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Article

Noise Isolation System for Indoor Industrial Ventilation

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Abstract: The prevalence of hearing loss among workers in Ecuador is concerning, with up to 40% affected. One of the root causes is the lack of insulation in sources of noise generation. This study presents a practical solution to reduce noise contamination in indoor industrial facilities and to extend the usability of functional old equipment by enabling the addition of accessories, specifically in the sanding and classification areas of an agglomerate manufacturing industry. An isolation camera was designed and implemented using a combination of insulating materials to reduce the noise of a main ventilator and to ensure compliance with local noise regulations. The design and simulation were carried out using CAD tools and the finite element method (FEM) to ensure a simple assembly design, and the camera was manufactured using rapid prototyping tools with lightweight and cost-effective materials, such as wood, foam, and metal. The camera was tested in situ, and its effectiveness was evaluated through functional tests and noise level measurements. The implementation of the camera resulted in a 16% reduction in pressure noise and a 95% reduction in noise frequency. With the additional use of earmuffs, the pressure reduction improved to 44%. These values ensured that noise levels remained 27% below the limit set by Decree 2393, significantly reducing the impact of noise on workers.

Keywords: indoor noise isolation; sustainable implementations; hypoacusia

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1. Introduction

Indoor industrial environments are often associated with high levels of noise pollution, which can have a detrimental effect on the health and well-being of workers. Noise pollution is a significant occupational hazard that can cause hearing damage, stress, and decreased productivity. Industrial hearing loss is a widespread occupational disease worldwide, which can be attributed to the high noise generated by machinery and production processes [1–3]. Approximately 40% of workers in industrial settings are typically exposed to high noise levels of 90 decibels or more, leading to hearing loss by age 65 or severe deafness [4,5]. Even low-level noise contamination with long exposures can have a critical impact on workers' health [6].

A great challenge has emerged focused on reducing noise pollution in industrial areas while maintaining current machinery and industrial equipment as long as possible, thus achieving a sustainable industrial environment. Minimizing noise has been identified as a sustainability objective, including implementations and innovations aimed at this purpose [7]. Thus, a series of studies focused on the development of new materials, structures, and strategies that allow for noise insulation at different levels have been reported [8,9]. Several studies have also been conducted in aeroacoustics to optimize geometries and structures with the purpose of reducing noise based on noise control approaches [10]. To address this challenge and to ensure the health and safety of workers exposed to noise contamination, engineers and industrial hygienists have developed various methods and systems to isolate and reduce indoor noise, effectively mitigating noise pollution in industrial settings [11–14]. The noise isolation system consists of several components that work together to reduce noise levels in the indoor industrial environment, such as sound barriers [15], acoustic panels [16], vibration dampeners [17], and mufflers [18,19]. The sound barriers are designed to prevent noise from escaping the industrial environment by providing an acoustic barrier between the source of the noise and the surrounding environment [14,20]. Many development structures have been designed using recyclable materials such as plastic and rubber to effectively minimize indoor noise and reverberation, yielding satisfactory outcomes [8]. Furthermore, the performance of structures has been analyzed to obtain sustainable sound-absorbing materials [15,21]. Despite there being many studies on the development of new materials and metamaterials, including sustainable materials [22], there is still a need for industry-level implementations that control the noise that can cause hearing loss. At this point, it has been necessary to link regulations to control overexposure to noise in workers.

Worldwide, norms and regulations have been implemented to prevent hearing loss in different environments, including industrial facilities. The Occupational Safety and Health Administration (OSHA) Noise Standards, for instance, require employers to provide hearing protection to workers in noisy environments and to establish permissible exposure limits for noise levels [23]. Similarly, the National Institute for Occupational Safety and Health (NIOSH) also provides Recommended Exposure Limits (RELs) that offer guidelines for safe noise levels in the workplace [24]. Meanwhile, the Environmental Protection Agency (EPA) Noise Control Act regulates noise emissions from various sources, such as transportation and construction [25]. Furthermore, the American National Standards Institute (ANSI/ASA S3.1-1999 (R2018)) provides guidelines for measuring and evaluating noise levels in occupational settings [26]. Additionally, the International Electrotechnical Commission (IEC) 60601-1-8 specifies requirements for medical electrical equipment and systems to reduce the risk of hearing loss in patients [27]. The European Union (EU) Directive 2003/10/EC establishes minimum requirements for the protection of workers from noise-induced hearing loss [28]. Moreover, the World Health Organization (WHO) Guidelines for Community Noise provide recommendations for reducing exposure to noise in community settings, such as residential areas and public spaces [29]. Related to heating, ventilation, and air conditioning systems (HVA), the rating and guidance of noise conditions are given by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). ASHRAE develops standards and guidelines that cover noise isolation in different ambient environments to address thermal conform, energy efficiency, and indoor air quality [30]. In a similar way, the ISO 21940-11:2016 standard provides guidelines for the balancing of rotating machinery, including components within HVAC systems, such as fans and motors [31]. By ensuring proper balancing, the standard helps reduce vibrations and associated noise levels emitted by these components. These regulations often include specific requirements for HVAC noise emissions, ensuring that noise does not exceed acceptable limits. Many countries adapt these norms and regulations to be applied in their territories according to their own needs.

In Ecuador, the Regulation on Safety, Workers' Health, and Improvement of the Working Environment is in force, where Decree 2393 specifies that exposure to noise for workers must not exceed 85 dB (A) in their working day [32]. There is also the norm NTE INEN-ISO 3743-1, which sets a series of procedures and requirements for noise measurement [33]. If exposure exceeds this norm, the worker must reduce exposure time; otherwise, bilateral hearing loss could occur irreversibly [5,34,35]. Despite the regulations in force in the country, many industries lack information and surveillance about hearing healthcare. Additionally, wood industries dedicated to the manufacture of chipboard generate high levels of noise due to the operation of the machinery needed for the transformation of wood, increasing the risk of hearing loss in workers [13,36,37]. Even though norms and regulations are in force, minimal implementations have been observed in the industry to minimize risks [38–41]. Non-practical and undocumented actions have been implemented in the industry to avoid noise, such as relocating transit routes and job spots, isolating the source of noise with temporal implementations, and even stopping the production process to perform activities in the contaminated area. Unexpectedly, the solutions may be obvious and simple, such as the use of protectors, isolating the noise sources, and avoiding machinery overload [42]. However, the application and correct use of these accessories also present a significant challenge for the local industry. This challenge stems from various factors, including a lack of control, minimal training, and the absence of rigorous monitoring by regulatory entities.

This study aims to provide a practical alternative solution for minimizing noise generated by the primary ventilation system in an industrial area. In this work, we implemented a noise isolation system to reduce the risk for workers in an indoor industrial environment. For this purpose, an isolation camera was tailored to reduce the noise of a ventilator during the drying process in the sanding and classification area. This process included implementing control methods to validate materials and designs that minimize the impacts of the high dB (A) levels to which workers are exposed, according to current regulations. Experimental measures were conducted to evaluate the effectiveness of the isolation system and to determine the level of noise exposure experienced by workers who correctly use protectors, ensuring compliance with the minimum requirements set forth in Decree 2393. These measures were undertaken to assess the level of noise reduction provided by the isolation system and to ensure that workers are adequately protected from excessive noise levels, which can result in hearing damage and other health issues.

2. Materials and Methods

To develop the noise isolation system, a well-defined sequence of steps was undertaken. This included a regulatory review to ensure compliance with relevant laws and standards, followed by the characterization of the nature of the noise (reverberance and contribution of additional noise sources), and the identification of the specific area within the industrial facility where the noise isolation system was to be installed. The next step involved quantifying the level of noise in the identified area, which served as a baseline for evaluating the effectiveness of the noise isolation system. Several combinations of materials were then evaluated to determine the most effective solution for noise reduction. The design of the noise isolation system was optimized based on the results of the material evaluation, and the design was further refined through simulations using the finite element method (FEM).

The noise isolation system was manufactured and tested to ensure compliance with the required specifications. The system was implemented in the designated area of the industrial facility, and regular performance evaluations were conducted to verify its ongoing effectiveness (Figure 1).

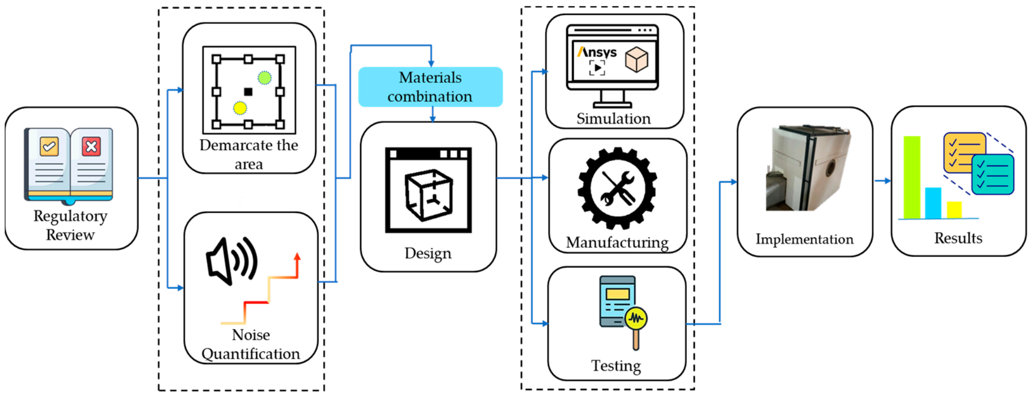

Figure 1. Flowchart for the implementation of the noise isolation system.

2.1. Regulations in Force in Ecuador

The NTE INEN-ISO 3743-1 standard establishes methods for measuring the sound pressure level emitted by machinery and equipment [33]. This standard outlines procedures and requirements for noise measurement, including microphone placement, calibration type, measurement duration, and other technical aspects. It is commonly used by environmental authorities and other entities to define permissible noise limits in various contexts. Chapter 5, Article 55 of Decree 2393 provides guidelines on noise and vibration. Specifically, numeral 7 specifies the permissible levels of continuous noise, measured in dB (A), which are directly linked to the duration of exposure [32]. This means that permissible noise levels are determined based on the duration of exposure to the noise, as shown in Table 1.

Table 1. Level of exposure/working day; a higher level of noise may be permitted for shorter periods of time, while a lower level of noise may be allowed for longer durations of exposure.

Sound Level/dB (A)	Exposure Time Per Day/h
85	8
90	4
95	2
100	1
110	0.25
115	0.13

2.2. Data Collection through Engineering Control

This study was conducted in an agglomerate manufacturing industry where workers were exposed to high levels of impact noises in the sanding and classification area. To obtain accurate data on the noise levels, measurements were taken at 6 different points surrounding the M350 ventilator for a duration of 5 days [43] at 4 different hours each day, as depicted in Figure 2. The measurement of noise in decibels, including its frequencies, was carried out with a calibrated sound digital level meter HY1361 to obtain real and exact values of the dB (A) in the measurements.

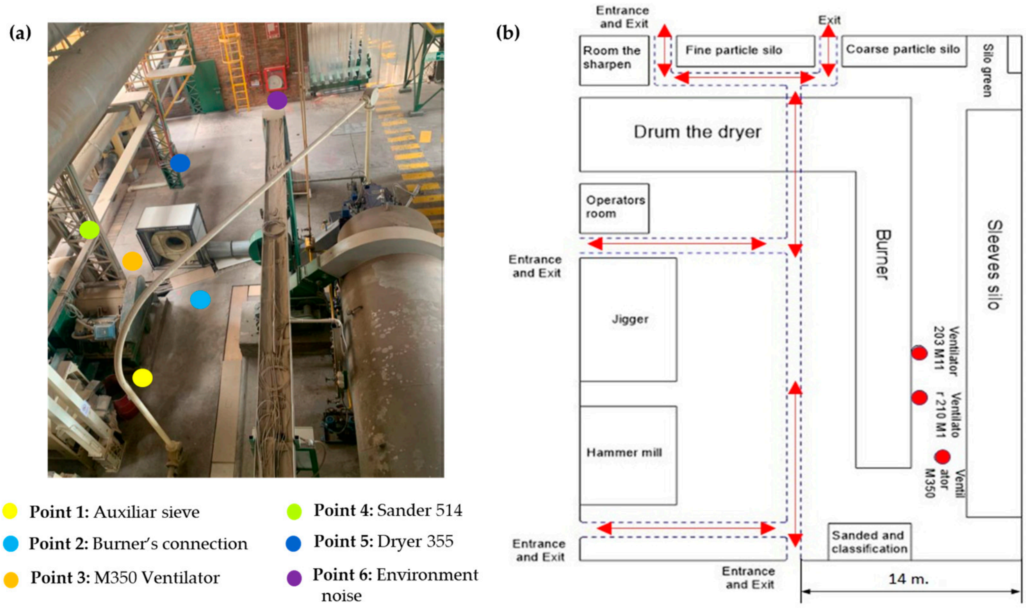

Figure 2. Area referenced. (**a**) Noise data collection points; (**b**) Map of sanding and classification area.

To ensure the safety of workers in the vicinity, it was crucial to assess whether the decibel levels were within a standard range or higher than normal. This information would then help in determining the potential risk of hearing loss for workers who are frequently exposed to this environment.

2.3. Hearing Shield Evaluation

In addition to referencing the study area, it was necessary to evaluate the sound insulation capacity of the workers with their hearing protector cup type (earmuffs 3M^{TM} PELTORTM X4P3E) and insertion (earplugs 3M^{TM} E-A-RTM Ultra FitTM) to know how much protection would be achieved against the high level of noise. Measures were taken among prepared workers and on a regular working basis to evaluate the impact of the correct use of protectors.

2.4. Materials Analysis

The process of designing an acoustic camera involved several steps, one of which was analyzing the materials that could be used as acoustic reducers on the walls of the camera. The selection of the material was based on several factors, such as weight, acoustic reduction capacity, and cost-effectiveness [44,45]. Simulations were carried out to determine the acoustic insulation capabilities of each combination of materials. This was performed to ascertain the effectiveness of the selected material and to ensure that it met the desired acoustic reduction requirements. By carrying out simulations with each combination of materials, we chose the material most suitable for achieving the desired acoustic insulation level. Table 2 describes the characteristics of the materials locally available.

Table 2. Characteristics of materials.

Material	Noise Reduction dB (A)	Weight (kg)
Steel	17.0	280.44
Wood	10.0	25.00
Ceramics	20.0	96.00
Plastic	4.0	10.80
Acoustic foam	11.7	0.83
Steel angles	8.0	1.50

2.5. Acoustic Camera Design

The design was made with SolidWorks version 2021 software, using the “Geometry” and “Extrude” tools to establish a closed camera-style structure in three dimensions. The model was a square chamber to cover an old version of fan M350. The geometry was established for a mount to be supported on the floor through a vibration pad and a metallic structure to support the walls of the isolation materials. The geometry was selected according to the propagation direction from the main ventilator using a perpendicular-to-noise-source structure with combined absorbers. The structure was designed to enclose the noise and the reverberation effect inside.

2.6. Acoustic Camera Operation Simulation

For the simulation, we used the software ANSYS R2 where the square geometry was loaded, establishing boundary conditions, material conditions, and a 2 cm meshing. The simulation was carried out for 3 min of ventilator operation, for which we calculated noise and dissipation values throughout the chamber, applying wavelength equations as a function of frequency, $f = \frac{v}{\lambda} = \frac{v}{2L} = f_o$, where L is the length, v is the wave speed, and $\lambda = 2L$.

2.7. Manufacture of the Acoustic Camera

For the manufacturing of the system, it was essential to ensure that it had adequate noise isolation. Various combinations of materials were tested. These combinations included foam–steel, foam–wood, foam–ceramic, and foam–plastic. Each combination was tested under various noise conditions to determine its effectiveness in reducing noise levels. This testing involved measuring the sound transmission loss through the materials, which was a measure of how much sound energy was absorbed or reflected by the material.

3. Results

To design and construct the camera, we began by measuring the noise levels produced by the M350 ventilator in the study area. Figure 3 illustrates the results of this process, including the range of frequency (rf) measured, with six different graphics representing six reference points, characterized in Figure 2a. The orange line in each graph indicates the average noise level recorded during a specific time of day over a period of five days per week. The sky-blue shaded area represents the standard deviation from the mean. In some of the noise graphics, a section can be observed with scattered points and a large standard deviation. These variations indicate fluctuations in the noise level, which were considered during the design and construction of the camera to ensure accurate noise level measurements. The referential Point 1 and Point 2 are positioned in the sound propagation path, similar to Points 5 and Point 6. Point 3 and Point 4 are situated on the lateral side of the ventilator, where the measured frequency represented nearly 14% compared to Points 1 and Point 2. Lastly, Point 5 and Point 6 represent 30% of the frequency observed at Points 1 and Point 2.

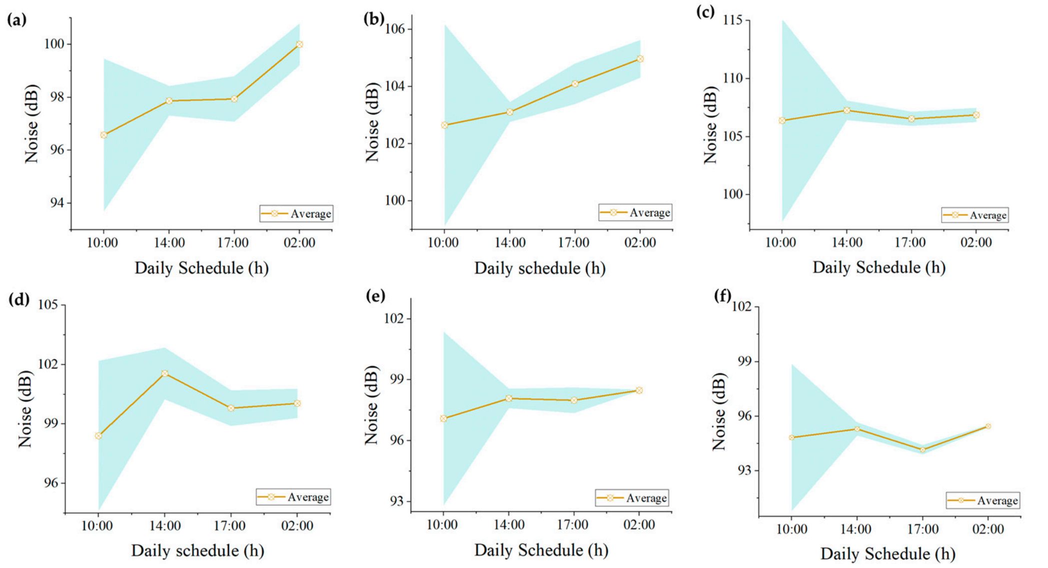

Figure 3. Initial data of the six reference points in the sanding and sorting room. (**a**) Point 1, rf : 655 ± 5 Hz; (**b**) Point 2, rf : 659 ± 4 Hz; (**c**) Point 3, rf : 94 ± 3 Hz; (**d**) Point 4, rf : 93 ± 3 Hz; (**e**) Point 5, rf : 331 ± 9 Hz; (**f**) Point 6, rf : 257 ± 4 Hz.

3.1. Analysis of Materials and Combined Structures

According to the selected materials, four combinations were made for the acoustic walls: (foam–steel), (foam–wood), (foam–ceramic), and (foam–plastic). We carried out a simulation of the acoustic insulator's working on a regular basis. Acoustic foam was chosen as the primary insulator for its exceptional acoustic efficiency and its ability to effectively control echoes.

To ensure that the system had adequate noise isolation, we evaluated four different combinations of materials for their noise reduction properties. The chosen combination consisted of a 34 cm thick structure, with a 2 mm separation gap between layers and a 10 cm distance from the ventilator to the insulating layer. Figure 4 visualizes the effectiveness of the noise isolation. In this simulation, the red color represents the area of maximum impact of the noise, while the blue color indicates the insulation area that manages the walls.

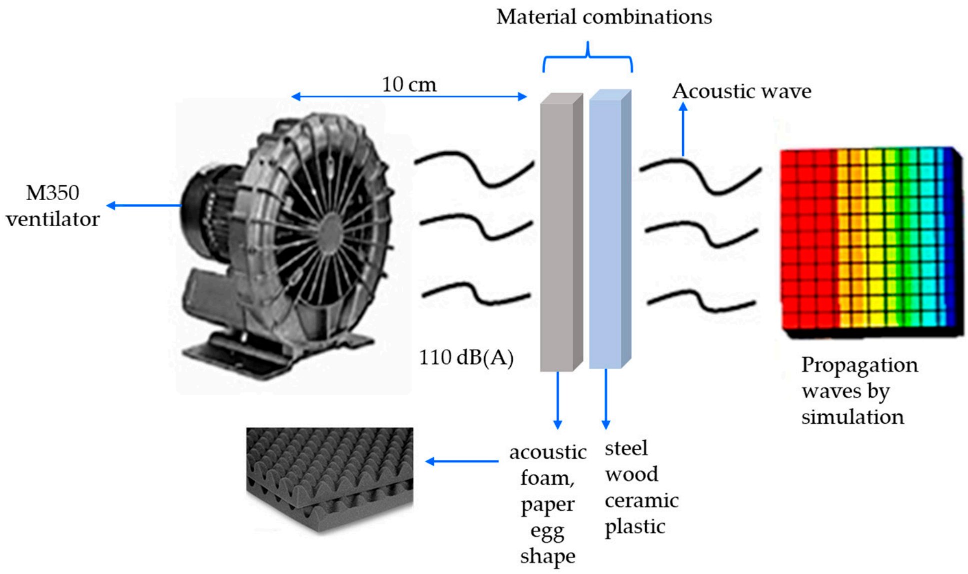

Figure 4. Material combination and simulation scheme.

We analyzed the noise attenuation levels for each of the combined materials, which are shown in Figure 5. The results indicated that the combinations of foam and ceramics, as well as foam and steel, provided the highest attenuation. However, the combination of foam and ceramics increased the weight of the structure, making it unsuitable for a suspended installation. Therefore, it was determined to be the best option for a camera installed on the floor. On the other hand, the combination of foam and wood resulted in a 9% noise reduction and was also advantageous due to its light weight and easy manufacturing process, making it a good option for the system [9,21].

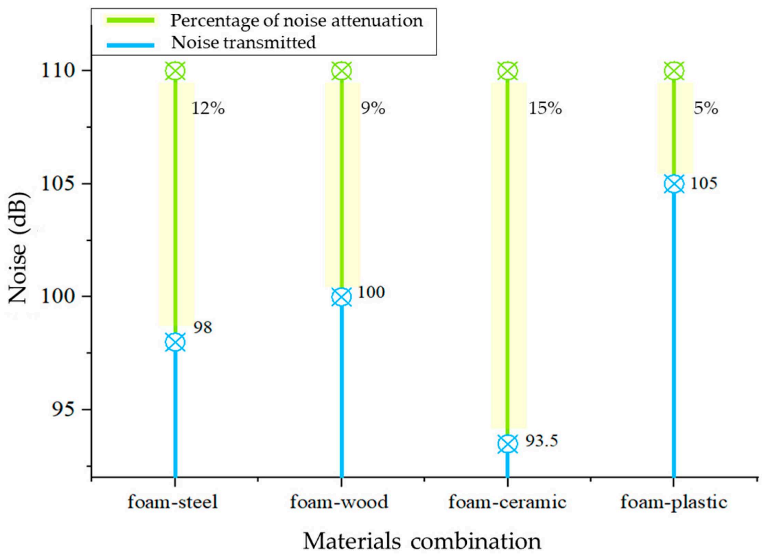

Figure 5. Percentage of noise attenuation and noise transmitted for each combined material analyzed.

3.2. Acoustic Camera Designs and Simulation

The design of the acoustic camera features a square-shaped structure with walls made from a combination of two materials. The first material is a 12 mm thick chipboard with foam, and the second material is wood of the same thickness. The back has a circular element to secure the engine of the M350 ventilator, as shown in Figure 6. The circular hole allows air to enter for feeding the ventilation system. The cavity allows for the escape of noise and also relaxes vibrations.

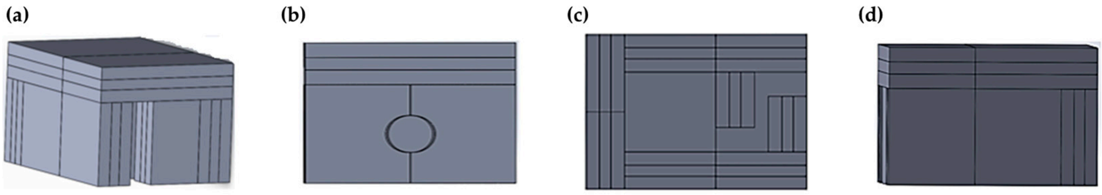

Figure 6. Square acoustic camera design. (**a**) Isometric view; (**b**) Back view; (**c**) Lower view; (**d**) Lateral view.

For the simulation, as shown in Figure 7, we imported the design into the ANSYS R2 program. We selected the wood-foam-wood combination of materials and applied a mesh size of 2 cm by 2.25 cm on the walls. The camera circle was assigned a mesh size of 1.75 cm. The simulation was conducted using the Harmonic Acoustics tool, resulting in an acoustic reduction of 15.98 dB(A).

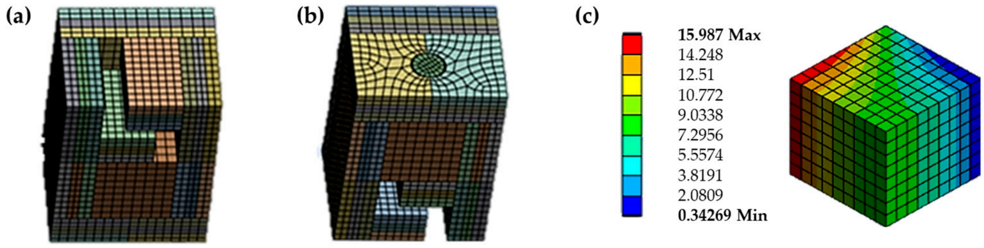

Figure 7. Meshing and simulation. (**a**) 2 cm meshing; (**b**) Meshing of 2.25 cm and 1.75 cm in the circle; (**c**) Acoustic waves model where the attenuation of noise for the camera configuration is illustrated.

3.3. Manufacturing

A prototype was made to take measurements of the acoustic reduction that the acoustic camera could offer in real form. Once the prototype was tested, the acoustic camera was implemented with the material (wood–foam–wood) in the ventilator as acoustic insulation (Figure 8). A basic metallic structure was implemented to ensure the structure of the walls and to keep a uniform distance between the layers of materials. The final weight of the system was 25 kg for a camera of 140 cm height and width and 194 cm length.

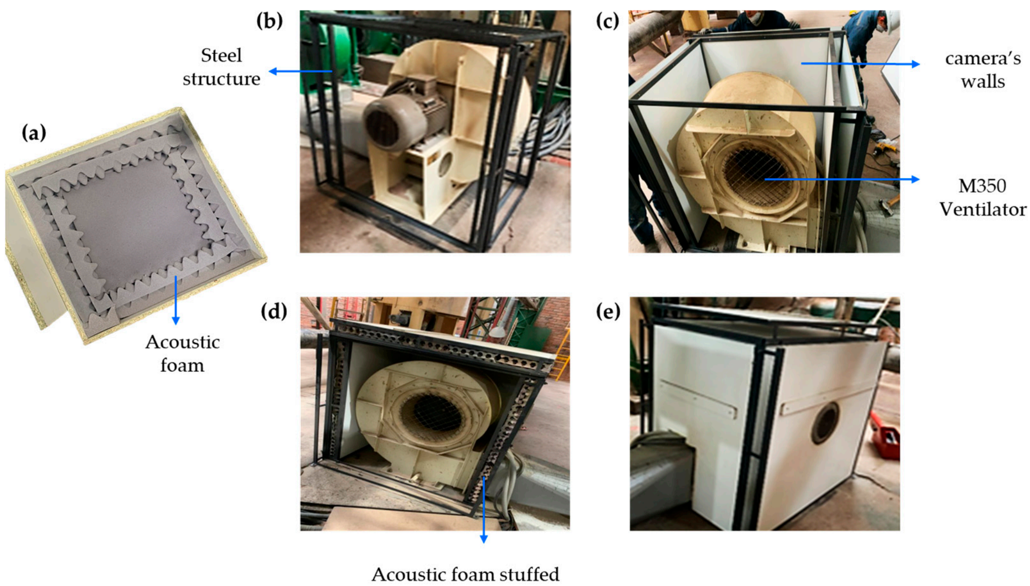

Figure 8. Manufacture of acoustic camera. (**a**) Prototype of the acoustic camera; (**b**) Steel camera frame; (**c**) Wooden walls of the camera; (**d**) Acoustic camera stuffed; (**e**) Acoustic camera mounted in the fan.

4. Discussion

According to the graphics of the initial data shown in Figure 3, Point 3 has the highest noise in this study's area; this point is located in the M350 ventilator that produces noise that overpasses the secure levels for workers. For that reason, it is necessary to implement the acoustic camera to isolate the source. All these graphics present at 10:00 h a high standard deviation due to dispersed values, but the other points have values near the average. The high standard deviation was attributed to the sum of the indoor noise produced by the starting of the equipment in the area, including the noise produced by workers starting the workday.

4.1. Selection and Combination of Materials

The combination of materials (wood–foam–wood) was selected as a first and low-cost option, adding the advantages of light weight; on the other hand, the intrinsic characteristic of wood allows the absorption of sound waves and vibrations. The prototype can be rapidly disassembled for fan maintenance purposes.

The combination of different materials gives alternatives to isolate the acoustic noise to a certain level. The results showed that the first combination of foam and steel resulted in a noise reduction of 12%, which is equivalent to 12 dB (A). In comparison, the second combination of foam and wood resulted in a noise reduction of 9%, equivalent to 10 dB (A). The third combination of foam and ceramic resulted in a noise reduction of 15%, equivalent to 16.5 dB (A), which was the highest reduction among all the tested combinations. Finally, the fourth combination of foam and plastic resulted in a noise reduction of 5%, equivalent to 5 dB (A). These findings highlight the potential of using foam as a soundproofing material in various applications. By selecting the appropriate combination of foam and the material to be soundproofed, it may be possible to achieve significant noise reduction, which could improve acoustic comfort and reduce the risk of noise-related health issues in indoor environments.

4.2. Acoustic Chamber Model and Simulation

The acoustic chamber model was installed in the industrial plant to evaluate the effectiveness of noise insulation. We conducted continuous measurements to verify the points where the noise level was under the norm. Figure 9 shows a comparison of noise levels for each case (initial noise, simulated noise, noise measured after acoustic camera installation, noise measured after camera installation and including the use of ear protectors on workers, noise defined by Decree 2393, and noise measured after camera installation and worker protections perfectly used ("ideal use")).

It can be observed that the red line represented by the acoustic insulation data indicates a considerable reduction in dB (A) compared to that emitted by the M350 ventilator (black line). The green line indicates that we comply with Decree 2393, which is purple, in which case workers are protected from suffering hearing loss disease with the noise control presented by the ventilator.

According to the reference points in Table 3, the implemented camera reduces the frequency range to only 5% of its original value before implementation. This reduction in frequency implies that the sound falls outside the range of frequencies to which the human ear is most sensitive [46]. By minimizing the impact within this sensitive range, the camera helps to mitigate potential adverse effects on the ears of workers.

In terms of acoustic pressure, we achieved a significant noise reduction of 16 dB (A) through the implementation of the camera structure. This reduction in noise levels was further complemented by the use of protective equipment to ensure the reduction of noise exposed to the range of 65 dB (A). Table 3 presents a comparison of noise measurements at reference points before and after implementation. The initial and final noise levels are clearly indicated, providing a clear picture of the improvement achieved through the implementation of the camera structure.

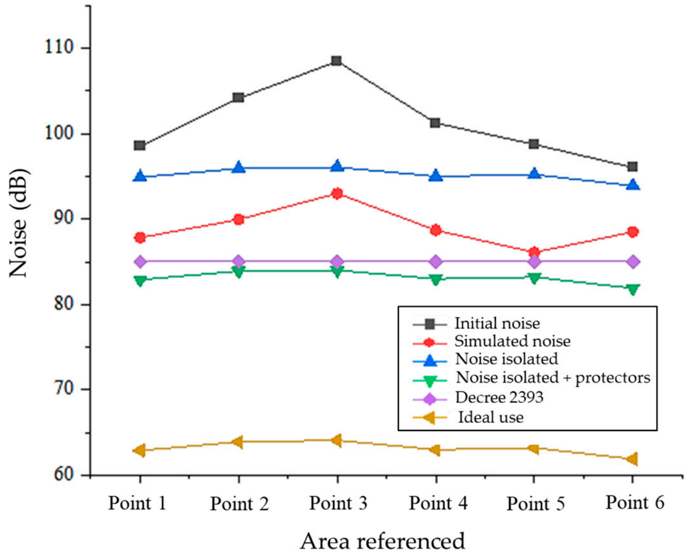

Figure 9. Comparison of results of noise measures and the effect of the insulation system to fulfil Decree 2393.

Table 3. Comparison of noise measurements across reference points.

Measures	**Point 1**		**Point 2**		**Point 3**		**Point 4**		**Point 5**		**Point 6**	
	dB (A)	**F (Hz)**	**dB (A)**	**F (Hz)**	**dB (A)**	**F (Hz)**	**dB (A)**	**F (Hz)**	**dB (A)**	**F (Hz)**	**D B(A)**	**F (Hz)**
Initial values	97.66	655 ± 5	103.41	659 ± 4	106.61	94 ± 3	99.81	93 ± 3	97.75	331 ± 9	94.74	257 ± 4
Values after implementation	94.9	20 ± 5	95.9	57 ± 4	99	18 ± 4	97.5	20 ± 3	95.2	83 ± 6	93.9	88 ± 5

The implementation of the acoustic camera represents a significant reduction in noise pollution. However, it is worth noting that relying solely on engineering controls, such as the use of an acoustic camera, may not be sufficient to eliminate all potential hazards to worker health. To further mitigate the risk of hearing loss among workers exposed to high levels of noise, the use of personal protective equipment, such as earplugs or earmuffs, should also be considered. While the use of personal protective equipment alone may not be enough to reduce noise levels to acceptable limits, it can complement engineering controls to further reduce noise exposure and protect workers from harm. It is also important to note that noise exposure and its effects on workers' health are influenced by various factors, including the duration of exposure, the intensity of the noise, the correct use of protectors, and individual susceptibility. Therefore, the implementation of a comprehensive hearing conservation program that includes regular monitoring and audiometric testing for workers is crucial to prevent occupational diseases, such as hearing loss.

5. Conclusions

In this work, we implemented an acoustic camera to address the noise pollution generated by a ventilator in an indoor agglomerate industry, with a primary focus on complying with Decree 2393's regulations to prevent industrial diseases, such as hearing loss. The camera's design was tailored to meet the specific needs of this study, achieving a noise reduction of 16 dB (A) and 95% of the noise frequency, exposing workers to 94 dB (A), which could be further reduced to 65 dB (A) with the use of personal protectors. The appropriate combination of wall materials ensured that the noise was reduced to an acceptable level while keeping the structure lightweight for easy disassembly in the event of a failure. Despite the successful implementation of engineering controls, it is vital to conduct periodic auditory surveillance checks on workers to identify any potential occupational hazards. The isolation system's implementation not only limits noise contamination in industrial indoor environments but also extends the usability of functional old equipment by enabling the addition of accessories. The capability of isolation can be improved by performing combinations of absorber materials in different geometries, following the principle of the internal structure in an anechoic chamber. Overall, this work highlights the significance of implementing effective noise reduction measures in the workplace to ensure a safe and healthy working environment for workers, thereby preventing the risk of industrial diseases related to noise contamination.

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