dBA) demonstrated high performance,

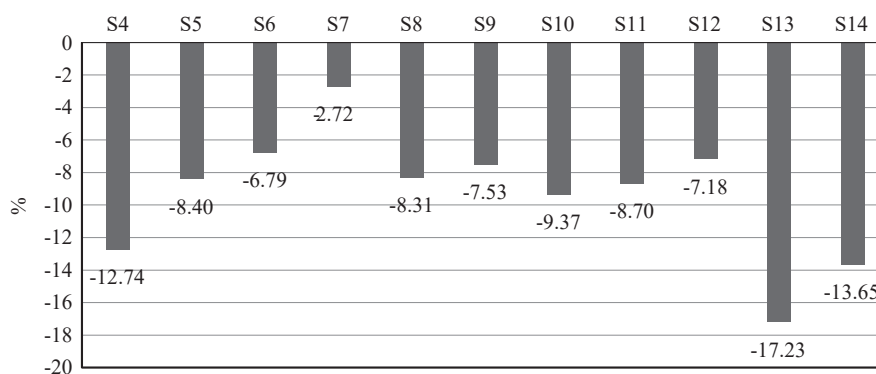


Figure 5 Cumulative representation of noise level changes across all measurement points (%)

Slika 5. Kumulativni prikaz promjena razine buke na svim mjernim mjestima (%)

Table 4 Material- and point-based mean distribution of LA_{eq} values based on hierarchical clustering results

Tablica 4. Srednja distribucija LA_{eq} vrijednosti za materijale i mjerna mjesta na temelju rezultata hijerarhijskog grupiranja

Scenario / Varijanta	Mean LA_{eq} , dBA
	Srednja LA_{eq} vrijednost, dBA
S13	45
S14	48.5
S11	49.5
S6	50
S8	52.5
S4	58
S7	60
S3	60
S5	61
S12	63
S9	65
S10	67

while S7 (54.9 dBA) and S12 (54.4 dBA) exhibited lower insulation efficiency. At P5, the lowest values were observed in Scenarios S13 (35.5 dBA) and S14 (40.8 dBA). At point P6, S13 (33.1 dBA), S14 (34.9 dBA), and S4 (35.8 dBA) yielded the best results, whereas S7 (44.0 dBA) showed the weakest performance.

A similar trend was observed at points P7 and P8, where S13 and S14 consistently recorded the lowest dB levels, standing out as the most effective materials in terms of sound insulation. To more systematically assess the noise reduction performance of different wood species, hierarchical clustering analyses were conducted for each measurement point. As a result, the data were grouped into five distinct clusters. This clustering approach enabled materials with similar acoustic characteristics to be grouped together, facilitating a more homogeneous and comparable evaluation process.

Considering the changes in noise levels across all measurement points, the material that achieved the greatest cumulative reduction was the 6 mm MDF-lam panel, with a total decrease of 78.6 dBA, as shown in Figure 5.

Table 4 presents the cluster-based LA_{eq} means for each material type across all measurement points. This table provides a comprehensive evaluation of sound insulation performance by accounting for both material diversity and measurement point variability.

4 DISCUSSION

4. RASPRAVA

As a result of the conducted study, noise measurements were performed for all scenarios at eight points within the facility. The wooden panels used for insulation led to varying degrees of noise reduction at all points except for the seventh measurement point. At point 7 – located closest to the noise source and at the same elevation – some materials resulted in an increase in noise levels.

The materials that caused an increase in noise at this point were identified as follows: 18 mm particleboard (4.4 dBA), 18 mm Scots pine solid panel (4.0 dBA), 12 mm MDF with sapelli veneer (1.6 dBA), 16 mm spruce plywood (1.0 dBA), and 12 mm poplar plywood (0.9 dBA).

In contrast, the materials that reduced the noise level at point 7 were: 8 mm MDF (9.8 dBA), 6 mm MDF (6.5 dBA), 30 mm sapelli solid panel (3.6 dBA), and 30 mm particleboard (2.4 dBA).

As shown in Figure 4, the noise level at this location increased due to sound reflection by certain materials, while it decreased through sound absorption by others. It can be concluded that the materials contributing to noise increase acted as sound reflectors, with the most reflective being the 18 mm particleboard. Specifically at point 7, the 18 mm particleboard and the 18 mm Scots pine solid panel appeared to reflect sound waves, thereby increasing the measured noise levels. In contrast, the 30 mm particleboard reduced the noise level, presumably due to greater sound absorption.

Additionally, while the 18 mm beech panel contributed to noise reduction at this location, the 18 mm Scots pine panel increased the noise level.

The eighth measurement point is located 50 cm above the insulation panels, making it the closest point to the noise source in vertical proximity. Based on the noise level measurements at this location, the materials providing the highest levels of noise absorption were identified as follows: 30 mm particleboard (28.9 dBA), 18 mm MDF (24.3 dBA), 8 mm MDF (18.0 dBA), and 6 mm MDF (17.1 dBA).

These results indicate that while material thickness generally has a positive impact on sound insulation, even thin MDF-laminate panels offer sufficient acoustic performance.

Accordingly, 6 mm and 8 mm MDF-lam panels are recommended for use as noise-absorbing panels among various solid wood and wood-based alternatives, due to their smaller spatial footprint, lighter weight, and lower cost.

In noise control applications, it is generally expected that materials used for sound insulation reduce noise levels not only at specific points, but throughout the entire workspace. In this context, the 6 mm MDF-lam panel outperformed all other materials used in the study in terms of cumulative noise absorption.

The exceptional acoustic performance of the 6 mm MDF-lam can be attributed to the structural properties of MDF itself. In the literature, Ünsal *et al.* (2003) identify MDF as the most efficient sound-insulating wood-based panel, due to its homogeneous fiber structure and high density. Similarly, Karademir and Özdemir (2005) state that the tight bonding of fibers within MDF facilitates the dispersion and attenuation of sound waves within the panel.

Based on the results of this study, it would be expected that increasing the thickness of MDF-lam panels would enhance sound absorption. However, this trend was not observed in the case of the 18 mm MDF-lam panel. Cumulatively across all measurement points, the 6 mm MDF-lam panel achieved a noise reduction rate of 17.23 %, whereas the 18 mm MDF-lam panel reached only 8.4 %.

Sound absorption occurs through the transformation of sound energy into other forms of energy. Materials such as MDF, which exhibit homogeneous fiber orientation, absorb part of the incoming sound waves through microscopic vibrations. These vibrations induce internal friction and damping within the material, leading to a loss of acoustic energy (Ünsal *et al.*, 2003).

From this perspective, it can be inferred that the 6 mm MDF-lam panel exhibited more intense vibration than the 18 mm panel, thereby achieving greater sound wave attenuation.

In the furniture workshop that served as the study area, it was determined that changes in noise levels within faculty offices, classrooms, corridors, and laboratory spaces were generally linearly related to the distance from the noise source. However, measurements

taken in the classroom and corridor did not show a proportional decrease relative to distance. According to the literature, the difference in sound levels between the source and a measurement point in an enclosed space is influenced not only by physical distance but also by the acoustic characteristics of the intervening structural elements—such as wall materials, ceiling height, furniture density, glass surfaces, and corridor geometry (Egan, 2007; Beranek and Vér, 1992; Long, 2014; ISO 3382-1, 2009).

Although similar levels of noise reduction would be expected between two measurement points located close to each other in terms of straight-line distance, discrepancies were observed at certain points (specifically points 3 and 5). Despite being only 15 meters away from the noise source, point 3 exhibited a smaller reduction in noise level compared to point 5, which was located 17 meters away. As noted in the literature, this inconsistency may be attributed to the ceiling height of the classroom and the fact that it shares a common ceiling with the noise source area.

Regarding the sound insulation performance of particleboard (suntalam), two panels with thicknesses of 30 mm and 18 mm were used. Similar noise reduction values were recorded across most measurement points, except for points 7 and 8. At these two points, the 30 mm particleboard demonstrated better noise attenuation performance than the 18 mm panel. This suggests that the effectiveness of increased thickness in particleboard becomes less distinguishable at measurement points farther from the noise source, where the sound attenuation performance of different thicknesses tends to converge. When examining the performance of MDF-lam panels, an inverse relationship was observed between panel thickness and noise attenuation at locations farther from the noise source. Specifically, the thinner panels – 6 mm and 8 mm – showed greater noise reduction compared to the 18 mm panel, indicating that thinner MDF-lam materials can be more acoustically effective in such contexts.

The correlation analysis conducted to examine the relationships among the measurement points revealed strong positive associations between several locations ($\rho > 0.7$). In particular, a high correlation was observed between points P1 and P5 ($\rho = 0.875$), as well as between P1 and P8 ($\rho = 0.764$). Similarly, strong correlations were found between P3 and P4 ($\rho = 0.864$) and P3 and P8 ($\rho = 0.911$). Additional significant associations were also reported between P4 and P8 ($\rho = 0.904$) and P5 and P8 ($\rho = 0.902$). These high correlation coefficients indicate that the corresponding measurement points exhibit similar sequential trends in noise level changes. In other words, when the noise level increases at one point, a corresponding increase is also likely to occur at the other correlated points.

As a result of the correlation analysis, strong negative correlations were identified between P2 and several other measurement points ($\rho < -0.7$). In particular, significant inverse relationships were observed between P2 and P3 ($\rho = -0.813$), P2 and P4 ($\rho = -0.853$), and P2 and P8 ($\rho = -0.772$), indicating an opposing trend in noise level changes among these points. These findings suggest that as the noise level increases at point P2, there may be a corresponding decrease in noise levels at points P3, P4, and P8. Following the implementation of insulation, a general pattern emerged in which positive correlations diminished while negative correlations became more pronounced. This indicates that the insulation application generated more heterogeneous effects across the measurement points, meaning that it influenced different areas to varying degrees. In other words, the insulation system did not produce a uniform impact throughout the space, resulting in certain zones exhibiting greater or lesser acoustic effectiveness.

5 CONCLUSIONS

5. ZAKLJUČAK

This study evaluated the sound insulation performance of various wood-based materials used to reduce industrial noise generated by an air compressor in a furniture workshop. LA_{eq} measurements were conducted at eight different points throughout the facility, and 14 different material scenarios were assessed using statistical analyses, including the Kruskal–Wallis and Dunn post-hoc tests. Hierarchical clustering further enabled systematic grouping of materials based on their acoustic behavior.

The findings revealed statistically significant differences in noise reduction performance among the tested materials. Notably, the 6 mm MDF-lam panel demonstrated the greatest cumulative noise reduction (17.23 %, corresponding to 78.6 dBA), surpassing even thicker panels such as the 18 mm MDF-lam. Among the tested materials, the 6 mm MDF-lam panel yielded the most favorable results in terms of noise reduction, which may be influenced by its structural properties; however, further investigation is required to confirm the underlying mechanisms.

Additionally, it was observed that certain materials – such as 18 mm particleboard and solid Scots pine panels – led to an increase in noise levels at measurement points closest to the compressor, likely due to sound wave reflection and lack of absorption. In contrast, materials like 30 mm particleboard showed better performance at these points, indicating the relevance of both material thickness and structural properties in localized noise control.

Overall, this study highlights the importance of material selection in industrial noise insulation, especially in environments where spatial constraints and cost-efficiency are significant considerations. The results support the use of thinner, high-density MDF-lam panels as viable alternatives for reducing compressor-related noise in workshop settings. Future research will incorporate frequency and vibration analysis to further investigate the acoustic behavior of wood-based materials under different installation conditions.

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