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ORIGINAL RESEARCH

Development and evaluation of agro-waste composite for sound insulation

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Abstract

The palm kernel shell is a by-product of palm kernel oil production and is commonly used in the natural biomass energy industry. Coconut husk fibre is extracted from the coconut fruit. To find a use for palm kernel shells and coconut husk fibre, a composite insulator plate was developed by the addition of a binder through a process of grinding, sieving, mixing, heating, hot-pressing and cooling in a mould. An Ahuja speaker AU60 was fixed at one end of a baffled tube and a sound level meter was placed 2 m away from the output to record sound transmission loss at 5s intervals for twenty minutes. The plates of 3, 4, 5, and, 6 mm thickness were fixed in the baffled tube at a distance of 475 mm away from the input one after the other to filter the input sound. The results showed that the setup without a composite insulator recorded the highest noise of 226.8 dB. The average recorded sound transmitted loss was 185.40, 72.47, 74.54, 76.06, and 82.85 dB for no insulator, 3, 4, 5 and, 6 mm composite insulators respectively. The introduction of the 3, 4, 5, and, 6 mm thickness composite insulators resulted in 55.3 %, 59.0 %, 59.8 % and 60.9 % reduction in noise level. The application of agro-waste composite material as a sound insulator in a baffled tube has proven to be effective by 58.7 % on average. The study has confirmed that agro-waste materials can be used in sound insulation applications.

Keywords: Baffled Tube, Composites, Natural Fibres, Sound Transmission Loss, Agro-waste

Introduction

Noise pollution has emerged as a significant environmental concern to public health over the past two decades (Firdaus and Ahmad, 2010). The awareness of the harmful effects of noise has promoted the development and use of sound absorbers and insulators in various fields of engineering. Synthetic fibres such as mineral wool and polymeric foams are used as sound absorbers in the construction and building sectors (Liang *et al*., 2022). Generally, synthetic and mineral materials used as sound absorbers provide high sound absorption, thermal insulation, and better fire-controlling properties than natural fibres. However, several studies in the literature report an increase in the interest in using agro-waste materials as sound absorbers or insulators. Natural fibres are increasingly used as interior lining for apartments, music recording studios, aircraft, ducts, and bio-composite products (Rahman *et al*., 2017).

Madurwar *et al*. (2013) report that the general reason for using natural fibres from agro-waste is its low density, biodegradable and low cost. Natural fibres have numerous advantages over synthetic fibres because they are renewable, abundant, non-abrasive, eco-friendly and have fewer health and safety concerns in terms of handling and processing. Literature shows that natural fibre has good sound absorption properties. Some researchers over the years have used animal fibres and vegetative covers such as cotton, kenaf, sisal, bagasse, coir, and wool (Nair and Joseph, 2014). others have also used agricultural by-products and waste as sound-absorbing materials (Rubino *et al*., 2019). Several researchers Khedari *et al*. (2003), and Zulkifli *et al*. (2008) have succeeded in developing particle composite boards using agricultural wastes. For instance, Jayamani *et al*. (2014) produced rice straw-wood particle composite boards whose properties are to absorb noise, preserve the temperature of indoor living spaces and be able to partially or completely substitute for wood particleboard and insulation board in wooden construction. The authors reported that the sound absorption coefficient of board made from rice straw-wood particle composite was higher than other wood-based materials which are in the range of 500-8000 Hz. The authors attributed the outcome to the low specific gravity of composite boards, with higher porosity than other wood-based materials. In another research, Kalauni and Pawar (2019), and Khair *et al*. (2016) developed vegetable fibre from coconut, palm, sisal, and acai, which were used as sound absorbing Panels.

Experimental assessment of the models using a measurement scale reverberation chamber shows promising acoustic performance results for all panels. Similarly, Koizumi *et al*. (2002) developed bamboo fibre as a sound-absorbing material. They reported that the bamboo fibre material has equivalent acoustics properties to glass wool. Subsequently, Jayamani and Hamdan (2013) sound absorption coefficient of urea-formaldehyde and polypropylene mixed with kenaf fibre. They reported that the kenaf fibre reinforced with polypropylene demonstrates higher sound absorption coefficients than the kenaf fibre reinforced with urea formaldehyde. These previous studies presented a better understanding of the microstructure and physical parameters of material that could help in developing high-performance acoustic materials. Current research shows that agro-waste from oil palm extraction has the potential to be used as a good sound absorption material. For instance, Taban *et al*. (2020), and Samsudin *et al*. (2016) used (empty fruit bunches) EFB and investigated the effects of density, thickness and air gap on sound absorption characterization (SAC). They found that 40 mm and 50 mm samples with a density of 292 kg/m^3 had the best sound absorption characterization (SAC) of 0.9 on average above 1 kHz.

The authors also found that the performance of (empty fruit bunches) EFB is similar to that of rock wools. Samsudin *et al*., (2017) studied a mixture of (empty fruit bunches) EFB and melamine formaldehyde (MF) with urea formaldehyde (UF) as the binder to generate an acoustic panel (empty fruit bunches mesocarp fibre) EFBMF using 15 % of UF as matrix binder achieved 0.58 noise reduction coefficient at a density of 0.4 g/cm^3. In another research using reverberation room measurement, an acoustic panel made from 100 % MF coir had the best

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sound insulation rating according to ISO 11654 (Samsudin *et al*., 2018, Ong *et al*., 2020). This means that the panel could absorb more than 90 % of the incident sound. Further studies conducted by (Nasidi *et al*., 2018) used palm fronds and urea formaldehyde (UF) as a binder and were observed to have excellent sound absorption capability. Also, Nasidi *et al*., (2018) studied the effects of fibre length and UF content on sound absorption characterization (SAC) of empty fruit bunches (EFB). The optimum fibre length was reported to be 2-5 mm. In terms of UF content, all the samples up to 40 % showed a good noise reduction coefficient of 0.70 and above with a density of about 0.3 g/cm^3. Current research has shown that oil palm wastes including kernel shells can be used as an acoustic insulator, therefore this research sought to (1) develop a sound insulator using a composite of palm kernel shells and coconut husk fibre, (2) experimentally evaluate the model sound insulator for acoustic performance characteristics and (3) propose an application for the model sound insulator.

Materials and Methods

Palm kernel shell, coconut shell, and coconut husk composite (PKCSCH) development

The PKCSCH was prepared from 23.4 g of palm kernel shell, 23.3 g of coconut shell, and 23.3 g of coconut husk particulate reinforcement of size 75 µm and Epoxy matrix. The composite was designed according to the formulation given in Table 1. The epoxy was sourced from the local market and palm kernel shells, coconut shells and coconut husk were obtained from a local palm oil processing firm in Koforidua magazine and some disposal joints respectively. The agro waste was washed with distilled water and oven-dried for 24 hrs. to remove moisture. It was then surface-treated by soaking in 5 % NaOH solution for 24 hrs. To achieve better fibre-matrix bonding.

Table 1 Composite formulation

	PKCSCH	Epoxy
Mass Fraction %	70	30

After the surface treatment, the shells were oven-dried for 24 hrs. and pulverized to obtain a particle size of 75µm. Seventy (70 g) of the pulverized PKCSCH was weighed and transferred into a beaker containing 30 g of epoxy, the ingredients were mixed until a homogeneous mixture was obtained. The mix was transferred into the Mould and tightly closed; it was then placed in an oven at a temperature of 22 – 27 ℃ for 20 minutes to initiate curing. After which it was removed from the oven and the composite was allowed to continue curing in the mould for 24 hrs. at ambient temperature. The mould was opened after 24 hrs. to obtain the composite.

Description of composite mould

The mould was formed using a galvanized steel pipe and mild steel plate. Four different rings of 108 mm as inner diameter with a thickness of 3 mm were machined from a galvanized pipe into the following sizes: Height of 11 mm, 12 mm, 13 mm and 14 mm respectively.

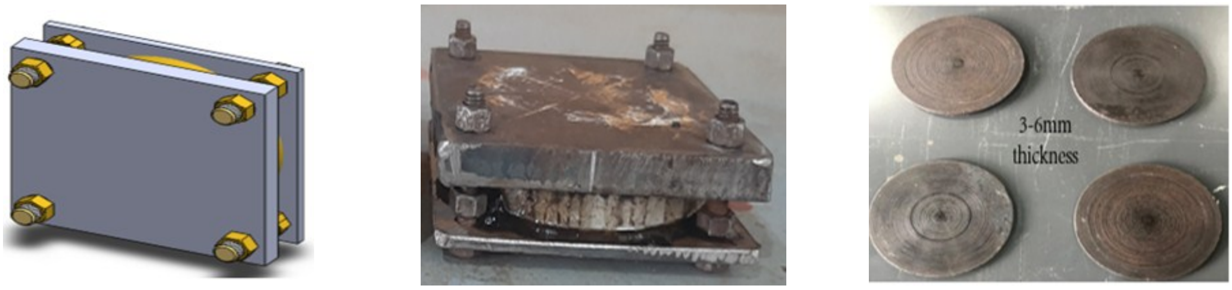
A stepped diameter of 116.9 mm with a height of 8mm was machined from the mild steel plate of dimension 150 × 150 ×12 mm. This was used to achieve the varying thickness of the composite. A cover plate with dimensions 150 × 150 × 12 was used to achieve maximum compression during curing. The components of the mould are presented in Figure 2.

Development of an experimental baffled tube

For this study, an experimental baffled tube is developed to evaluate the sound insulation performance characteristics of the

(a) Palm kernel shell (b) Coconut shell (c) Material Treatment (d) Coconut husk (filler)

Figure 1 Agro-waste materials

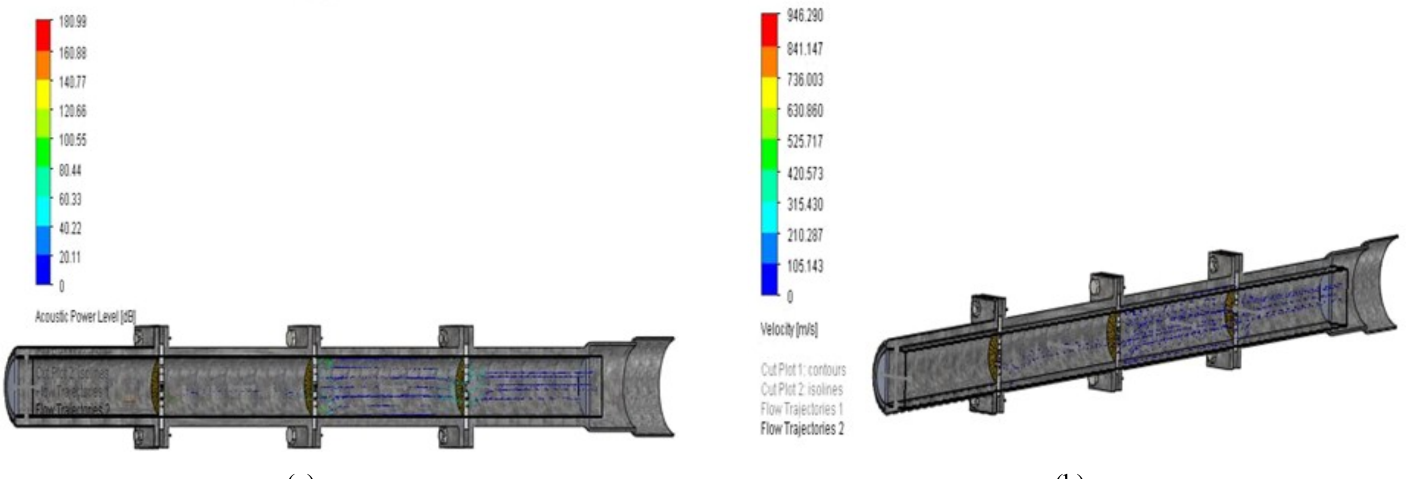


(a) (b) (c)

Figure 2 (a) Complete mould, (b) fabricated mould, and (c) moulded composite

(a) (b)

Figure 3 (a) 3D view of the baffling tube, and (b) skeletal view



(a) (b)

Figure 4 CFD contour plots of acoustic power level, and (b) fluid velocity

developed composite material. The tube is made from steel comprising four separate parts firmly supported with bolts and nuts. The joints serve as support ends for the composite material developed.

An Ahuja speaker AU 60 model is fixed at one of the tubes to serve as an input for sound wave transmission. The dimensions of the baffled tube include; the full length of the tube of 1900 mm and an inside diameter of 108 mm.

Computational fluid dynamic analysis on the baffled tube- Computational fluid dynamics is applied to a wide range of research in engineering. CFD is used to simulate fluid flows and analyze flow characteristics using numerical methods (Afshari *et al.*, 2018). Applying a differential form of continuity equation to the baffled tube yields:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0 \tag{1}$$

Conservation of momentum is defined by equation (2):

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v}\vec{v}) = -\nabla p + \nabla(\overset{=}{\tau}) + \rho \vec{g} + \vec{F} \tag{2}$$

Equations (1) and (2) form the simplest and generally used turbulence model. The standard is a known turbulence model used for solving practical engineering flow problems (Hanjalić and Kenjereš, 2008). The transport equations for the standard $k-\in$ model is expressed in Equation (3) and (4):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_1}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho \in - Y_M + S_k \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \in) + \frac{\partial}{\partial x_1}(\rho \in u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\in}\right)\frac{\partial \in}{\partial x_j}\right] + C_{1\in}\frac{\in}{k} + (G_k + C_{3\in}G_b) - C_{2\in}\rho\frac{\in^2}{k} + S_\in \tag{4}$$

The equation of turbulence viscosity is defined by Equation (5):

$$\mu_t = \rho C_\mu \frac{k^2}{\in} \tag{5}$$

The model constants are given as:

$$C_{1\in} = 1.44, C_{2\in} = 1.92, C_\mu = 0.09, \sigma_k = 1.0, \sigma_\in = 1.3 \tag{6}$$

Computational fluid dynamics was performed on the designed baffled tube to verify the acoustic flow path using the SolidWorks Flow simulation 2022 version. In the simulation, thermodynamic properties such as pressure and temperature were set at 101325 Pa and 293.2 K respectively.

The computational domain was set in all directions to enclose the baffled tube. The inlet and outlet boundary conditions of the baffled tube were defined. An input speed of 5 m/s was set as the speed for the incoming fluid (air) velocity through the defined input end of the baffled tube. The flow path showed that once sound enters the tube from the input end its transmission to the output is free without interference. The contour flow plots acoustic power level and velocity of fluid flow are presented in Figure 4. The CFD simulation sequence is presented as follows:

- Creating the study (baffled tube)
- Assigning material (e.g., pressure, temperature, Mach number etc.)
- Applying restraints/ boundary conditions
- Meshing the baffled tube
- Running CFD analysis
- Visualizing the results

Sound transmission loss measurement within the baffled tube

The experimental setup for evaluating the sound insulation performance characteristics of the developed composite material models is presented below; the experimental setup comprises of AU60 Ahuja speaker, amplifier, sound level meter, microphone, computer, composite and baffled tube. Data logging instrumentation for the experiment consisted of a precision grade sound level meter (according to IEC 651 type 2, ANSI S1.4 type 2 class standards), 1/2-in. condenser microphone and 1/3-octave filter with the frequency range of 31.5Hz - 8kHz respectively. The instrument was calibrated by the internal sound level calibrator before taking measurements. To evaluate the sound insulation characteristics of the composite, four models of thickness 3mm,4mm,5mm and 6mm respectively were developed. The developed models were inserted between the flanged ends of the tube and firmly held with bolts and nuts. The sound meter level was used to record the noise in the baffled tube without a composite model in between the gaps of the flanged ends. Subsequently, the 3 mm composite model was fixed between the gaps in the baffled tube and the noise in the tube measured behind the composite to determine the amount of noise the composite can insulate within 20 minutes. The

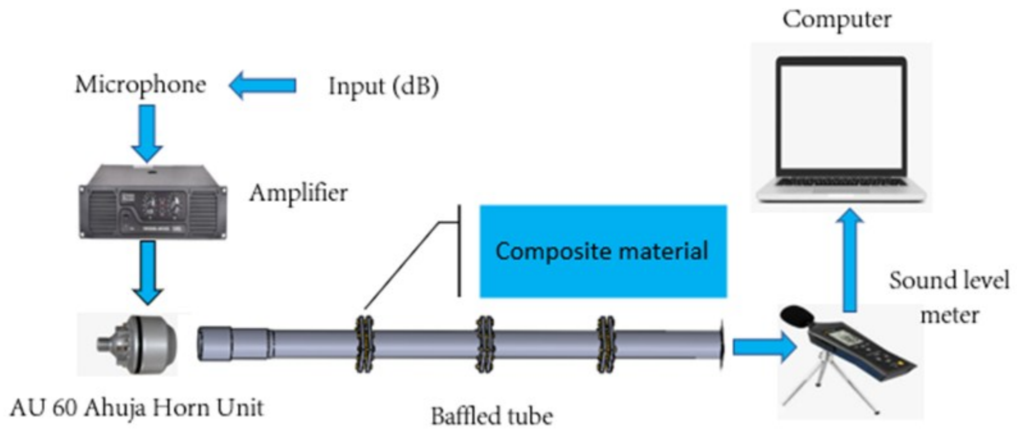


Figure 5 Experimental setup

measurement was done twice and the average noise in decibels was recorded. This was done to reduce environmentally induced errors or errors due to the sound-to-air ratio. The process was replicated for the 4 mm, 5 mm and 6 mm composite models.

The models served as baffles within the transmission paths of sound emanating from the AU 60 Ahuja horn speaker inserted at the input end of the tube. The sound level meter was used to measure the quantity of noise generated behind each model composite inserted between the transmission gab. It was fixed at a distance of 2 m from the output end of the baffled tube. L_{Ai} (A-weighted instantaneous sound pressure level) measurement was recorded at intervals of 5s for 20 minutes per sample composite material fixed in the baffled tube. A total of 200 data points were recorded within the stipulated time frame for every sample composite. The recorded sound transmission losses with the insertion of the composite materials within the baffle tube are compared to noise levels in the baffle tube without any insulating composite material. The experimental setup is presented in Figure 5 with a background noise of 181 - 226.8 dB.

Signal processing of sound transmission loss waveform

Fast Fourier transformation

Sound transmission loss waveforms were obtained in the range of 1-1000 seconds time-domain. The sound transmission loss was converted to the corresponding frequency-domain spectra by fast Fourier transformation (FFT). FFT is a fast computation method of discrete Fourier transform (DFT), which is given by:

$$F(k)=\sum_{i=0}^{N-1} f(n)e^{-j\left(\frac{2\pi}{N}\right)nk} \tag{9}$$

Given that, $$W_N = e^{-j\left(\frac{2\pi}{N}\right)} \tag{10}$$

$$F(k)=\sum_{i=0}^{N-1} f(n)*W_N^{nk}(k=0,1...,N-1) \tag{11}$$

Where N is the transform size, and f (n) is the sequence of the input. In this study, the FFT function provided by OriginLab was employed to decompose the original N-point sequence into a series of short sequences. The FFT makes complete use of the symmetry and periodic properties of the exponential factors in the DFT program. Subsequently, it obtains the corresponding transformations of these short sequences and makes the fitting combination to achieve the purpose of deleting the repeated calculation. In addition to the time domain spectra, an integer power of two (2) was required as the transform size. If the data length of the time-domain spectra is not equal to the transform size, adding zero is required.

Normalization of sound transmission loss waveform

Maximum normalization was applied to the data because of the great variation among the recorded sound transmission loss for each treatment. The maximum normalization was realised by dividing the sound transmission loss value for each treatment by the peak intensity value in each data set. The maximum normalization (STL_N) is given by the following equation;

$$STL_N = \frac{S_{(A-Z)}}{S_{(Max)}} \tag{12}$$

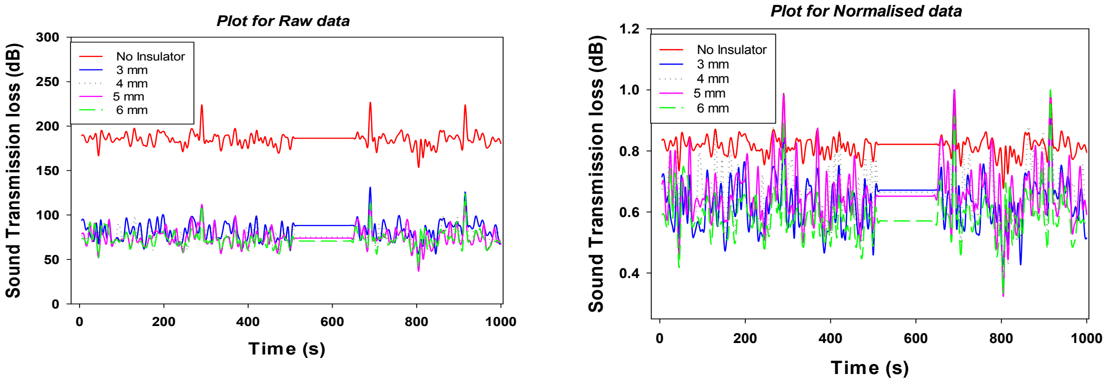
Where S is equal to the measured sound at a given point within the data set, A and Z are the initial and final data recorded for a given data set. $S_{(max)}$ is the maximum value obtained in the data set for a given treatment.

Statistical analysis of data

A statistical method such as partial least square regression (PLSR) was examined to obtain information on the performance of the composite material. PLSR can simply treat data matrices in which each item is described by hundreds of variables like sound transmission loss data (Nelson *et al.*, 1996). This technique can extract the relevant portion of the information for a large data matrix and produce the most dependable models. The correlation coefficient (R) of the prediction set *(R_p)* and the root mean square error of the prediction set (RMSEP) are used to evaluate prediction precision. *(R_p)* measures the degree of correlation between the predicted and measured values. It is computed by the following expression:

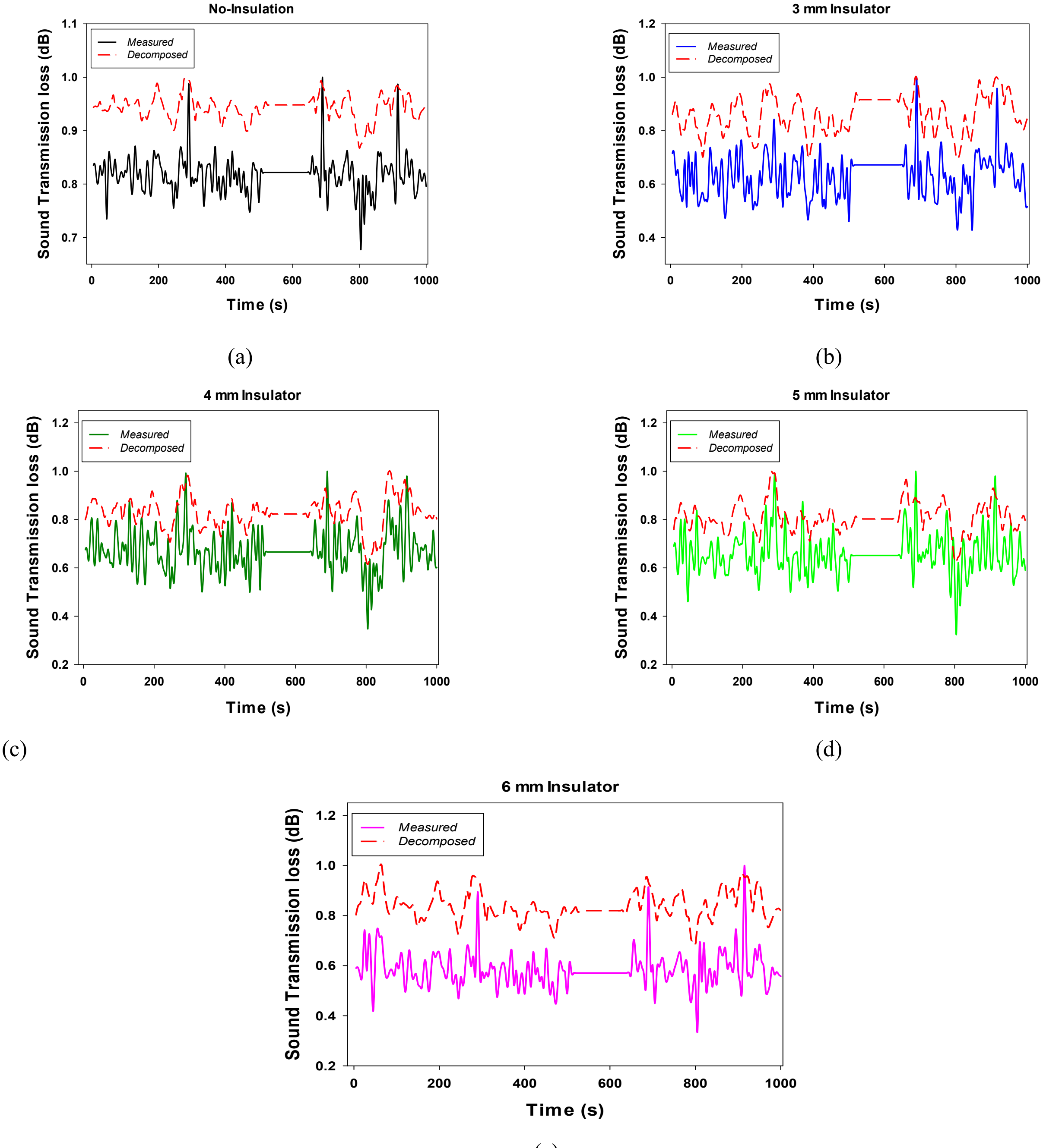
$$R = \frac{\sum_{i=1}^{N}(T_{is}-\overline{T}_{is})(S_{ip}-\overline{S}_{ip})}{\sqrt{\sum_{i=1}^{N}(T_{is}-\overline{T}_{is})}*\sqrt{\sum_{i=1}^{N}(S_{ip}-\overline{S}_{ip})}} \tag{13}$$

Where T_{is} and $\overline{T_{is}}$ are the reference values of the i^{th} sample and the average values of the reference values respectively; S_{ip} and $\overline{S_{ip}}$ are the predicted values of the and the average values of the predicted values respectively; N is the number of the samples. The RMSE of the predicted values S_{ip} for observations; I, of a regression's dependent variable, T_{is} is computed for N different predictions as the square root of the mean of the



(a) (b)

Figure 6 Sound transmission loss data plots (a) directly recorded, and (b) normalized

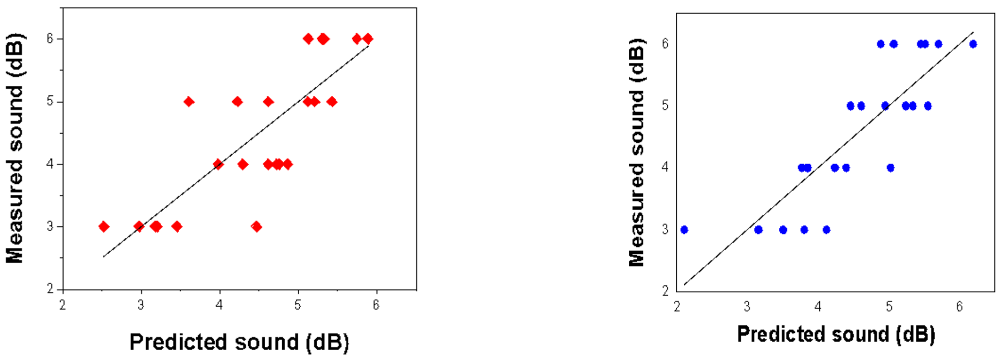


(a) (b)

(c) (d)

(e)

Figure 7 Smoothing and normalized plots at different order polynomial



(a) (b)

Figure 8 Scatter plots of statistical modelling (a) from measured, and (b) filtered

squares of the deviations. It is given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (S_{ip} - T_{is})^2}{N}} \quad (14)$$

Results and Discussion

Effects of insulator thickness on sound transmission loss

The experimental results for the various treatments are presented in Figure 6. Figure 6b is an improvement over Figure 6a. The gaps between the data values for the different treatments and control variables were significantly reduced due to the normalization. The sound level in the tube without an insulator is very high and ranges from 181 - 226.8 dB with an average of 185.40 dB. Further analysis showed that the introduction of 3, 4, 5 and 6 mm, thickness composite materials into the baffled tube resulted in average significant transmission loss of 72.47, 74.54, 76.06, and 82.85 dB respectively. The introduction of the 3, 4, 5, and 6 mm, thickness composite insulators resulted in 55.3 %, 59.0 %, 59.8 % and 60.9 % reduction in noise level respectively using No-insulator as a reference with significant differences ($P < 0.05$). The application of agro-waste composite material a as sound insulator in a baffled tube has proven to be effective by 58.7 % on average.

Sound-to-air ratio optimization

In other to improve the sound-to-air ratio and optimize the model performance, the FFT function of OriginLab was used to decompose the end-point signals of the sound transmission loss at 2 Savitzky–Golay. The results obtained for all treatment was plotted against the time sequence and presented in Figure. 7. There was no significant change between the recorded and the decomposed sound waveform for all treatments. However, the peak value of the decomposed sound was reduced by 13.5, 26.68, 19.16, 18.81, and 30.41 % for no-insulator, 3, 4, 5, and 6 mm, thickness composites respectively.

Model performance evaluation

To establish a more perfect PLSR model, it is necessary to decompose the endpoints signal of the sound transmission loss and reduce the surrounding sound that may exist in the dataset. Given this, smoothing at 2 order Savitzky–Golay was applied to the data for each treatment. The PLSR models without the decomposed endpoints and the model with the decomposed endpoints signal were built respectively and presented in the form of scatter plots (Figure 8). The scatter distributions of the PLSR model with the decomposed endpoints (Figure 8b) had a better fitting effect between the predicted and actual values compared with the original PLSR model (Figure 8a).

The PLSR models without the decomposed end points signals and the model with the decomposed end point signals were built respectively and presented in Table 2. Compared with the original model (R = 0.5238; $RMSE$ = 0.9829), the model of samples with the decomposed endpoints was more accurate with increased values of R_p and decreased values of RMSE (R = 0.7182; $RMSE$ = 0.5949). It means the model developed with the smoothed signal was considerably better than the model developed with original data by 27.1 % in correction coefficient and 39.5 % in RMSE.

Table 2 Partial least square analysis

Model	R	RMSE
Measured	0.5238	0.9829
Decomposed at 2 Savitzky - Golay	0.7182	0.5949

Conclusion

In this research, a composite from agro-waste material has been developed and its sound insulation characteristics determined. The areas considered were the influence of the variations in composite insulator thicknesses on sound transmission loss and the effect of decomposed signals on the performance of partial least square regression (PLSR) models in resolving the problems with overlapped signals. The experimental results showed that the setup without a composite insulator had the highest recorded noise of 226.8 dB. Furthermore, the average recorded sound transmitted loss was 185.40, 72.47, 74.54, 76.06, and 82.85 dB for No insulator, 3, 4, 5 and 6 mm composite insulators respectively. The introduction of the 3, 4, 5, and 6 mm thickness composite insulators resulted in 55.3 %, 59.0 %, 59.8 % and 60.9 % reduction in noise level. Statistical modelling using partial least square regression models shows a high correlation between measured and predicted sound transmission levels. The application of agro-waste composite material as a sound insulator has proven to be effective by 58.7 % on average for all models considered.

The quantitative result obtained from the PLSR of the decomposed signals was significantly better than the original PLSR. The combination of the Agro-waste composite and PLSR implemented the direct determination of the insulator thickness's effect on sound transmission loss and can also be used for quantitative analysis of other composite combinations that could be applied during sound transmission. The technique highlighted the spectra differences of different insulator thicknesses and provided excellent quantitative analysis. The study has confirmed that agro-waste materials can be used in sound insulation applications. The authors recommend that the technique should be applied to quantify the effect of composites of different Agro-waste materials on sound transmission loss.

Conflict of Interest Declarations

The authors declare that there is no conflict of interest with the information presented in this paper.

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