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Numerical Assessment of the Efficacy of Various Exhaust Muffler Liner Materials on Acoustical Performance

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ABSTRACT

Noise levels have rapidly increased in recent years, largely due to the proliferation of modern appliances and critical noise sources like engine exhaust mufflers. Controlling muffler-radiated noise could reduce its impact on the surrounding communities. Generally, conventional mufflers utilize expensive sound-absorbing, fibrous, porous materials with high cost and harmful effects. Thus, eco-friendly materials are being used as alternative materials for their lower cost and less effects. The objective of this study is to evaluate natural material fiber's potential as an effective sound absorber in exhaust absorptive mufflers. Also, evaluate an elliptical muffler's performance by studying several factors, including liner materials, liner thickness, and how these factors affect sound transmission loss. The finite element method is used to simulate and analyze the sound transmission loss of a three-dimensional elliptical muffler model built using COMSOL Multiphysics. This paper proposed an exhaust muffler model with a waste of (date palm trunk, coconut or coir, and corn fiber) as an eco-friendly sound-absorbing material. In addition, a parametric study with a frequency range of up to (6000) Hz was done to evaluate the effect of liner thickness and inlet/outlet tube diameter on transmission loss. The results indicated that airflow resistivity (Rf) is the effective factor that governs sound transmission loss; higher airflow resistivity materials provide better attenuation. Absorbing material with higher airflow resistivity showed an incremental rise in transmission loss beyond 500 Hz, with notable peaks appearing at (1.25, 2.5, 3.4 & 5) kHz. Moreover, it is effective to reduce inlet/outlet diameter and increase liner thickness.

Keywords: Absorptive muffler, Acoustic, Sound absorptive materials, Sound transmission loss.

1. INTRODUCTION

Urban noise pollution, encompassing industrial and social noise, particularly road traffic, substantially affects people's productivity and psychological health **(Mosa et al., 2024)**. Reducing

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noise is a top priority for governments and researchers **(Li et al., 2024**). Engines, such as vehicles, are the most significant source of road traffic noise and can be quite varied. The exhaust mufflers could be one of the primary sources of noise in these engines. Monitoring these noise levels is crucial for creating effective mitigation strategies **(Reddy, 2017)**.

An engine's exhaust system produces two primary types of noise: low-frequency "breathing noise" and high-frequency "flow noise," the latter occurring between 800 and 1000 Hz. Traditional passive mufflers are effective at middle and high frequencies but perform poorly for low-frequency noise **(Bordonga et al., 2022; Kashikar et al., 2021; Zhu et al., 2017)**. Mufflers have long been utilized in car exhaust systems for their mid-to-high-frequency broadband capabilities**(Amuaku et al., 2019; El Chami et al., 2024)**. Positioned between the manifold and the catalytic converter.

Mufflers come in two types: absorptive and reactive, with various designs. Automotive mufflers typically combine both qualities **(Potente, 2005).** An absorptive muffler typically consists of pipes and chambers lined with sound-absorbing materials. Upon entering the muffler, sound waves engage with the materials, which absorb a significant amount of sound energy, converting it into heat and effectively reducing the intensity of the noise that exits the system **(Mosa et al., 2023)**. The absorptive muffler's disadvantage is its inability to damp low frequencies due to large wavelengths, though this can be mitigated by adjusting the thickness of the absorbent material **(Vimaladass, 2022)**.

Two issues that modern society needs to solve are waste management and noise pollution. The adoption of new alternative materials that absorb sound can significantly mitigate these issues. Therefore, it is very desirable to have low-cost, easily created, thin, and lightweight materials that have high rating sound absorption in a broad frequency range**.** The majority of sound-absorbing materials are made from synthetic and waste materials such as foams, recycled rubber, glass wool, and polyester fibers, which can harm the environment, endanger human health, and disrupt workplace operations. Therefore, utilizing natural materials would be excellent since their porous cell structure and relatively low density are becoming increasingly attractive due to their renewable, nonabrasive, low cost, and availability. Additionally, they perform better in terms of energy saving and pose fewer health risks during handling and processing **(Arenas and Asdrubali, 2018)**. The acoustic effectiveness of these materials is verified by their ability to convert incoming sound energy into heat or vibrations rather than reflecting it into the air. An effective sound-absorbing material should minimize sound energy reflection and maximize sound energy absorption. The material's efficacy is measured by how well it can transform incident sound energy into other forms of heat or vibrations instead of reflecting it into the surrounding air. As longitudinal sound waves penetrate porous materials, the air within the pores undergoes periodic compression and decompression **(Jang, 2023; Yang et al., 2020)**. This results in molecular vibrations that strike the pore walls, creating resonance and leading to energy dissipation. Reduced sound energy reflection and increased sound energy absorption are desirable properties of an effective sound-absorbing material. Thus, researchers exhibit significant interest in natural materials from plants due to their potential as sound absorbers in acoustic engineering not only in terms of cost-effectiveness but also in sustainability **(Cao et al., 2018; Suhaeri et al., 2024)**. Given that their capabilities could rival costly synthetic materials used for noise reduction. Subsequently, several studies focused on improving their acoustic capabilities for use in absorptive mufflers to reduce emitted noise pollution including the type of materials, fiber thickness, and liner thickness. Results indicated that a denser absorptive layer absorbs more energy within the muffler, enhancing sound transmission loss **(Ranjbar and Alinaghi, 2016; Kalita et al., 2015). (Xu et al., 2004)** studied how enhancements in fiber properties affect the acoustic dissipation performance of dissipative mufflers. In the low-to-medium-frequency range, a higher area ratio increases the noise reduction. Moreover, a rise in transmission loss occurs in the mid-to-high-frequency range.

One of the recognized natural materials is Corn Husk Fiber **(Sari et al., 2016)** which has been of interest to researchers due to its ability to significantly enhance sound absorption through a simple method **(Sari et al., 2017)**. The results indicate that these materials perform high sound-absorbing performance and could address environmental issues and mitigate noise pollution. Natural hemp fiber was also considered alongside corn husk in composite materials by **(khdier et al., 2020)**, resulting in improved acoustic insulation properties.

Studies on the sound wave propagation pressure in a lined muffler for an internal combustion engine were presented, featuring a rectangular resonator chamber **(Vasile et al., 2011; Antebas et al., 2013)**. Their objective was to apply finite element analysis to demonstrate both inductive and resistive damping in pressure acoustics. The findings of this research focus on transmission loss, aiding in the sequencing of acoustic analysis and the implementation of precise boundary conditions. Subsequently, Kosała tried clay granulates as a muffler-lined welling to improve the acoustic performance. A modified formula is proposed for better predictive accuracy. The theoretical model has been verified with experimental tests. Results showed that thicker granulate layers enhance transmission loss across varying frequencies**(Kosała, 2022).** Additionally, a study of an exhaust muffler is presented to improve its acoustic performance by using MPP backed by different depths of parallel-arranged cavities **(Min et al., 2024).** Numerical simulations of sound absorption and transmission are conducted with experiments. Outcomes showed that acoustic performance improves when modifying the length of the muffler and moving to lower frequencies with the increase of cavity depth.

Subsequently, multiple research projects are presented on improving the acoustic performance of mufflers, however, there is still a need to enhance their performance by using recognized natural materials. Thus, this study evaluates the potential of natural fiber materials as effective sound absorbers in exhaust mufflers and determines the performance of elliptical mufflers by assessing factors such as liner materials and thickness, and their impact on sound transmission loss. In this paper numerical simulation of a muffler based on FEM is accomplished using COMSOL Multiphysics represent in the methodology part. This covers the Mesh, boundary conditions, material, and model design structure.

2. METHODOLOGY

2.1 Theory

A sudden change in the particle positions within a medium produces a sound pressure wave. The tiny variation in the ambient static pressure concerning the total value of the ambient static pressure itself causes the sound pressure wave to propagate through space. These sound pressure waves usually move through an exhaust system's pipes as plane waves in the frequency range that matters for silencer analysis. In the mid-to-high frequency range, in particular, three-dimensional wave propagation can occur inside the muffler **(Roy, 2011).** The acoustic performance of an exhaust muffler is evaluated using various parameters, one of which is the sound transmission loss, formally denoted as (TL) **(Chichvarina and Smirnov, 2020)**. The architectural feature of the muffler plays a crucial role in disrupting the path of sound waves, thereby enhancing the overall transmission loss. TL is defined as the ratio of the incident sound energy entering the muffler to the transmitted sound energy exiting downstream **(Venkataraman and Raj, 2014)**. As sound waves encounter absorptive liners within the muffler, they undergo reflections and absorptions, which contribute to a reduction in noise levels emitted from the exhaust system **(Ranjbar and Kermani, 2015).**

$$TL = 10log\frac{w_i}{w_o} \quad (1)$$

where w_i the incident sound power and w_o The transmitted sound power. Since the sound's power is a function of both the area of the tube and the square of the sound pressure amplitude, Eq. (1) becomes: **(Ranjbar and Kermani, 2015)**

$$TL = 20log\left(\left|\frac{p_i}{p_t}\right|\right) + 10log\left(\frac{A_i}{A_o}\right) \quad (2)$$

p_i Refer to the incident pressure and p_t Refer to transmitted pressure. The variables show that the cross-sectional areas of the inlet and outlet tubes are A_i and A_o, Respectively **(Kalita and Singh, 2023)**. If $A_i = A_o$ Then, Eq. (2) becomes:

$$TL = 20log\frac{p_i}{p_t} \quad (3)$$

Based on earlier studies done by Delany and Bazley and the work done by Lord et al., the complex acoustical impedance (Zc) and wave number (kc) of an element could be found as indicated in Eqs. (4) and (5) **(Kalita and Singh, 2023; Lord and Gatley, 1987; Delany and Bazley, 1970)**.

$$k_c = k_o.\left(1 + 0.098.\left(\frac{\rho_o f}{\sigma}\right)^{-0.7} - i.0.189\left(\frac{\rho_o f}{\sigma}\right)^{-0.595}\right) \quad (4)$$

$$Z_c = Z_o.\left(1 + 0.057.\left(\frac{\rho_o f}{\sigma}\right)^{0.734} - i.0.087\left(\frac{\rho_o f}{\sigma}\right)^{-0.732}\right) \quad (5)$$

where the term Z_o is the characteristic impedance, σ the airflow resistivity, f the frequency, and ρ_o The density of the material.

2.2 Simulation

Besides transmission loss, parameters such as frequency response and impedance matching are crucial in determining the performance of any muffler. An efficient design is crucial to guarantee that the muffler effectively functions throughout a wide range of frequencies, especially those that are most common in the engine's exhaust profile. Engineers can optimize muffler design by fine-tuning parameters to reduce objectionable noise while ensuring adequate exhaust flow. Furthermore, selecting appropriate materials can also play a significant role in dampening sound frequencies.

Simulation is implemented using COMSOL Multiphysics software v6 based on the finite element method (FEM) since the software offers a reliable foundation for modeling the intricate interactions between sound waves and various material characteristics of the muffler.

The study started by building geometry primitives corresponding to the proposed muffler model featuring a centered single inlet and outlet at each end. Initially, a proposed model of a circular muffler was built as depicted in **Fig. 1,** featuring inlet and outlet tubes with a diameter and a length of 150 mm. The muffler chamber has a diameter of 203.2 mm and a length of 457.2 mm.

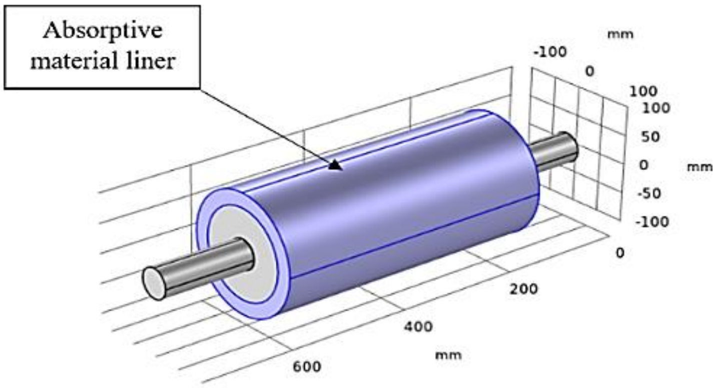


Figure 1. Initial circular exhaust muffler model with liner.

The proposed model was validated by comparison against analytical values obtained through other models from the literature **(Kalita et al., 2015)**. The result showed an accurate outcome for the proposed model compared to the Kalita model for varied liner thickness, as depicted in **Fig. 2.**

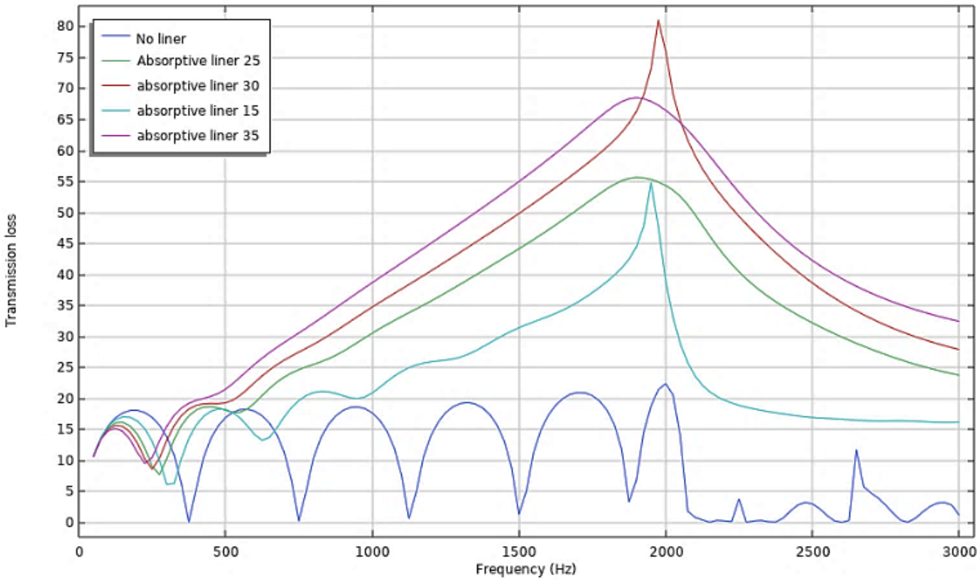


Figure 2. Model validation with the Kalita model for varied thicknesses **(Kalita et al., 2015)**.

2.2.1 Developed Model

Depending on the intended use, automotive mufflers are available in a wide variety of sizes, shapes, and styles. Typically, oval or round-shaped chambers are the more enormous fits between an inlet and an output tube in an automotive exhaust muffler, therefore, the initial design is developed into an oval, followed by the creation of a three-dimensional model, first without a liner and then with a liner layer. The sound-absorbing material is built as a liner layer of the muffler and analyzed using various absorptive materials and thicknesses as detailed in **Table 1** and **Fig. 3.**

Table 1. Design dimensions of the exhaust absorptive muffler.

Muffler dimensions in (mm)	
Inlet/outlet tube diameter	80
Inlet/outlet tube length	150
Muffler chamber height	150
Muffler chamber width	300
Muffler chamber length	600
Liner thickness	15, 25, 35

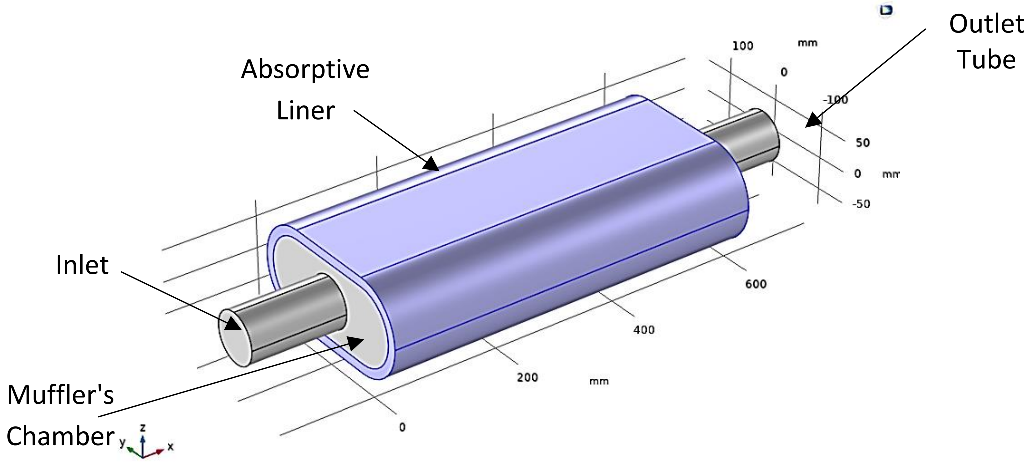


Figure 3. Exhaust muffler geometry with sound absorption liner.

2.2.2 Boundary Conditions

This study utilizes a specific boundary condition to calculate the muffler's sound transmission loss. This boundary condition is essential for precisely modeling the acoustic environment within the muffler model in COMSOL software, allowing for a detailed assessment of sound wave propagation and reflection.

1- The pressure incident wave is set to 1 Pa at the inlet, and the radiation condition is taken at the outlet.
2- All the outer muffler boundaries are considered solid hard wall boundaries with zero velocity.
3- The simulation analysis covered a frequency domain of up to 6000 HZ.
4- All model walls are considered hard sound walls to prevent any vibration.

2.2.3 Materials

The study utilized three waste materials as muffler liners to evaluate their sound absorption capabilities. The waste materials selected for this investigation included recycled corn husks, as well as the waste of date palm and coconut fiber.
It is essential to ascertain the airflow resistance of these materials; the values of these material attributes were derived from prior research that examined acoustic performance. **(Sari et al., 2016; Taban et al., 2021; Fouladi et al., 2011)**. Understanding the airflow

resistance can help better predict how these materials perform in real-world applications. To further comprehend how changes in material composition might impact sound absorption, it is necessary to conduct a comprehensive analysis of the correlation between airflow resistance and acoustic dampening capabilities. The material's characteristics are shown in **Table 2**.

Table 2. Sound absorption materials characteristics.

Material	Airflow resistivity ($Pa.s/m^2$)	porosity	Fiber diameter (μm)	Fiber Density (kg/m^3)
Date palm	2173	0.87	-	125
coconut	1680	-	252	821
Corn husk	1375	0.88	-	344

2.2.4 Mesh

The next step is to create the model mesh after constructing the geometry and assigning the physics. Mesh generation is a crucial preprocessing step in FEM, which can be time-consuming for analysts. Meshing is a technique of partitioning an infinite geometric domain into discrete elements and nodes **(Prasad and Thiagarajan, 2015).** A well-designed mesh ensures accuracy in capturing the system's behavior under study. The domain must be appropriately meshed into elements of certain forms, such as triangles and quadrilaterals. No overlaps or gaps are permitted. Information, such as element connectivity, must also be generated during meshing for later simulation **(Liu, 2002)**.
Depending on the level of discretization the user of the FEM desires to perform, a series of algorithms that might be relatively basic or rather difficult are used for this **(Wördenweber, 1984)**. By reducing complex structures to a finite set of equations that computers can solve, discretization makes it possible to approximate physical processes numerically. It links an academic model and an actual simulation, transforming intangible ideas into measurable information **(Madier, 2023).** A mesh was created based on the muffler geometry shown in **Fig. 4.** A physics-controlled mesh with fine element size was chosen as the sequence type, this mesh is structured so that the size of each element does not vary from element to element. The number of mesh elements per wavelength is chosen as automatic. Finally, the Complete mesh consists of 268819 domain elements, 19952 boundary elements, and 1100 edge elements.

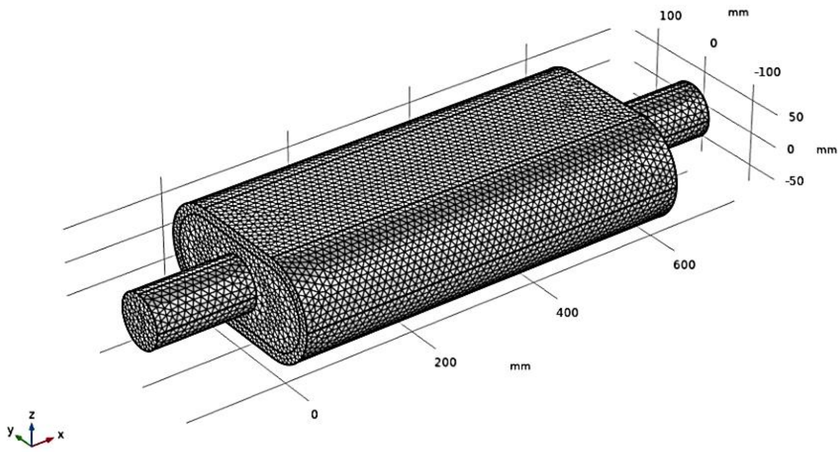


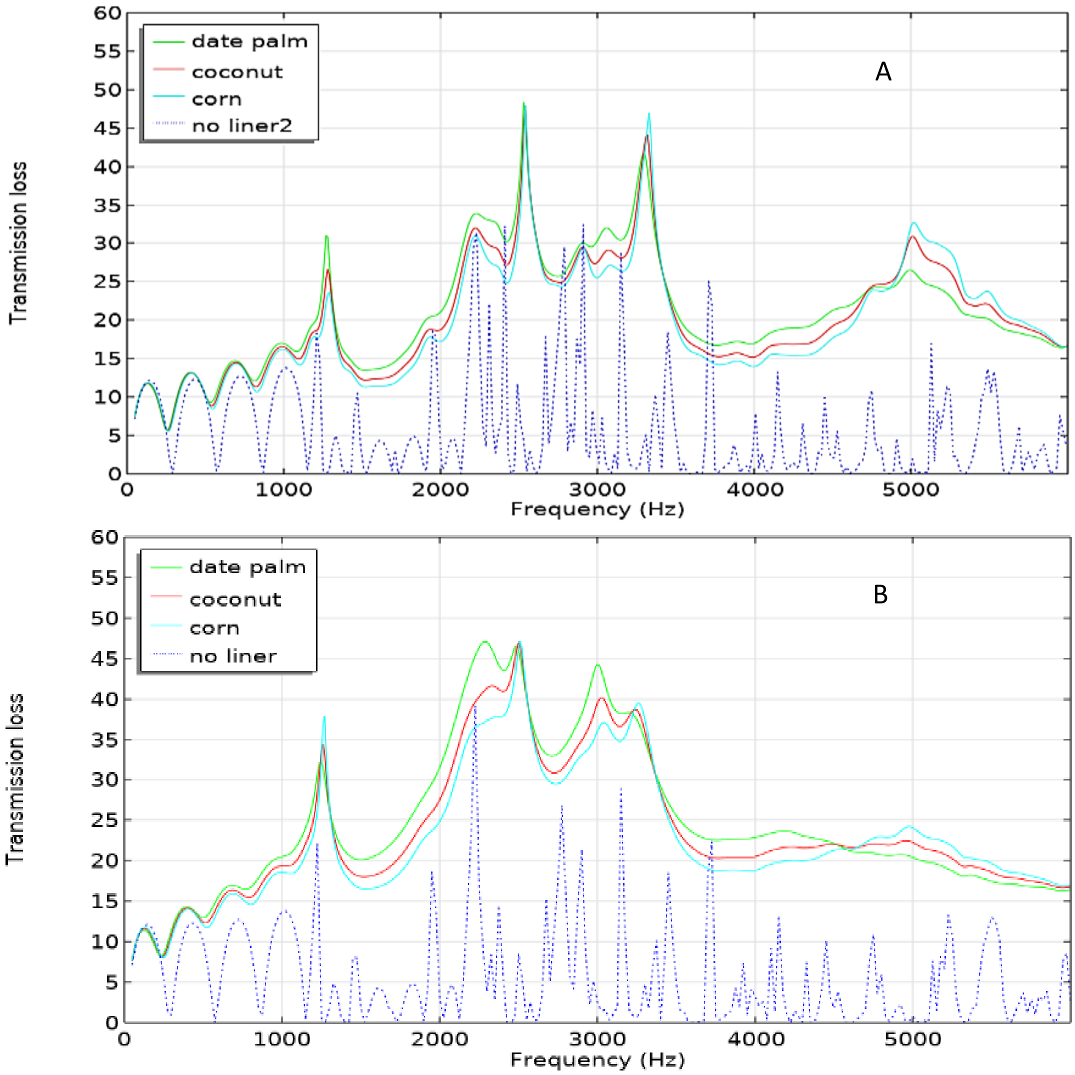
Figure 4. Meshed geometry of an exhaust muffler.

3. RESULTS AND DISCUSSION

Numerous variables, including sound transmission loss, noise reduction, and insertion loss, can be used to assess a muffler's acoustic properties **(Arslan et al., 2020).**
The study evaluated a muffler's performance by assessing many factors such as liner materials, liner thickness, and inlet/outlet diameter. The objective is to determine the best combination of these parameters. Also, evaluate natural material fiber's potential as an effective sound absorber in exhaust absorptive mufflers.

3.1 Materials and Liner Thickness

A simulation analysis was initially conducted to evaluate the transmission loss of a muffler without an absorptive liner. Additionally, several absorbent materials were utilized in the muffler lining simulations. **Fig. 5** illustrates the effect of three absorbent materials (date palm trunk, coconut, and corn) and their thickness on the muffler's transmission loss in decibels (dB) across a frequency range of up to 6000 Hz. According to these results, a muffler without a liner was initially studied to investigate the effect of the liner on muffler sound attenuation. The numerical analysis of a liner thickness of 15 mm revealed that all materials exhibited diminished peaks up to 500 Hz.



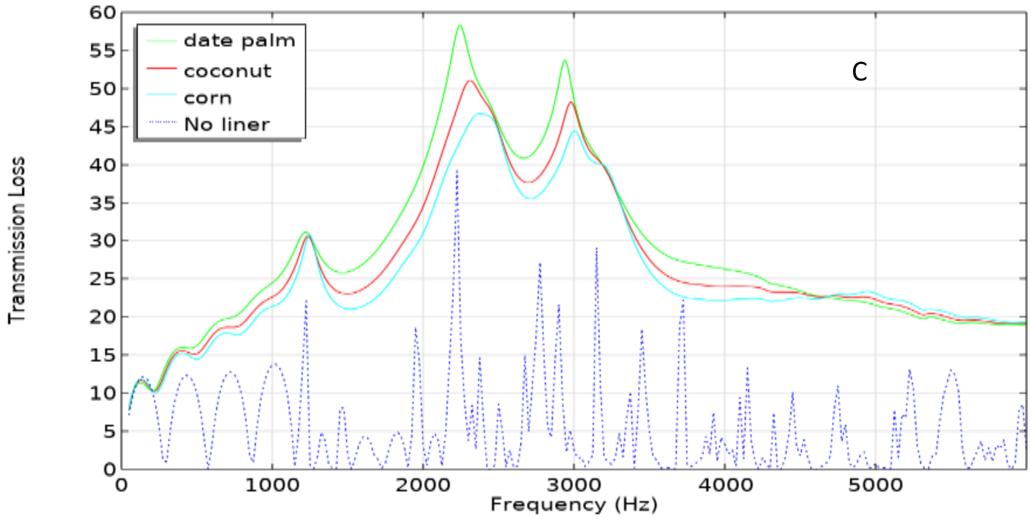


Figure 5. Exhaust muffler sound transmission loss with liner thickness (A) 15 mm, (B) 25 mm, (C) 35 mm.

In contrast, the date palm absorbing material, which has a higher airflow resistivity, demonstrated a gradual increase in transmission loss beyond 500 Hz, with significant peaks occurring at 1.25, 2.5, 3.4, and 5 kHz, reaching transmission loss levels of 31, 49, 46, and 33 dB, respectively. After this point, the transmission loss steadily decreased until it reached 17 dB. This indicates that the primary determinant of the acoustic materials' ability to transmit and absorb sound is airflow resistivity.
An investigation into transmission loss has been conducted on three cases of muffler liner thicknesses: 15 mm, 25 mm, and 35 mm. This study indicates that absorptive mufflers with thicker liners enhance sound transmission loss for all three materials used.

3.2 Inlet/ Outlet Diameter

For this study, three diameters were selected for the inlet and outlet tubes: the first diameter is 50 mm, while the others are 80 mm and 100 mm. The results for muffler transmission loss, both with and without a liner, indicate that a decrease in inlet/outlet diameter results in an increased transmission loss of the absorptive muffler, as illustrated in **Fig. 6**. This phenomenon occurs because an increase in tube diameter leads to a decrease in sound wave pressure. According to the sound transmission loss equation discussed in the theory section, if the logarithmic value of the incident to transmitted sound pressure ratio increases, the sound transmission loss also increases. Initially, mufflers without liners show increasing transmission loss in all frequencies over the frequency range (0 to 6000 Hz) when the inlet/outlet tube diameter decreases. Then the muffler with absorptive liner across the frequency up to 1000 Hz shows a small increase in the transmission loss value. At the frequency range of 4000 Hz and above, we also notice a noticeable increase in sound transmission loss value until it gradually decreases until the frequency of 6000 Hz.

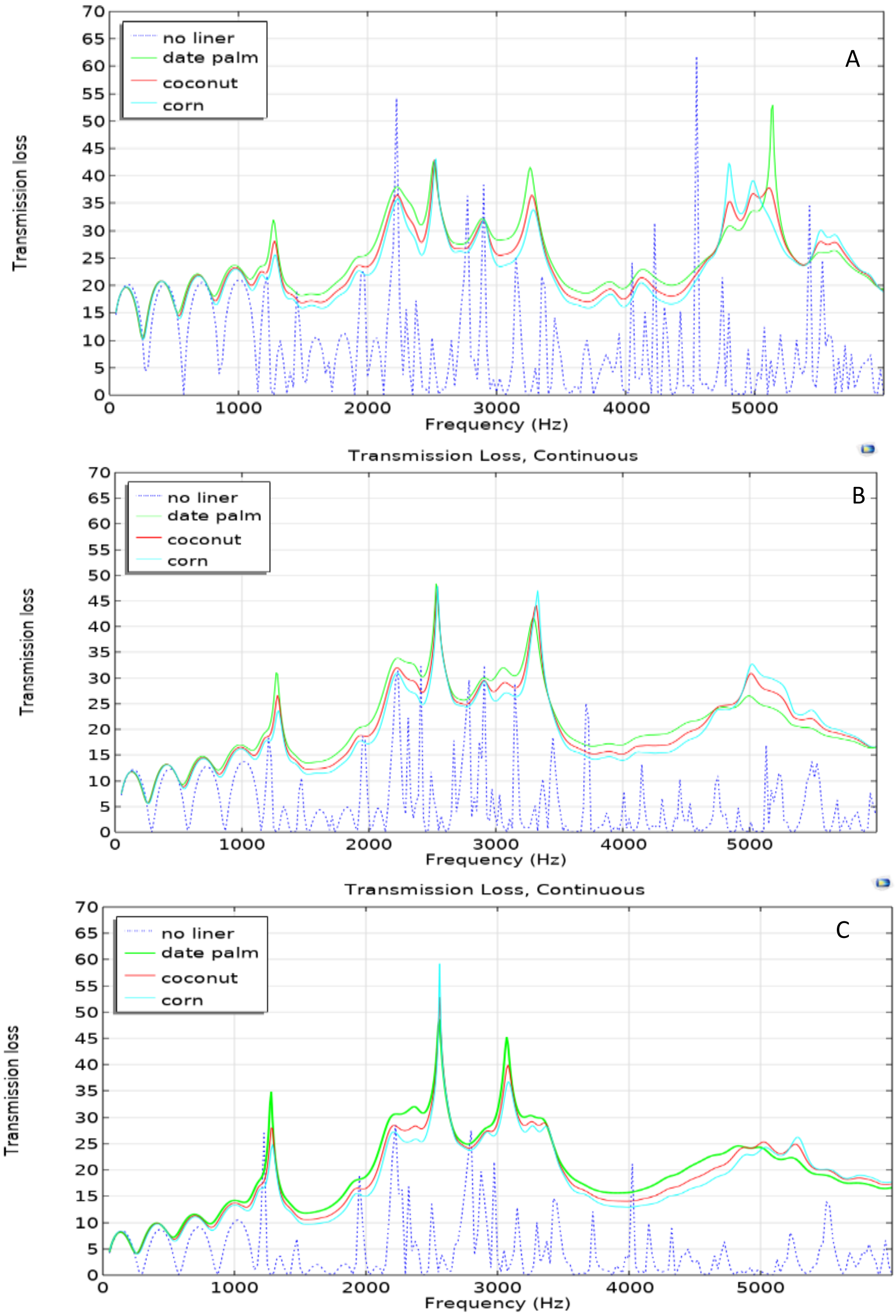


Figure 6. Exhaust muffler transmission loss with liner thickness of 15mm and inlet/outlet tube diameter of A) 50 mm, B) 80 mm, C)100 mm, respectively.

4. CONCLUSIONS

Pressure acoustic frequency domain analysis was employed to calculate the transmission loss and determine the optimal sound-absorbing material for use in mufflers. Initially, the transmission loss of a muffler without a liner was studied. The date palm, coconut, and corn fibers were utilized as absorptive muffler liners. The liner materials were analyzed at three thicknesses (15, 25, and 35 mm) and three inlet/outlet diameters (50, 80, and 100 mm). A deeper comprehension of how geometry influences noise transmission loss in an absorptive muffler can be achieved by investigating various inlet/outlet diameters and liner thicknesses. Based on the materials' airflow resistivity (Rf), the results indicated that materials with higher Rf values exhibit better sound attenuation characteristics. The analysis also suggests that a reduction in the inlet/outlet diameters increases the transmission loss of the absorptive muffler. Additionally, the two upper peaks of the curves for liner thickness shift to lower frequencies, with different materials displaying distinct tendencies in this regard.

NOMENCLATURE

Symbol	Description	Symbol	Description
A_i	Area of the inlet tube	w_o	Transmitted sound power
A_o	Area of the outlet tube	Zc	Complex acoustical impedance
p_i	incident pressure	Z_o	Characteristic impedance.
p_o	Transmitted pressure	ρ_o	Density of material (kg/m^3).
TL	Transmission Loss.	σ	Airflow resistivity (Pa.s/m^2).
w_i	Incident sound power		

Credit Authorship Contribution Statement

Asmaa O. M. Raoof: Writing – review & editing, Writing – original draft, Validation, Software, Methodology. Ali I. Mosa: Supervising and following up the research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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التقييم العددي لفعالية مواد بطانة كاتم الصوت العادم المختلفة على الأداء الصوتي

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الخلاصة

شهدت مستويات الضوضاء ارتفاعًا سريعًا في السنوات الأخيرة، ويعود ذلك بشكل رئيسي إلى انتشار الأجهزة الحديثة ومصادر الضوضاء الحرجة، مثل كاتمات عوادم المحركات. ويمكن للتحكم في الضوضاء الصادرة عن كاتمات الصوت أن يقلل من تأثيرها على المجتمعات المحيطة. وعادةً ما تستخدم كاتمات الصوت التقليدية مواد ليفية مسامية باهظة الثمن، تمتص الصوت، وتتميز بتكلفة عالية وتأثيرات ضارة. لذا، تُستخدم مواد صديقة للبيئة كمواد بديلة نظرًا لانخفاض تكلفتها وتأثيراتها السلبية. تهدف هذه الدراسة إلى تقييم إمكانات ألياف المواد الطبيعية كممتص فعال للصوت في كاتمات امتصاص العادم. كما تهدف إلى تقييم أداء كاتم صوت بيضاوي الشكل من خلال دراسة عدة عوامل، بما في ذلك مواد البطانة، وسمكها، وكيفية تأثير هذه العوامل على فقدان انتقال الصوت. تُستخدم طريقة العناصر المحدودة لمحاكاة وتحليل فقدان انتقال الصوت في نموذج كاتم صوت بيضاوي ثلاثي الأبعاد، مبني باستخدام برنامج COMSOL Multiphysics. وقد اقترحت هذه الورقة نموذجًا لكاتم صوت عادم باستخدام نفايات (جذع نخيل التمر، وجوز الهند أو جوز الهند، وألياف الذرة) كمواد صديقة للبيئة لامتصاص الصوت. بالإضافة إلى ذلك، أُجريت دراسة بارامترية بنطاق ترددي يصل إلى (6000) هرتز لتقييم تأثير سُمك البطانة وقطر أنبوب المدخل/المخرج على فقدان النقل. أشارت النتائج إلى أن مقاومة تدفق الهواء (Rf) هي العامل المؤثر الذي يحكم فقدان نقل الصوت؛ حيث توفر المواد ذات مقاومة تدفق الهواء الأعلى تخفيفًا أفضل. أظهرت المواد الماصة ذات مقاومة تدفق الهواء الأعلى ارتفاعًا تدريجيًا في فقدان النقل بعد 500 هرتز، مع ظهور قمم ملحوظة عند الترددات (1.25، 2.5، 3.4 و5) كيلوهرتز. علاوة على ذلك، فهي فعالة في تقليل قطر المدخل/المخرج وزيادة سُمك البطانة.

الكلمات المفتاحية: كاتم الصوت الماص، الصوتيات، مواد ماصة للصوت، فقدان نقل الصوت.