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DETERMINATION OF FLAX FIBER QUALITY INDICATORS TAKING INTO ACCOUNT SOUND-ABSORBING PROPERTIES FOR ROBOTIC LANDSCAPING SYSTEMS

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ABSTRACT

The confluence of increasing global sustainability demands and the imperative for real-time quality control in advanced manufacturing systems provides the foundation for this study. We address this by initially conceptualizing an active robotic noise-mitigation panel based on flax fiber designed for autonomous deployment in landscaping and urban noise control environments. The feasibility of this active system, which relies on the dynamic manipulation of a passive flax core integrated with AI-driven sensing and actuation, is fundamentally dependent on precise and rapid assessment of the raw fiber's acoustic potential and physico-mechanical quality. Confronting the scarcity of suitable non-destructive pre-assessment techniques, this paper details the subsequent development and comprehensive validation of a novel methodology utilizing the sound absorption effect to characterize flax fiber quality. A specialized device was engineered and rigorously optimized, establishing critical operational parameters: a 10 g sample mass, an emitter frequency of 1750 Hz (optimally aligned with the $\lambda/4$ thickness), and a reference moisture content of 12%. The research successfully established a robust statistical correlation between the acoustic attenuation measurements and key industrial indicators, specifically linear density, breaking load, and flexibility. Statistical validation using the Student's t-test confirmed a high degree of agreement with established standards (DSTU 4015-2001), demonstrating excellent reproducibility and high precision (relative expanded uncertainty below 5 %). Furthermore, empirical power and logarithmic regression formulas were derived to enable the direct calculation of quality parameters from the acoustic data. This integrated approach not only provides a reliable, rapid, and objective tool for industrial quality control, but also furnishes the essential material assessment capability required to transition sustainable flax materials into the demanding domain of smart, active noise-mitigation technologies.

KEYWORDS

Active noise mitigation; Breaking load; Flax fiber; Linear density; Non-destructive testing; Quality control; Sound absorption; Sustainable materials.

INTRODUCTION

Flax fibers play a significant role in modern technology and production due to their exceptional mechanical properties, biodegradability, and sustainability. They are widely used in the textile industry, composite materials, automotive manufacturing, and eco-friendly packaging. The growing demand for natural and renewable materials highlights the need for simple and effective methods to assess the physical and mechanical properties of flax fibers.

Robotic landscaping systems represent an emerging technological direction within smart urban infrastructure and automated environmental management. Such systems may include autonomous service robots, adaptive architectural elements, and intelligent environmental control units

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designed to improve comfort in public and residential spaces. In the context of noise management, robotic systems can deploy mobile or reconfigurable acoustic panels that dynamically adapt their position, orientation, or configuration in response to changing acoustic conditions. Natural fibrous materials, particularly flax fiber, are promising candidates for such applications due to their low density, porosity, and high sound absorption capability. The effectiveness of these acoustic elements largely depends on the structural parameters of the fibrous layer, including fiber fineness, packing density, flexibility, and internal pore structure, which determine the mechanisms of acoustic energy dissipation within the material.

However, the successful integration of flax-based acoustic materials into such robotic noise-control systems requires reliable and rapid methods for evaluating the quality of the raw fibrous material. The acoustic performance of fibrous layers is strongly influenced by the physico-mechanical properties of the fibers, including linear density, flexibility, and structural uniformity. Therefore, the development of simple, efficient, and non-destructive methods for assessing these parameters is an important task both for industrial quality control and for the design of advanced acoustic systems based on natural fibers.

Flax fiber-based panels are increasingly considered for use in robotic noise control systems due to their natural sound-absorbing properties. Such systems include mobile or adjustable panels in urban environments, smart buildings, and public spaces that autonomously reduce noise by optimizing panel placement and orientation. Given the wide range of potential applications, from city landscaping to interior acoustic management, it becomes crucial to develop simple and effective methods for assessing the physical and mechanical properties of flax fibers, particularly their sound absorption capabilities. Efficient evaluation techniques would ensure consistent quality and performance of flax-based acoustic materials in these advanced robotic systems. Reliable and rapid evaluation techniques can improve quality control, optimize production processes, and enhance the performance of flax-based materials in various applications. The development of non-destructive testing methods, such as those based on sound absorption, provides an innovative and efficient approach to fiber characterization, supporting advancements in both scientific research and industrial applications.

The analysis of indirect methods for determining the linear density of fiber based on air flow passage and illumination of a prepared fiber sample with a light beam indicates that some similarities can be found in the fundamental principles of these methods. According to the method of determining linear density by air flow passage, fiber samples of the same mass are used for research, the air pressure is also kept constant, and only the piston descent speed or the float rise height is recorded, both of which depend on the fiber thickness. Thus, the thinner the fiber, the slower the air passes through it. A similar phenomenon is observed when light and sound pass through the material - the thinner the fiber, the more it obstructs sound transmission or scatters and absorbs light. In this way, the absorption coefficient of the investigated material is determined [1].

The effect of energy loss by a sound wave as it passes through a material is used in many measuring instruments and various fields to determine the physico-mechanical properties of the studied materials, such as evaluating sound insulation efficiency or assessing the properties of fibrous and composite materials.

In the case of fibrous materials, it is necessary to consider that the acoustic properties of such a material depend on the properties of the fibers, the properties of the surrounding space, and the properties of the contacts between the fibers.

For a rapid assessment of fiber quality, the method of determining its sound absorption capacity can be used. In our study, we propose a method based on measuring the intensity of sound vibrations of a specific frequency that pass through a fiber sample of a defined mass. This study explores an alternative approach by utilizing the sound absorption effect to assess fiber quality, offering a rapid and non-destructive method. The originality of this approach lies in its ability to indirectly determine fiber density and structural uniformity through acoustic wave interaction, providing a novel perspective on fiber characterization.

LITERATURE REVIEW

In recent years, natural fibers, particularly flax fibers, have attracted growing interest among researchers due to their unique sound-absorbing properties. These characteristics make them suitable for the development of acoustic panels aimed at reducing noise in urban environments, residential buildings, and robotic landscaping systems. Beyond their technical advantages, such materials also offer environmentally friendly alternatives to synthetic absorbers, combining sustainability with practical applications for improving the quality of human living spaces.

An equally important research direction is the search for effective and straightforward methods to determine the physico-mechanical properties of flax fiber based on its sound-absorbing behavior. Such approaches not only simplify quality assessment but also provide rapid and non-destructive alternatives to traditional techniques. This makes them highly relevant for modern applications, where efficiency, precision, and sustainability are increasingly valued. In recent years, numerous scientific studies have focused on the utilization of flax fibers and the development of methods for analyzing their properties. Zhixiong Bi et al. studied the effect of voids on the sound absorption of 3D printed flax fiber reinforced PLA composites (CFFRCs). Using impedance tube measurements and numerical simulations, they found that voids inside flax yarns enhance absorption by increasing viscous friction, while voids between yarns reduce performance by altering sound propagation. The results provide insights for optimizing the acoustic properties of 3D printed flax fiber composites [2].

Sathesh Babu M et al. investigated the impact of Mahua oil cake microcellulose (MOCM) on the mechanical and sound absorption properties of flax fiber-reinforced polymer composites. The study found that adding 7.5 wt.% MOCM optimally enhanced tensile, flexural, and impact strength, while increasing MOCM content improved sound absorption. The findings highlight MOCM as a sustainable filler for enhancing both structural and acoustic performance in composite materials [3].

Diwahar Periyasamy et al. investigated the recycling potential of waste HDPE films reinforced with flax fiber to create sustainable decorative tiles. The study analyzed mechanical, thermal, water absorption, and sound absorption properties, revealing that adding natural fibers improved tensile and flexural strength by up to 25% and impact strength by 38%. SEM analysis confirmed enhanced interfacial bonding, supporting the conclusion that HDPE/natural fiber composites offer a sustainable alternative for decorative tile production [4].

V. Bhuvaneswari et al. conducted a critical review of the hygrothermal and sound absorption behavior of natural-fiber-reinforced polymer composites, emphasizing their eco-friendly benefits and challenges. The study examined moisture absorption characteristics, highlighting the need to convert hydrophilic fibers into hydrophobic ones to enhance mechanical and thermal properties. Additionally, the review found that composites with greater thickness, porosity, and density exhibited superior sound absorption performance [5].

Andi Harisa et al. investigated the effects of moisture absorption on the mechanical and acoustic properties of flax/polypropylene (PP) composites. The study found that water uptake followed Fickian behavior in flax/PP at room temperature, while flax-carbon/PP hybrids exhibited deviations, with carbon fiber hybridization reducing water absorption by 25%. Moisture exposure significantly decreased stiffness and resonant frequency, while tensile strength remained largely unaffected, impacting the composite's acoustic performance [6].

Eulalia Gliscinska et al. investigated the sound absorption properties of biodegradable thermoplastic composites made from flax and polylactide fibers. They analyzed the effects of multilayer structures, profiling, and the arrangement of composite layers on sound absorption performance using a Kundt tube. The study found that profiling the composite plate and adding pre-pressed nonwoven layers improved sound absorption, shifting the peak absorption range toward lower frequencies [7].

Mohammadi M. et al. reviewed recent advancements in the use of natural fiber-reinforced composites as sound-absorbing materials, highlighting their acoustic, mechanical, and thermal properties. They examined different composite structures, chemical treatments, and nanomaterial coatings to enhance sound absorption efficiency. The study emphasized the environmental benefits of replacing synthetic materials with sustainable, cost-effective, and recyclable natural fibers, addressing noise pollution and ecological concerns [8].

Abhijit Kudva, Mahesha Gt, Dayananda Pai, Ian Philip Jones of reviewed the physical, thermal, mechanical, sound absorption, and vibration damping properties of natural fiber-reinforced and hybrid fiber-reinforced polymer composites. Their study highlighted that natural fiber composites exhibit enhanced sound absorption and vibration damping characteristics, making them suitable for acoustic applications. Additionally, combining natural and synthetic fibers was found to improve the overall mechanical performance of the composites [9].

Madushika and Lanarolle reviewed novel approaches to improving the sound absorption performance of textile fibers as alternatives to conventional soundproofing materials. They examined chemical modifications, such as plasma and alkali treatments, and physical modifications, including microfibers, nanofibers, hollow fibers, and aerogel-treated fibers. Their findings indicate that these modifications enhance sound absorption by increasing fiber surface area, roughness, and material tortuosity, with treated natural fibers achieving absorption coefficients up to 0.9 at mid and high frequencies [10].

Gumanová et al. investigated the sound absorption properties of natural fibers—cork, hemp, and fiberboard—compared to conventional insulating materials like mineral wool, propylat, and polyurethane foam. Using the impedance tube method (ISO 10534-2), they measured the sound absorption coefficient across different material thicknesses and frequencies. Their findings showed that hemp exhibited the highest absorption ($\alpha = 0.99$ at 2000 Hz, 20 mm thickness), while cork had the lowest performance at low frequencies, with mineral wool performing best among conventional materials [11].

Su et al. investigated the mechanical, thermal, and sound isolation properties of a novel three-dimensional orthogonal woven sisal/flax hybrid fiber biocomposite (3DOWSBCs). They compared its performance to traditional laminated composites and used a finite element model (FEM) to analyze the strengthening effects of Z-yarns. Their results showed that 3DOWSBCs exhibited significantly improved flexural and shear strength, along with low thermal conductivity (0.29 W/m·K) and high sound transmission loss (63 dB), highlighting their potential for sustainable industrial applications [12].

Rotini et al. investigated the acoustic properties of polylactic acid (PLA) foam composites reinforced with plant fibers, specifically grape stems and wood straw, for sound insulation applications. They conducted acoustic tests to evaluate absorption, reflection, and impedance, analyzing different material configurations and thicknesses. Their findings highlight the potential of these eco-friendly composites for sustainable construction, emphasizing the influence of plant fiber characteristics on acoustic performance [13].

Liang et al. reviewed the sound absorption mechanisms, material modifications, and structural designs of synthetic fiber materials for industrial noise reduction, addressing their limitations in absorption coefficient and frequency range. They analyzed predictive models like Delany-Bazley and Johnson-Champoux-Allard (JCA), highlighting differences in how they account for air viscosity and thermal conduction. The study also explored methods to enhance the acoustic properties of polymers, metal fibers, and inorganic fibers through structural modifications, material combinations, and advanced fabrication techniques [14].

Eun-Suk Jang summarized studies on sound-absorbing green materials from agricultural by-products, such as flax and nettle fibers. The review highlighted thickness, density, and air cavity as key factors determining acoustic performance [15].

Daira Sleinus et al. developed eco-friendly composites from flax fiber, sphagnum moss, vermiculite, and sapropel for sound absorption and moisture buffering. The study showed that flax fiber–vermiculite composites provided more stable sound-absorbing and mechanical properties than other mixtures, confirming the potential of flax fiber as a sustainable acoustic material [16].

Tao Yang et al. reviewed the sound absorption properties of natural fibers as sustainable alternatives to synthetic materials. They emphasized that many natural fibers, including flax, can achieve sound absorption comparable to glass fiber while being safer for human health and more environmentally friendly. The review highlights flax fiber as a promising candidate for eco-friendly acoustic applications, particularly in sustainable construction and noise control systems [17].

This review highlights the growing interest in utilizing flax fibers for sound absorption applications, particularly within sustainable composite materials designed for urban and architectural noise mitigation, including advanced robotic systems. Various studies have investigated factors such as fiber structure, moisture absorption, and the inclusion of fillers to enhance sound absorption performance. Innovative approaches like 3D printing, hybrid fiber combinations, and the use of biodegradable matrices, such as PLA, have been extensively explored to enhance the acoustic and mechanical properties of flax-based composites, providing potential solutions for sustainable construction and industrial noise reduction. However, while the acoustic performance of the final flax-based product is well-documented, the literature reveals a significant gap regarding rapid, non-destructive, and straightforward methods for determining the initial physico-mechanical quality indicators of the raw flax fiber itself, which fundamentally dictates the final product’s sound-absorbing potential.

RESEARCH METHODOLOGY

Our work is centered on the development of an active robotic noise-mitigation panel based on flax fiber designed specifically for landscaping and urban noise control systems. The fundamental concept integrates the sustainable, natural acoustic properties of flax with real-time, adaptive robotic control to achieve superior noise reduction efficiency. The panel's architecture is anchored by the flax fiber sound-absorbing layer, which forms the core of its passive noise reduction capability. This layer may be deployed as pure flax or integrated into a biopolymer composite to enhance structural integrity and longevity. A noise sensor module, comprising micro-microphones and acoustic transducers, continuously surveys the ambient environment, providing real-time data on the noise intensity and its frequency spectrum. This input is fed directly to the Controller/Artificial Intelligence Module, which instantly analyzes the current configuration's efficacy and calculates the optimal adjustments required to maximize absorption (Figure 1).

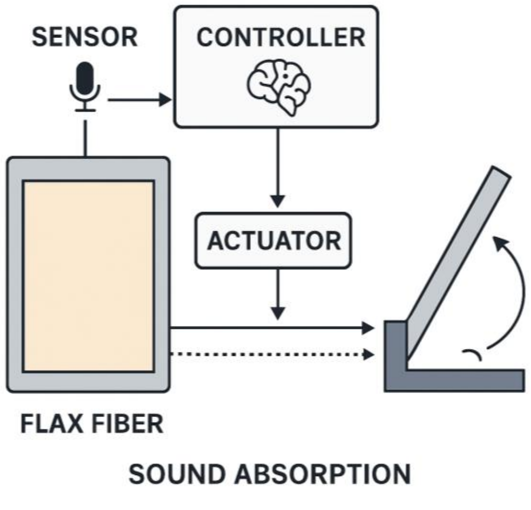

Figure 1. Conceptual diagram illustrating the operating principle of the active robotic noise-mitigation panel based on flax fiber.

Physical adaptation is achieved by actuating elements, such as servomotors or piezoelectric components. These effectors dynamically manipulate the panel's position, altering its tilt, distance from the noise source, or, where necessary, adjusting the configuration of auxiliary acoustic chambers designed to selectively enhance the absorption of lower frequencies through resonance. The entire functional apparatus is supported by a robust panel frame and structural support, guaranteeing mechanical stability and facilitating the necessary range of motion and configurational changes. The operating cycle is continuous: noise is detected, analyzed, and the panel is actively adjusted to maintain optimal absorption, creating a perpetual feedback loop that adapts to shifting noise profiles.

It is during this foundational development phase, particularly in designing the flax-based core and validating its acoustic performance for robotic deployment, that we encountered a critical necessity: the existing methods for rapid quality assessment were insufficient. This challenge compelled us to develop and validate a dedicated, non-destructive technique for determining the sound-absorbing properties of the flax fiber itself, an innovative methodology that is detailed in the subsequent sections of this article.

For rapid assessment of flax fiber quality, the method of determining its sound absorption capacity can be used. Based on the obtained results, the fiber can be objectively characterized by properties such as flexibility, linear density, and tensile strength. The proposed method is based on measuring the intensity of sound vibrations of a specific frequency passing through a fiber sample of a defined mass. The measurement is conducted in a sealed cylindrical chamber of constant volume, which eliminates the influence of external environmental sounds on the measurement results.

Based on the research findings, a device was designed to determine the degree of sound wave absorption by fibrous material. Its operating principle is based on determining the sound pressure level as the sound wave passes through a specific volume of fibrous material. The intensity of the sound wave passing through the material is monitored by an acoustic sensor—a condenser microphone. The measured sound signal is then linearly converted into a direct current, the voltage of which is processed by a microcontroller, and the result is displayed on a digital screen. Figure 2 shows the structural diagram of the developed device.

Figure 3 shows the functional diagram of the device. The device consists of the following main elements: a controlled sinusoidal oscillator, a low-frequency amplifier, an emitter, a measurement chamber with the tested material, a sound signal sensor, an amplifier, an amplitude detector, and a specialized signal processing circuit.

The determination of sound pressure is carried out by an acoustic sensor (e.g., a condenser microphone), which is connected to a specialized sound processing circuit. This circuit is responsible for signal amplification and subsequent linear conversion of the alternating acoustic signal into a constant voltage, which is then fed into an Analog-to-Digital Converter (ADC). In our implementation, the data is typically fed into an analog input pin of the Arduino Nano microcontroller. The obtained digital data is processed by the microcontroller according to the developed algorithm, and the final calculation results are displayed on a digital screen. The signal amplifier within the device is calibrated so that the maximum measurable sound pressure value corresponds to 5 V (the maximum analog reference voltage of the Arduino Nano), which the 10-bit ADC then digitizes into 4095 relative units (ranging from 0 to 1023, assuming a standard 10-bit ADC resolution for 5 V). Figure 4 presents the circuit diagram of the device.

The acoustic properties of flax raw material were analyzed using the developed device (Figure 5). The device consists of a plastic housing (1), a sound emitter (4), an acoustic sensor (6), and a measurement chamber (5). Inside the housing are the electronic sound processing module and the sound frequency generator (2), an amplifier, a digital indicator (3), and control buttons. For the study, a 10 g fiber sample is cut into approximately 2 cm pieces, placed into the measurement chamber (5), and then inserted into the device (Figure 6).

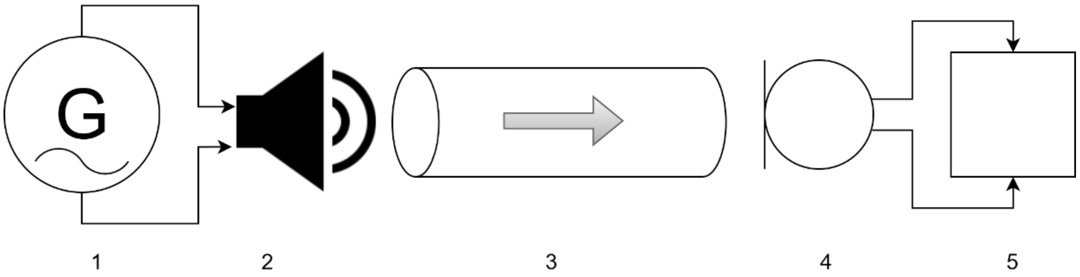

Figure 2. Structural diagram of the device for determining the sound absorption coefficient: 1 – generator; 2 – sound emitter; 3 – measurement chamber with the tested material; 4 – sound sensor; 5 – signal processing and result display unit.

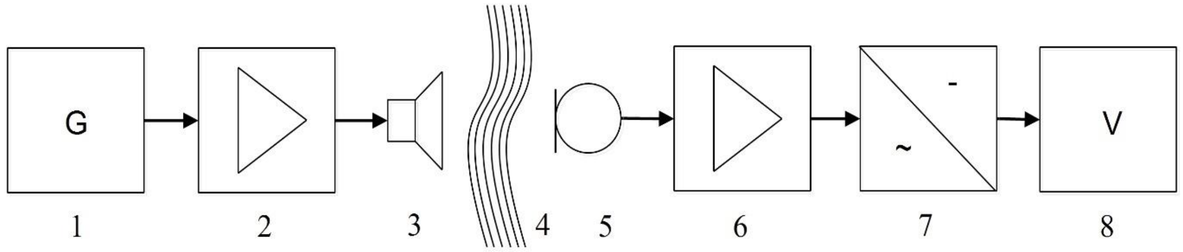

Figure 3. Functional diagram of the device for determining the sound absorption coefficient: 1 – generator; 2 – signal amplifier; 3 – sound emitter; 4 – tested material; 5 – sound sensor; 6 – signal amplifier; 7 – amplitude detector; 8 – signal processing and measurement display unit.

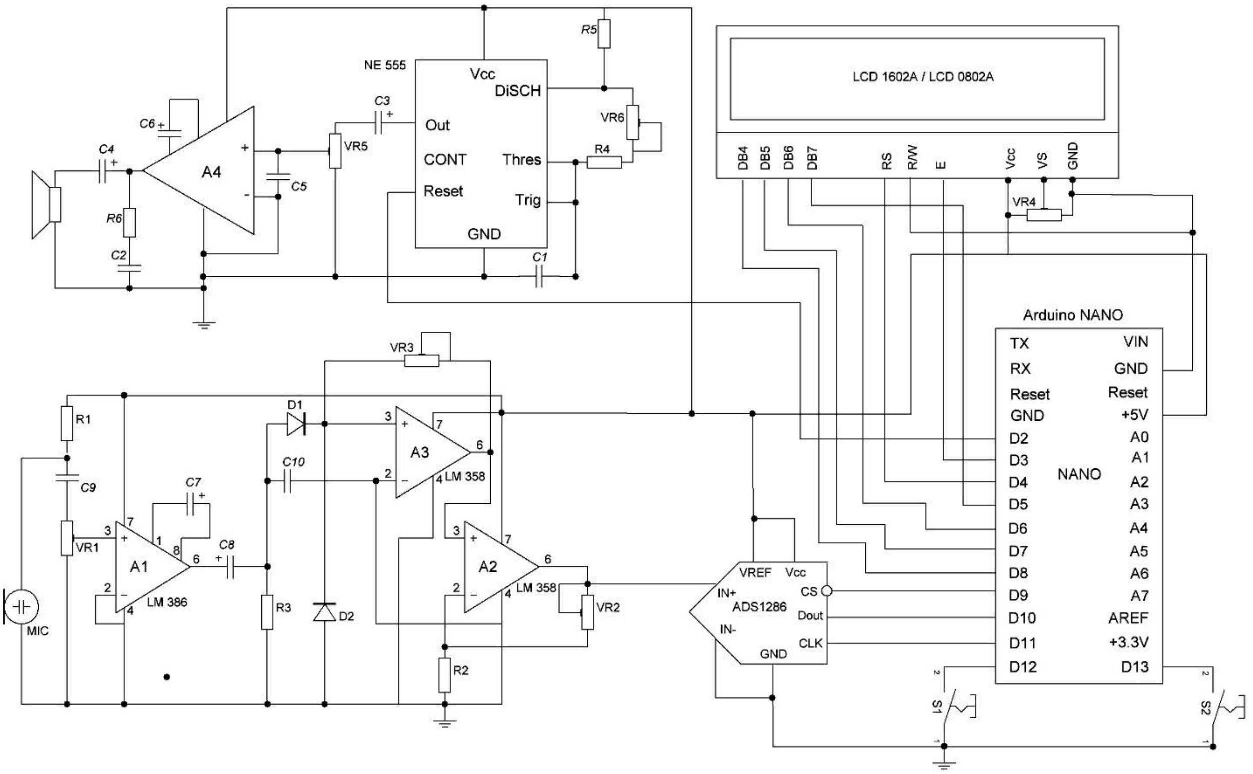

Figure 4. The circuit diagram of the device.

Using the control buttons, the desired operating mode is selected according to the developed algorithm, and the measurement is performed. The measurement result is taken as the arithmetic mean of ten samples from the same batch, calculated to the second decimal place and then rounded to the first decimal place. The device is powered by a 12 V DC source with a current of at least 0.25 A.

The developed device algorithm has a combined structure, integrating a control button processing unit and an operation mode selection unit. It includes several modes: 1) Emitter Testing Mode – Verifies the generator, amplifier, emitter, acoustic sensor, and digital circuit. It allows sound absorption analysis within a selected frequency range or a default range (500 Hz–2000 Hz, step 50 Hz); 2) Frequency Range Selection Mode – Sets the working frequency range for material analysis; 3) Measurement Mode – Conducts multiple measurements with statistical processing; 4) Result Display Mode – Shows measurement results on the digital display.

To evaluate quality using the developed device, it is necessary to determine its parameters and those of the fiber sample. Key parameters include the emitter's operating frequency and the sample mass. The device's algorithm provides test and working modes to select and apply a specific emitter frequency or a frequency range for further analysis.

The cross-sectional size of the measurement chamber depends on the device's design, with the fiber length for analysis being approximately 80% of the chamber diameter (28–30 mm). To determine the sample mass and emitter frequency, an analysis of the empty measurement chamber was conducted

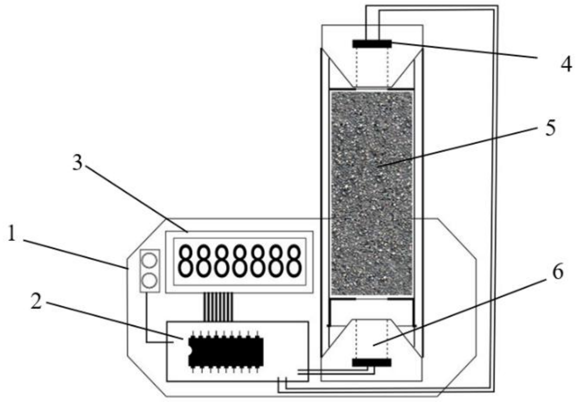

Figure 5. Schematic diagram of the device: 1 – housing; 2 – sound signal processing module and frequency generator; 3 – digital display; 4 – sound emitter; 5 – measuring chamber with fiber; 6 – acoustic sensor.

Figure 6. Device appearance: 1) in operating condition; 2) with the measuring chamber removed.

across the working frequency range (500–2000 Hz) with a step of 50 Hz. The results indicate that as the emitter frequency increases, the sound pressure on the acoustic sensor (a microphone) decreases.

Each measurement was repeated ten times. The presented values correspond to the mean value of the measurements. The number of repetitions was determined based on preliminary statistical analysis, ensuring that the relative experimental error did not exceed 5%.

Prior to measurement, flax fiber samples were conditioned to a standard moisture content of 12%, according to the requirements of the relevant standards for flax fiber testing. For each measurement, a sample with a mass of 10 g was prepared. The fibers were cut to a length of approximately 28–30 mm, which corresponds to about 80% of the diameter of the measuring chamber. The length of the prepared flax fibers was approximately 80% of the diameter of the measuring chamber, which ensured uniform filling of the chamber volume and provided controlled geometric conditions for the acoustic measurements.

The prepared fiber sample was loosely placed into the cylindrical measuring chamber of constant volume without forced alignment of individual fibers. This approach results in a randomly oriented but reproducible fibrous structure that reflects the natural arrangement of fibers in bulk material. To minimize the influence of spatial orientation on the acoustic response, the measurements were performed with ten repetitions and the results were statistically averaged.

Such a preparation procedure ensures comparable packing density and consistent experimental conditions for all tested samples. To minimize the possible influence of spatial fiber orientation on the acoustic response, each measurement was repeated ten times, and the final values were calculated as the average of the obtained results.

To determine the optimal sample mass for analysis, two fiber batches with the lowest and highest linear densities were selected. Measurements were conducted using samples of 5, 10, and 15 g, with each measurement repeated ten times.

The results indicate that 5 g samples have minimal impact on the intensity of the sound wave reaching the acoustic sensor (Figure 7, Figure 8). However, as the sample mass increases, the density of the measurement chamber filling rises, enhancing sound absorption, which is evident at 10 g and 15 g. Due to the chamber's design, samples exceeding 15 g cannot be accommodated.

For 15 g samples, the absorption curve for low-density fibers rapidly approaches zero at emitter frequencies above 1550 Hz, leading to inaccurate measurements. In contrast, 10 g samples provide nonzero readings up to 1900 Hz, making this mass the optimal choice for further measurements (Figure 7).

To determine the required operating frequency range of the emitter, two batches of fiber with the lowest and highest linear density values are selected, and measurements are performed on pre-prepared samples weighing 10 g. The graphical representation of the experimental results is shown in the Figure 9.

Analyzing the obtained data, it can be determined that noticeable attenuation of the sound wave when using samples with different linear densities begins at an emitter frequency of 1400 Hz, although at this frequency the difference between the device readings is minimal. In the emitter frequency range of 1650–1850 Hz, the maximum difference in device readings is observed when testing samples with the most contrasting linear densities.

The selection of the operating frequency and the sample mass was based on preliminary experimental studies carried out using the developed device. Measurements were performed within a frequency range of 500–2000 Hz with a step of 50 Hz in order to determine the most informative working frequency. The analysis showed that the difference between the readings obtained for flax fibers with significantly different linear density becomes most pronounced in the frequency range of 1650–1850 Hz. Therefore, the working frequency of 1750 Hz, corresponding to the middle of this range, was selected for further measurements.

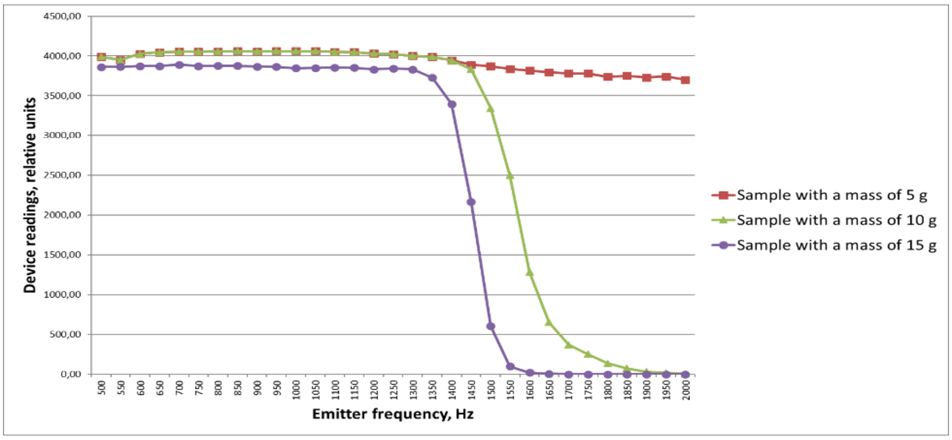

Figure 7. Dependence of the device readings on the emitter frequency for samples of different masses with the lowest linear density.

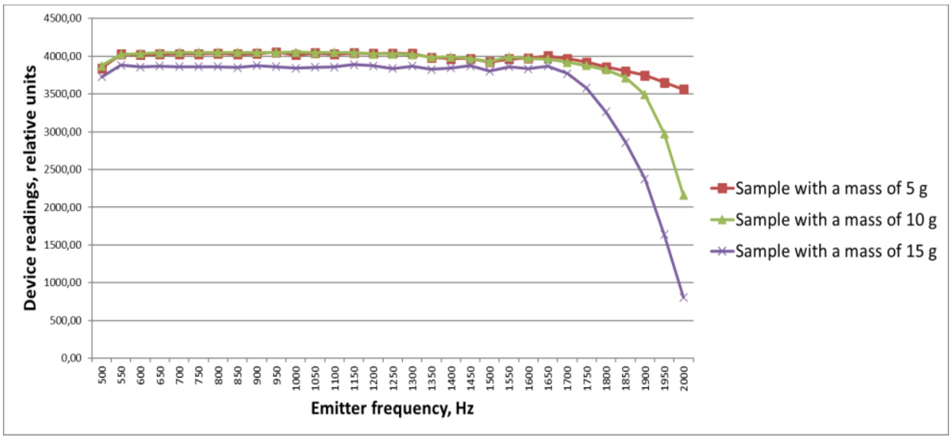

Figure 8. Dependence of the device readings on the emitter frequency for samples of different masses with the highest linear density.

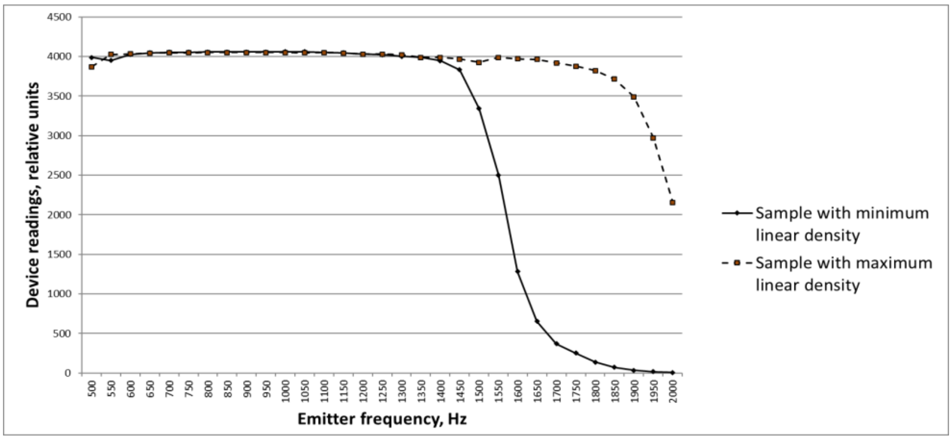

Figure 9. Dependence of device readings on emitter frequency for samples with different linear densities.

The mass of the tested samples was determined experimentally by comparing measurements performed with samples of 5 g, 10 g, and 15 g. It was observed that samples with a mass of 5 g had only a minor effect on the acoustic signal passing through the measuring chamber. At the same time, samples with a mass of 15 g led to excessively strong attenuation of the acoustic signal at higher frequencies, resulting in near-zero readings and reduced measurement sensitivity. A sample mass of 10 g provided stable and informative readings across the investigated frequency range and was therefore selected as the optimal value for further experiments.

The obtained results demonstrate that at the selected operating frequency of 1750 Hz the device readings show the highest sensitivity to variations in fiber linear density, which allows reliable differentiation of flax fiber samples with different fineness.

Sound absorption in porous materials occurs due to viscous forces that impede air movement through pores, causing part of the kinetic energy of oscillating air particles to dissipate as heat. The absorption efficiency depends on air viscosity and density, pore geometry, and material thickness.

The effect becomes significant at frequencies where oscillating air particles transfer energy to the porous structure. For effective absorption, the sample thickness should equal at least one-quarter of the wavelength. In this study, the optimal emitter frequency was selected as 1750 Hz, corresponding to a wavelength of 0.19 m, which defines an effective sample thickness or chamber length of about 48 mm.

In order to obtain reliable experimental data using the developed device, based on determining the intensity of the sound wave after passing through the tested fiber sample, it is necessary to establish the required number of repeated measurements.

For this purpose, samples from five batches of flax fiber with different values of linear density were prepared and measured using the developed device with repeated measurements. The obtained experimental data were mathematically processed. Based on a predetermined relative experimental error of 5%, the minimum number of repetitions required for each sample was calculated.

The results of this analysis are presented in Table 1.

Analysis of the data presented in Table X shows that, in order to obtain reliable measurement results and to ensure objective evaluation of the physico-mechanical characteristics of flax fibers, the experiments should be performed with ten repetitions. Under these conditions, the relative experimental error does not exceed 5%. Therefore, all experimental results presented in this study represent the mean values obtained from ten repeated measurements.

To ensure reliable results, fiber samples from five batches with different linear densities were tested on the device, and the data were statistically processed. At a relative error of 5%, the required number of repetitions for each sample was determined. The analysis showed that to obtain objective measurement results and evaluate the physico-mechanical properties of the tested material, experiments should be performed with ten repetitions, ensuring that the relative error does not exceed 5%.

To determine the effect of the actual moisture content of the tested fiber on the instrument readings, measurements were carried out using fiber samples with varying moisture levels. The measurements were performed with different repetitions according to the above recommendations. Since the actual moisture content of scutched flax used in production is 12%, and considering that all previous experiments were conducted at this level, 12% was taken as the reference value. Measurements were then performed with samples having moisture contents ranging from 8% to 20%, adjusted in 4% increments through artificial humidification and drying.

The analysis of measurement results showed that as the actual fiber moisture increased from 8% to 20%, the instrument readings rose from 1285 to 3718 relative units. This effect can be explained by the reduction in energy losses of the sound wave passing through the tested fiber sample with higher moisture content. Therefore, the optimal moisture content of the fiber suitable for measurements with the developed device should be 12%.

To evaluate the repeatability, accuracy, and uncertainty of the measurements obtained using the developed device, an experimental study was carried out using 30 flax fiber samples with different physical and mechanical properties. Each sample was measured with ten repetitions under identical experimental conditions according to the previously described measurement procedure. The obtained experimental data were statistically processed, and the mean values, standard deviation (σ), standard error of the mean (±m), and coefficient of variation (C, %) were calculated. The results of the statistical processing of the measurements are presented in Table 2.

Analysis of the obtained results shows that the coefficient of variation for most samples does not exceed 8%, which indicates good repeatability of the measurements obtained using the developed device.

To verify the reliability and practical applicability of the developed measurement method, a correlation analysis was performed between the device readings and the main physical and mechanical quality indicators of flax fiber: linear density, flexibility, breaking load, and color group. The correlation coefficients obtained are presented in Table 3.

The obtained results demonstrate a strong correlation between the device readings and the linear density of flax fiber (*R* = 0.95). Moderate correlations were observed with flexibility and breaking load (R = ±0.68). No statistically significant correlation was found with the fiber color group (*R* = –0.20).

The results of the statistical and correlation analysis confirm the presence of a significant relationship between the acoustic characteristics measured by the developed device and the main physical-mechanical properties of flax fiber at a significance level of 0.05.

Table 1. Determination of the minimum number of experimental repetitions.

Experimental results	Fiber sample number				
	1	2	3	4	5
Mean device reading, rel. units	3876.7	3841.2	3274.5	348.3	253.3
Standard deviation	46.80	84.05	125.75	21.63	15.31
Coefficient of variation, %	1.27	2.45	4.05	6.55	6.37
Student's t-coefficient			2.26		
Acceptable relative error, %			5		
Required number of experiments	1	2	4	10	9
Total number of experiments			10		

Table 2. Statistical processing of measurement results obtained using the device.

Batch No.	Mean device reading (rel. units)	σ (standard deviation)	±m (standard error)	C [%] coefficient of variation
1	1324.6	51.18	31.72	4.07
2	550.8	42.82	26.54	8.20
3	1250.2	47.74	29.59	4.03
4	1203.4	70.26	43.55	6.15
5	1148.5	90.11	55.85	8.27
6	957.4	75.52	46.81	8.31
7	747.5	49.43	30.64	6.97
8	1121.3	76.19	47.22	7.16
9	1577.4	53.67	33.27	3.59
10	773.7	49.65	30.77	6.76
11	1982.6	82.37	51.05	4.38
12	204.4	14.93	9.26	7.70
13	435.3	25.46	15.78	6.17
14	902.4	52.87	32.77	6.18
15	754.8	39.45	24.45	5.51
16	1343.0	70.43	43.65	5.53
17	985.3	69.02	42.78	7.38
18	3876.6	66.43	41.17	1.81
19	1533.0	65.39	40.53	4.50
20	677.7	44.05	27.30	6.85
21	422.7	32.59	20.20	8.13
22	253.3	15.31	9.49	6.37
23	554.8	42.52	26.36	8.08
24	450.9	35.07	21.74	8.20
25	181.5	14.45	8.96	8.39
26	391.9	19.55	12.12	5.26
27	552.4	38.29	23.73	7.31
28	652.5	38.84	24.07	6.27
29	627.2	35.30	21.88	5.93
30	603.2	19.21	11.91	3.36

Table 3. Correlation between device readings and physical-mechanical properties of flax fiber.

Quality indicator	Correlation coefficient (R)
Linear density	0.95
Flexibility	–0.68
Breaking load	0.68
Color group	–0.20

RESULTS AND DISCUSSION

During the analysis of flax fiber, the developed device was used for rapid quality assessment by measuring its sound-absorbing properties. Based on the obtained results, the fiber can be objectively characterized in terms of flexibility, linear density, and breaking load. To identify the relationship between the device readings and fiber quality parameters—linear density, breaking load, flexibility, and color group—a correlation analysis was performed using the described methodology. MS Excel was used for the analysis.

Table 4 presents the data used to determine the relationship between the fiber's sound-absorbing properties, as measured by the developed device, and its linear density, flexibility, breaking load, and color group.

To establish the relationship between the sound absorption properties of flax fiber and its physical and mechanical characteristics, measurements of 30 fiber samples were carried out on the developed device with tenfold repetition according to the above recommendations. To determine the dependence of the instrument readings on quality indicators such as linear density, breaking load, flexibility, and color group, a correlation analysis was conducted between the fiber quality parameters and the instrument readings. Based on this analysis, correlation coefficients were calculated and the following equations were obtained (1), (2), (3).

Relationship between the device readings x_1 and the linear density of flax fiber y_1:

$$y_1=0.9487\ x_1^{0.365} \tag{1}$$

Relationship between the device readings x_1 and the flexibility of flax fiber y_2:

$$y_2=208\ x_1^{-0.269} \tag{2}$$

Relationship between the device readings x_1 and the breaking load of flax fiber y_3:

$$y_3=8.3932\ \ln(x_1) - 29.05 \tag{3}$$

The Figure 10 below shows a graphical representation of this relationship as an example.

The results of statistical processing and correlation analysis indicate a significant correlation at the 0.05 significance level between the device readings and all tested quality indicators of flax fiber, except for the color group, which shows no correlation, as evidenced by a correlation coefficient of 0.20.

Table 4. Source data for determining the relationship between the device readings and the physico-mechanical quality parameters of the fiber.

Batch number	Device readings, relative units	Quality indicators			
		Linear density, tex	Breaking load, daN	Flexibility, mm	Color group
	y_1	x_1	x_2	x_3	x_4
1	1324.6	12.5	29.2	42.7	2.2
2	550.8	10.0	26.8	43.5	1.7
3	1250.2	13.0	32.3	42.8	2.9
4	1203.4	12.5	29.3	37.4	3.0
5	1148.5	12.7	31.7	41.9	2.2
6	957.4	10.9	26.4	43.1	2.2
7	747.5	10.7	28.2	43.1	3.0
8	1121.3	12.5	31.5	38.7	2.4
9	1577.4	13.7	29.7	34.8	1.9
10	773.7	11.3	37.4	46.5	3.2
11	1982.6	14.7	32.0	40.5	3.0
12	204.4	7.1	22.2	65.6	2.6
13	435.3	8.9	24.5	49.0	3.1
14	902.4	11.0	24.6	45.2	3.0
15	754.8	10.2	20.1	51.9	1.8
16	1343.0	13.5	33.1	41.4	1.9
17	985.3	11.9	27.4	49.0	1.8
18	3876.6	19.8	40.3	32.5	1.9
19	1533.0	14.4	32.6	40.3	2.3
20	677.7	10.4	27.6	50.1	2.1
21	422.7	8.9	24.4	54.3	2.9
22	253.3	7.2	15.2	70.0	3.0
23	554.8	9.7	21.6	50.3	2.2
24	450.9	8.9	24.3	54.2	2.4
25	181.5	6.0	5.0	82.1	2.9
26	391.9	7.9	18.4	55.8	2.8
27	552.4	9.0	24.7	46.9	1.5
28	652.5	9.4	25.5	50.2	2.0
29	627.2	9.6	33.4	50.1	2.8
30	603.2	10.3	17.1	47.0	1.5

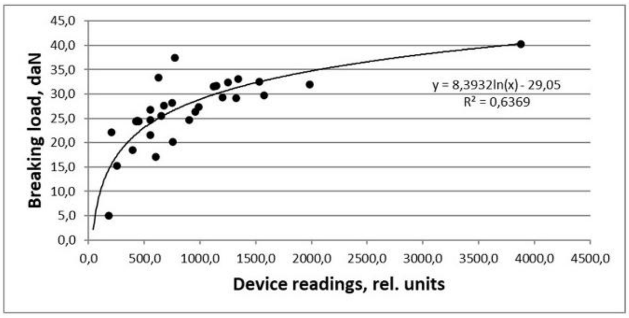

Figure 10. Relationship between instrument readings and the breaking load of flax fiber.

To test for differences in the mean values of samples obtained by measuring flax fiber quality indicators using the standard method according to DSTU 4015-2001 and calculated using the proposed formulas, the Student's t-test was applied. Analysis of the flax fiber quality indicators determined using the standard methods (DSTU 4015-2001 and GOST 10878-70) and those calculated by the proposed methods with the device showed a high degree of agreement. The empirical Student's *t*-test values for linear density, flexibility, breaking load, and color group were significantly lower than the critical value ($t_{critical} = 2.05$) at a 0.95 significance level, allowing the null hypothesis (H_0) of no significant difference between measurement results to be accepted with 95% confidence. Furthermore, high correlation coefficients (ranging from 0.80 to 0.99) confirm a strong positive relationship between the standard methods and the proposed approaches. Thus, the developed methods provide reliable assessment of the physical and mechanical properties of flax fiber, accurately reflecting the trends established by standard methods.

Thus, when using the device, the fiber sample mass should be 10 g, the operating frequency of the device set at 1750 Hz, the height of the measurement chamber 48 mm, and the measurements must be performed with tenfold repetition.

The reproducibility and accuracy of the proposed sensory method must be evaluated against existing instrumental standards, as precision alone does not guarantee compliance with measurement correctness. Therefore, both accuracy and precision should be monitored and maintained over time. To assess measurement stability, Shewhart control charts were used, serving as a diagnostic tool to identify sources of variability in the measurement process. For this purpose, a random batch of flax fiber was selected, from which twenty samples were taken and measured.

The measurement uncertainty was evaluated as follows: over four days, flax fiber from a single batch was measured using the proposed device, with eight measurements taken each day. The calculated Fisher criterion was F_{emp}=1.04, while the critical value for a 0.95 confidence level with 3 and 28 degrees of freedom was F_{tab}=2.95. Since $F_{emp} < F_{tab}$, the data homogeneity is satisfactory. The estimated variance was S^2=184.2, giving an expanded measurement uncertainty of U=58.4. The relative error at a 0.95 confidence level was 1.99%, the confidence interval ±24.8, and the relative expanded uncertainty 4.7%. Therefore, the measurement result is 1245.7±24.8, which is acceptable, as the error is below 5%.

Thus, the developed methods for determining the quality indicators of flax fiber are consistent with the evaluation levels established by standard methods, as confirmed by the Student's *t*-test, and demonstrate the same evaluation trends, as evidenced by the significance of the correlation coefficients.

The analysis of the obtained results indicates that, at a statistical significance level of 0.05, there is a certain correlation between the fiber number and the readings obtained using the described method and device. Specifically, a significant direct relationship was established between the fiber number N (according to the State Standard of Ukraine) and the instrument readings characterizing the acoustic sound absorption properties of the fiber, as confirmed by the correlation coefficient r_3 = 0.65.

According to the analysis results, the sound absorption coefficient was determined, which can be expressed by the following equation:

$$K=1.005\text{-}8\cdot 10\text{-}6\cdot r_3 \qquad (4)$$

This coefficient is applied in the derived empirical formula, which makes it possible to calculate the fiber number by taking into account the measurement results of the light-reflecting, light-absorbing, and sound-absorbing properties of flax fiber, as demonstrated in our research. The relevance of the developments is confirmed by the obtained Patent of Ukraine No. 47840.

To verify the validity of Equation (4), additional analysis was carried out by comparing the acoustic response measured using the developed device with the sound-absorbing properties of flax fiber samples characterized by independent physical-mechanical parameters. The analysis was performed on 30 samples with ten repeated measurements for each sample. The obtained statistically significant correlations confirm that the proposed acoustic measurement approach adequately reflects the sound-absorbing behavior of the fibrous material.

To validate Equation (4), an experimental study was carried out using a dataset of 30 samples of scutched flax fiber with different physical and mechanical properties. For each sample, the following parameters were measured: fiber length L, acoustic response of the fibrous layer ZP obtained using the developed acoustic device. The reference quality parameter was the fiber number determined according to DSTU 4015-2001.

Statistical analysis of the experimental data showed that the average fiber number was 12.6 (range 8–15), the average fiber length was 64.6 (41–88.6) and the average acoustic response was 934.7 relative units (181.5–3876.6).

To determine the significance of the factors, pair correlation coefficients between the fiber number and the measured parameters were calculated. The strongest correlation was observed for fiber length (r=0.93), while acoustic response also showed significant positive correlations with fiber quality (r=0.65). Finally, the coefficient K describing the acoustic properties of the fibrous layer was obtained (Equation 4).

The results demonstrate that the acoustic response parameter shows a statistically significant correlation with the standardized fiber quality indicator (r=0.65). This confirms that the acoustic measurement approach used in the developed device can serve as an informative indirect indicator of flax fiber quality and supports the validity of the empirical relationship expressed in Equation (4).

The presented research introduces a novel, non-destructive acoustic method for the rapid quality assessment of flax fiber by measuring its sound absorption properties. The study successfully established a measurable link between the device's readings and critical quality indicators like linear density, breaking load, and flexibility. This acoustic approach offers a significant advantage in speed and efficiency compared to conventional, time-consuming testing methods, directly addressing the industry need for better real-time quality control.

While the methodology successfully defined optimal operating parameters — a 10 g sample mass, a 1750 Hz operating frequency, and a critical 12% moisture content — a closer look reveals areas for discussion. The dependence on a precisely controlled moisture level (12% reference) suggests a practical limitation; any deviation in ambient humidity or fiber storage conditions could necessitate pre-conditioning, partially undermining the "rapid" nature of the test.

Furthermore, the strong statistical validation using the Student's t-test and high correlation coefficients (ranging from 0.80 to 0.99) is compelling evidence that the method reflects the trends of standard methods. However, the mechanism of correlation, particularly the inverse relationship with flexibility (Equation (2)), warrants deeper physical modeling. The current analysis attributes sound absorption to bulk density and structural properties. Future work should investigate the role of fiber fineness distribution and the porosity/tortuosity of the packed sample more directly, as these microstructural factors fundamentally govern acoustic energy dissipation in fibrous media.

A key limitation is the device's reliance on a packed fiber sample (10 g within a fixed volume). This packed state creates an artificial acoustic medium whose properties are influenced by how the sample is prepared (e.g., initial packing pressure or fiber orientation). This could introduce a source of variability not fully captured by the current uncertainty analysis, despite the tenfold repetition.

The successful derivation of an empirical formula and the determination of the sound absorption coefficient *K* (Equation (4)) are crucial for standardizing the new method. Ultimately, the relevance of this patented device will depend on its ability to transition from a laboratory tool to a robust, low-maintenance instrument capable of consistently and economically outperforming the existing standard tests in industrial settings, which remains the final benchmark for true innovation in fiber quality assessment.

CONCLUSIONS

This research successfully demonstrated and validated a novel, non-destructive method for the rapid determination of key quality indicators of flax fiber utilizing the principle of sound absorption. Through the development and rigorous optimization of a new measuring device, critical operational parameters essential for ensuring the accuracy and repeatability of results were established. The optimal settings for objective fiber quality assessment were determined to be a 10 g sample mass, an emitter operating frequency of 1750 Hz (corresponding to the required chamber length of $\lambda/4$), and a reference fiber moisture content of 12%. The most significant outcome is the discovery of a strong statistical correlation between the instrument readings, which reflect the acoustic properties of the sample, and the main physical and mechanical characteristics of the fiber. Specifically, a direct and significant relationship was established with linear density and breaking load, alongside an inverse relationship with flexibility. This confirms that the acoustic response of the packed fiber is a reliable indicator of its structural integrity and mechanical performance. The high degree of agreement between the results obtained using the developed device and those determined by standard methods (DSTU 4015-2001) was confirmed by the Student's *t*-test, which showed no statistically significant difference between the mean values. This, coupled with high correlation coefficients (up to 0.99), strongly validates the reliability and reproducibility of the proposed methodology. Furthermore, empirical formulas were derived, allowing for the direct calculation of quality indicators from the acoustic measurements. This, along with the acceptable estimation of expanded measurement uncertainty (relative error below 5 %), positions the developed method as a reliable and precise tool for industrial quality control. Beyond the development of the quality assessment tool, this research established the foundation for practical, high-value applications by formulating the conceptual diagram of the active robotic noise-mitigation panel based on flax fiber. This conceptualization integrates the passive acoustic absorption properties of flax with a dynamic control system utilizing real-time sensor feedback and actuation elements. This innovative framework is designed to enable the fiber's use in advanced robotic landscaping systems for autonomous noise control in urban and public environments. The need to accurately and rapidly assess the quality and acoustic potential of the flax fiber core for this active panel directly motivated the development of the sound-absorption based testing method presented herein. In conclusion, the developed acoustic method constitutes a viable, rapid, and non-destructive alternative for quality control in flax fiber processing. Crucially, the integration of this reliable material assessment capability supports the advancement of sustainable materials into the domain of smart, active noise control technologies, providing the industry with efficient means for both objective material evaluation and innovative product development.

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