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Periyasamy, Aravin Prince; Karunakaran, Geyandraprasath; Rwahwire, Samson; Kesari, Kavindra

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# Nonwoven fabrics developed from agriculture and industrial waste for acoustic and thermal applications

Aravin Prince Periyasamy ·  
Geyandraprasath Karunakaran ·  
Samson Rwahwire · Kavindra Kesari

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**Abstract** Numerous researchers in the field of noise control and acoustics have found success in using biomaterials to create a porous sound absorber that is both effective and environmentally friendly. This paper discusses the utilization of fibers extracted from the waste from coffee husk (CH) and waste from the cotton (CO) spinning industry to be an alternative to synthetic-based acoustic materials. The study was conducted within the range of 50–6300 (Hz) frequency. Five well-known mathematical prediction models, namely Delany–Bazley (D–B), Garai–Pompoli (G–P), Miki, Allard Champoux (AC), and Johnson–Champoux–Allard (JCA) models are

theoretically used to predict the sound absorption coefficient of nonwoven fibrous materials. When compared with the experimental data, it was discovered that the JCA and AC model is the most acceptable model for predicting the absorption behavior of CH/CO nonwoven fibrous materials. Additionally, the thermal insulation of nonwoven fibrous materials has been experimentally and numerically studied. It is noteworthy that, when compared to the Herman model, the Bhattacharyya model's results showed slightly greater thermal conductivities. Overall, this work used an environmentally friendly way to turn waste into a valuable product.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10570-023-05285-7>.

**Keywords** Agrowaste · Coffee husk · Cotton waste · Sound absorption · Waste management

A. P. Periyasamy · K. Kesari  
Department of Bioproducts and Biosystems, School  
of Chemical Engineering, Aalto University, Espoo, Finland

A. P. Periyasamy (✉)  
Textile and Nonwoven Materials, VTT Technical Research  
Centre of Finland Ltd, P.O. Box 1000, 02044 VTT Espoo,  
Finland  
e-mail: aravin.periyasamy@vtt.fi

G. Karunakaran  
Department of Chemical Engineering, University  
of Chemistry and Technology, Prague, Czech Republic

S. Rwahwire  
Department of Polymer, Textile, and Industrial  
Engineering, Busitema University, Busitema, Uganda

## Introduction

The lifestyles of people who live in both urban and rural areas have changed as a result of the industrial revolution which impacts global pollution such as environmental and noise pollution. Noise pollution is a resurgence issue across Europe (Eulalia Peris 2020), and it is due to industrialization (Ahmed and Gadelmoula 2022), transportation (Wang et al. 2021), air traffic (Floud et al. 2013; Gély and Márki 2022), construction, social events (Lokhande et al. 2022), catering, and nightlife. To enjoy this sophisticated lifestyle, people must tolerate noise pollution as a

necessary by-product of modernization. Long-term noise exposure has physiological and psychological impacts on humans, resulting in hearing loss (Lokhande et al. 2022), interrupted sleep, stress, exhaustion, and cardiovascular disease (Floud et al. 2013; Eulalia Peris 2020), in addition to affecting biodiversity significantly (Sordello et al. 2020). The European environment agency (EEA) published a report, one in five Europeans is exposed to road traffic noise levels. On the other hand, the European Union (EU) states that the noise levels from road traffic are exceeding 55 decibels (dB), which impacts 40% of the EU population. In western Europe alone, at least 1.6 million healthy years of life are wasted because of road traffic noise (Zsuzsanna Jakab 2018). Currently, there is a growing demand for acoustic pollution management materials, which is critical. There are several ways to alleviate noise pollution. Using noise reduction materials is one of the ways to ameliorate noise pollution. Synthetic materials such as foams, glass fibers, polyester, and mineral wool are the widely used noise reduction materials, however, these are produced by petrochemical products (Rwawiire et al. 2017). The usage of hydrocarbon-based polymeric materials has high risks due to the minimal resource and high impact on environmental pollution as it affects the sustainable development goals (SDGs) SDGs6, SDGs13, SDGs14, and SDGs15. Currently, eco-friendly and sustainability are important criteria and researchers paid attention to the development of bio-based materials, due to advantages like degradability, renewability, abundant source, sustainability, and less pollution to the environment compared to hydrocarbon-based materials. Since most of these wastes are disposed of in landfills, these wastes could pose harm to the environment. Agricultural wastes are generally underutilized (Ahmed et al. 2020). Perhaps, turning agricultural waste into valuable products such as sound absorption material could reduce the consumption of existing synthetic materials resulting in the reduction of greenhouse gas (GHG) emissions in accordance Kyoto protocol (Rao and Riahi 2006), and the Paris agreement (Leahy et al. 2020) on global climate change. Rice-straw (Arumugam et al. 2021), wood-based materials (Cherradi et al. 2021), hemp waste-based materials (Fernea et al. 2019), tea leaf fiber materials (Prabhu et al. 2021), bamboo (Pu et al. 2022) and coconut coir materials (Bhingare

and Prakash 2021), and sisal fibers (Abdel-Hakim et al. 2021) are some bio-based materials researchers have investigated before and found these bio-based materials are on par with synthetic noise reduction material. According to the above findings, this study focuses on the materials derived from biological sources that possess sound-absorbing properties that are promising and offer excellent replacements for synthetic sound-absorbing materials.

In this work, coffee husk has been selected since it is agricultural waste, used to make a noise-reduction material. Globally, 7177 million kilograms of coffee were consumed in 2021, and it is expected to grow to 9.3 million kilograms by 2025 (2022). On the other hand, waste generation in coffee production results in pollution and the destruction of sustainability (Durga et al. 2021; Chilakamarry et al. 2022). The main goal of this work is to reuse the biomass waste generated during coffee processing and used it for acoustical applications. On this occasion, the fibers are extracted from the coffee husk and then blended with cotton fibers from industrial waste from the spinning industry to produce potential bio-based nonwoven fabrics for acoustical and thermal insulation materials for domestic applications which can be a substitute for traditional hydrocarbon-based materials. Additionally, this work is applied different mathematical models, including Delany-Bzaley, Garai-Pompoli, Miki, AC, and Johnson-Champoux-Allard, which are used to estimate the sound absorption coefficient (SAC) and sound absorption average (SAA) values of nonwoven fabrics, and the best models are reported in this paper. In addition, the thermal conductivity of the produced nonwoven fabric is studied, and then it is compared to two distinct thermal conductivity models, namely the Herman model and the Bhattacharyya model. Finally, the relationship between thermal and acoustic properties is discussed in detail in the paper.

## Materials and methods

### Materials

The cellulose fiber extraction process starts by collecting the coffee cherries (i.e., *Coffea arabica*) in the agricultural fields located in Yercaud (11° 54' 10.1" N 78° 14' 39.9" E), TN, India. Cotton (CO) fibers (i.e., comber waste) were collated

from the spinning mills in Salem, TN, India. The chemicals like NaOH (CAS:1310-73-2) and H<sub>2</sub>O<sub>2</sub> (35%; CAS:7722-84-1) were purchased from Pure chemicals, India. All chemicals were of analytical grade and used without further purification (Table 1).

#### Extraction of coffee husk by wet processing method

The depulping process was carried out to extract the husk from coffee cherries by a simple wet processing method. The extracted husk was sun-dried as it was the raw material to produce fiber and followed by the non-woven web production delignification process was carried out to remove the lignin compounds under the following conditions (NaOH: 5 g/L, 90 °C, 120 min), the parameters like alkali concentration, temperature, and time of the process have been optimized before the delignification process and it is well reported in our previous work (Karunakaran et al. 2023). The bleaching process for the husk fibers was carried out by using H<sub>2</sub>O<sub>2</sub> (3-g/L) under an alkaline medium (pH:11–12) at 90 °C for 45 min. The conventional chlorine-based bleaching process was replaced by H<sub>2</sub>O<sub>2</sub>, as it is environmentally friendly and does not leach the residual chlorine. During the bleaching

process, the natural pigments are oxidized and hence helped to remove. After the bleaching process, the fibrous materials appear bright and clean and are ready to produce nonwoven fibrous materials.

#### Web formation

The inherent limitation of 100% coffee husk fiber as it is not possible to produce nonwoven fibrous materials due to its lower cohesion and shorter fiber length, thus cotton fibers must be added to create the web-like structure (Ghali et al. 2014; Kalabek and Babaarslan 2016; Yan et al. 2017; Thenmozhi and Thilagavathi 2022). As mentioned, processability issues were raised if the coffee husk fiber proportion was beyond 80%, leading to web falling and breakage during web formation in the miniature carding machine. As a result, it combined the CH fibers with the CO fibers to make the porous web, and it employed six different blend proportions to prepare the web, and Table 2 provides the physical properties of the resulting nonwoven fibrous materials. Further, the carded web was processed with a needle-punching machine to produce the nonwoven fibrous materials. In this work, three layers of the web were parallel laid, overlapped, and

**Table 1** Physical properties of used fibers

Properties	Fibers (coffee husk) extracted from the agro waste	Fibers (cotton waste) collected from the spinning industry
Fiber length (mm)	18 ± 15	19 ± 4
Fiber diameter (µm)	25.98 ± 21	15.2 ± 3
Moisture regains (%)	8.4	8.5
Tenacity (g/tex)	3.69 ± 4	18 ± 2
Elongation (%)	5.2 ± 6	4.29 ± 0.8

**Table 2** Various physical properties of the produced nonwoven fibrous materials

Sample code	Blend ratio (weight %)		Thickness (cm)	Ariel density (g m <sup>-2</sup> )	Porosity (%)
	Coffee husk fibers	Cotton fibers			
CH:CO (0:100)	0	100	2.1 ± 0.12	310.4 ± 8	70.11 ± 1.0
CH:CO (20:80)	20	80	2.3 ± 0.18	325.5 ± 15	71.23 ± 0.9
CH:CO (40:60)	40	60	3 ± 0.14	360.2 ± 6	72.52 ± 1.4
CH:CO (50:50)	50	50	3.2 ± 0.21	368.1 ± 9	80.77 ± 2.4
CH:CO (60:40)	60	40	3.9 ± 0.24	420.5 ± 12	79.44 ± 1.8
CH:CO (80:20)	80	20	4.1 ± 0.48	508.8 ± 24	82.21 ± 2.1

processed in the needle-punching machine to develop a nonwoven fibrous material. The needle-punching machine has 6000 needles and punches the web at a rate of 25 punches per cm<sup>2</sup> with a penetration depth of 12 mm. Two-needle boards with a down stroke make up the needle-punching machine. The machines and web's working widths are 8000–10,000 and 600 mm, respectively. The machine's in-feed speed is 0.31 m/min, and the draw-off speed is 0.40 m/min, with a stroke frequency of 121 strokes per minute, the short description of web manufacturing is given in Fig. 1.

## Testing and characterization

### Scanning electron microscope (SEM)

The morphological properties of the extracted coffee husk fibrous materials were studied by Tescanvega 3 SEM according to the ASTM E986-04(2017) standard (ASTM 2017a). Before the measurement, a thin layer (4 nm) of gold was sputter coated on the surface of the fibrous materials to make them conductive in the vacuum chamber. The SEM images were taken at the required magnification range to observe the surface changes clearly at 20.0 kV electron voltage.

### Sound absorption properties of CH/CO nonwoven fibrous materials

The sound absorption coefficient of CH/CO nonwoven fabrics was measured using an impedance tube kit (50 Hz–6.3 kHz; testing condition: 25 °C) Type 4206 (Bruel & Kjaer, Denmark) in accordance with ASTM E1050-12 (ASTM 2019), the usual set-up of the instrument is depicted in Fig. 2. The impedance tube kit had a diameter of 29 mm, hence the testing was done on circular samples, so, five different measurements taken, and the average value was the one that was utilized to plot the graphs (Muhammad Khusairy Bin Bakri 2015; Jayamani et al. 2015, 2016a, b).

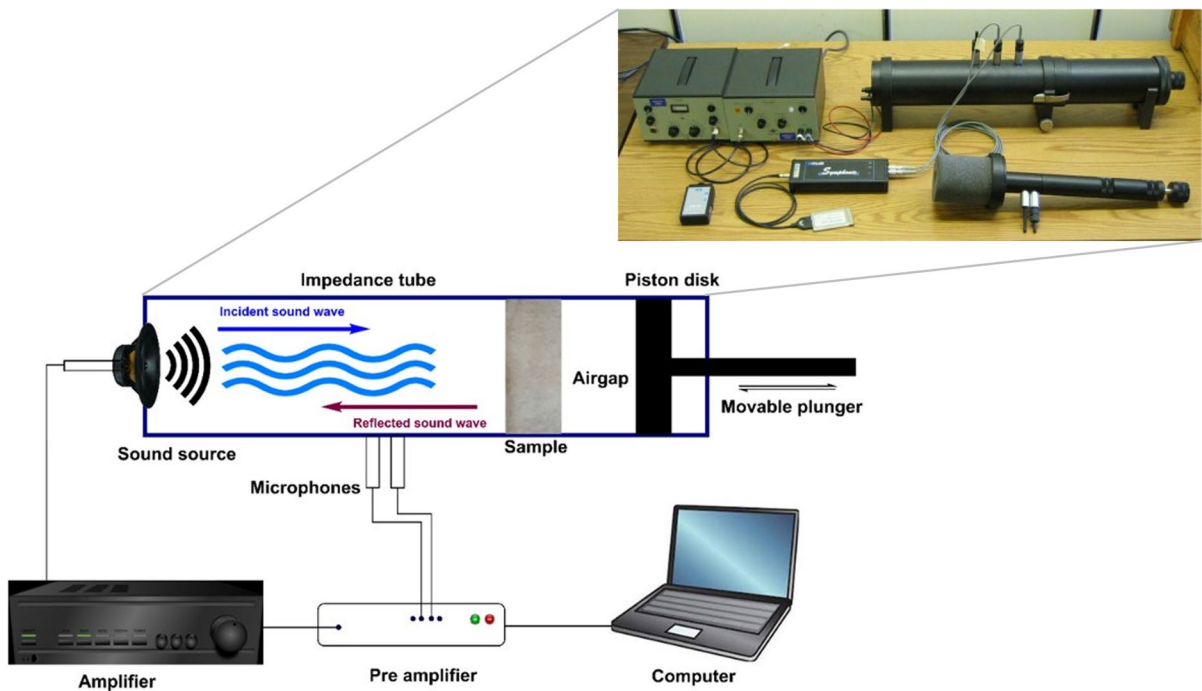
### Calculation of the porosity

The porosity of a nonwoven fiber nonwoven fibrous material factor that influences sound absorption, therefore, the porosity of the nonwoven fabrics is calculated using the following equation (Asanovic et al. 2019),

$$P(\%) = \left(1 - \frac{\delta}{\rho_f}\right) \times 100 \quad (1)$$



**Fig. 1** Various stages to prepare sustainable sound absorption nonwoven materials



**Fig. 2** Experimental setup for diagnosing sound absorption coefficient behavior of produced nonwoven fibrous materials by using impedance tube

where the fiber density ( $\rho_f$ :  $\text{g cm}^{-3}$ ); bulk density of the nonwoven fabric are ( $\delta$ ;  $\text{g cm}^{-3}$ ). However, there are two different fibers with different densities in the current analysis, therefore, the porosity of the fabrics can be computed by using the weight average of the fibers ( $\rho_{fm}$ ) was used instead of fiber density ( $\rho_f$ ) in Eq. 1. So, both fabric bulk density of the fabric and fiber density can be calculated by using Eqs. 2 and 3 respectively.

$$\delta = \left(1 - \frac{M_a}{T}\right) \times 10^{-3} \tag{2}$$

$$\rho_{fm} = \left(\frac{(P_{CH} \cdot \rho_{CH}) + (P_{CO} \cdot \rho_{CO})}{P_{CH} \cdot P_{CO}}\right) \tag{3}$$

where  $P_{CH}$  and  $P_{CO}$  are the percentages of blend proportion of coffee husk and cotton fibers respectively;  $\rho_{CH}$  and  $\rho_{CO}$  are the density of coffee

husk fibers ( $0.36 \text{ g cm}^{-3}$ ) (Zhang et al. 2012; Amena et al. 2022) and cotton ( $1.14 \text{ g cm}^{-3}$ ) (Yong et al. 2021).

*Testing of other properties of nonwoven fibrous materials*

Nonwoven samples were preconditioned for 24 h at 65% relative humidity and 23 °C to be tested. Using the Vibroskop 400 (Lenzing Technik, Austria), the linear density of the fibers was calculated in accordance with ASTM D1577-07 (ASTM 2018a). A thickness tester (Shirley Developments Ltd., Manchester) was used to measure the thickness of the sample (t) in accordance with ASTM D5729-97 at various points on the samples (ASTM 2017b). Using a digital balance, the areal density was measured in accordance with ASTM-D3776 (ASTM 2020) (Shimadzu, model UX2200H, Japan). The air

permeability (ASTM D737), the volume of air in  $\text{cm}^3/\text{cm}^2/\text{sec}$ , is passed in one second through  $100 \text{ mm}^2$  of the web at a pressure difference of 10 mm head of water or 100 Pa pressure (ASTM 2018b; Liu et al. 2020). For all the above properties, five measurements were made, and the average was determined.

Empirical models for determining the sound absorption coefficient of coffee husk fiber

To assess the behavior of sound waves propagating through porous materials, several empirical models have been derived. In most cases, empirical models are used to estimate the acoustical properties of porous media. Since these models are based on an experimental framework, they can only be applied to the conditions for which they were designed, and it is limited to heterogeneous materials.

#### Delany–Bazley model

Delany and Bazley introduced the first empirical model for determining the bulk acoustic properties of porous substrates (Delany and Bazley 1970); this model may be only accurate for frequencies greater than 250 Hz (Egab et al. 2014),

$$Z_c = \rho_o c_o [1 + 0.057X^{-0.754} - j0.087X^{-0.732}] \quad (4)$$

$$k = \frac{\omega}{c_o} [1 + 0.0978X^{-0.700} - j0.189X^{-0.595}] \quad (5)$$

$$X = \frac{\rho_o f}{\sigma} \quad (6)$$

$$\alpha = 1 - |R|^2 \quad (7)$$

$$R = \frac{Z_s - \rho_o c_o}{Z_s + \rho_o c_o} \quad (8)$$

$$Z_s = -jZ_c \cot(kd) \quad (9)$$

where  $\rho_o$  and  $c_o$  stand for the air density and sound speed in the air, respectively. The propagation constant is  $k$ ,  $Z_c$  is the characteristic impedance,  $f$  is the frequency,  $\omega$  is the angular frequency,  $R$  is the sound pressure reflection coefficient,  $\sigma$  is the

airflow resistivity, and,  $j = \sqrt{-1}$ ,  $Z_s$  is the surface impedance; the thickness is  $d$ . For fibers with a diameter of 1 to 10  $\mu\text{m}$ , the DB model was developed. To increase accuracy at low-frequency levels, several researchers have attempted to alter the DB model by adding new  $c_1$ – $c_8$  coefficients. By changing the  $c_1$ – $c_8$  coefficients, Garai and Pompoli (GP) (Samaei et al. 2021) proposed new empirical formulas for fibrous materials with coarser fibers in 2005. Table S1 provides the  $c_1$ – $c_8$  coefficients of these models.

#### Garai and Pompoli model

Despite this, the DB model has now undergone revisions to allow it to be used with various fibers of bigger diameters. When Garai and Pompoli updated the model, they used it to simulate polyester fibers with a diameter of 20 to 50  $\mu\text{m}$  (Garai and Pompoli 2005).

$$Z_c = \rho_o c_o \left[ 1 + 0.078 \left( \frac{\rho_o f}{\sigma} \right)^{-0.623} - j0.074 \left( \frac{\rho_o f}{\sigma} \right)^{-0.66} \right] \quad (10)$$

$$k = \frac{\omega}{c_o} \left[ 1 + 0.127 \left( \frac{\rho_o f}{\sigma} \right)^{-0.53} - j0.159 \left( \frac{\rho_o f}{\sigma} \right)^{-0.571} \right] \quad (11)$$

Other researchers, like Miki, Mechel, and Pompoli, have developed a variety of coefficients for the DB model (Crocker 2007; Bonfiglio and Pompoli 2013; Kirby 2014).

#### Miki model

In 1990 Miki offered improved coefficients for porous materials replacing those suggested by Delany and Bazley model (Miki 1990).

$$Z_c = \rho_o c_o \left[ 1 + 5.50 \left( 10^3 \frac{f}{\sigma} \right)^{-0.622} - j8.43 \left( 10^3 \frac{f}{\sigma} \right)^{-0.632} \right] \quad (12)$$

$$k = \frac{\omega}{c_o} \left[ 1 + 7.81 \left( 10^3 \frac{f}{\sigma} \right)^{-0.618} - j11.41 \left( 10^3 \frac{f}{\sigma} \right)^{-0.618} \right] \quad (13)$$

### Allard and Champoux model

A model developed by Allard and Champoux is predicated on the idea that thermal effects are frequency-dependent (Champoux and Allard 1991).

$$\rho(\omega) = \rho_o \left[ 1 - i \left( \frac{\sigma}{\rho_o \omega} \right) G_1 \left( \frac{\rho_o \omega}{\sigma} \right) \right] \quad (14)$$

$$K(\omega) = \gamma P_o \left( \gamma - \frac{\gamma - 1}{1 - \left( \frac{i}{4P_r} \right) \left( \frac{\sigma}{\rho_o \omega} \right) G_2 \left( \frac{\rho_o \omega}{\sigma} \right)} \right) \quad (15)$$

$$G_1 \left( \frac{\rho_o \omega}{\sigma} \right) = \sqrt{1 + \frac{i}{2} \left( \frac{\rho_o \omega}{\sigma} \right)} \quad (16)$$

$$G_2 \left( \frac{\rho_o \omega}{\sigma} \right) = G_1 \left( \frac{\rho_o \omega}{\sigma} \right) \left[ 4P_r \left( \frac{\rho_o \omega}{\sigma} \right) \right] \quad (17)$$

where  $K(\omega)$  is the bulk modulus and  $\rho(\omega)$  is the effective density.

### Johnson–Champoux–Allard model (JCA)

Johnson, Champoux, and Allard's have developed this model (Johnson et al. 1987; Allard and Champoux 1992), as it assumes that the fibers are denser and heavier than the fluid, they can be simulated as a like fluid when inside a rigid frame. The calculation will take into account five physical characteristics, such as porosity ( $\phi$ ), tortuosity ( $\alpha_\infty$ ), airflow resistivity ( $\sigma$ ), viscous characteristic length ( $\Lambda$ ), and thermal characteristic length ( $\Lambda'$ ).

$$\rho(\omega) = \alpha_\infty \rho_o \left[ 1 + \frac{\sigma \phi}{j \omega \rho_o \alpha_\infty} \left( 1 + \frac{4i \alpha_\infty^2 \eta \omega \rho_o}{(\sigma \Lambda \phi)^2} \right)^{\frac{1}{2}} \right] \quad (18)$$

$$K(\omega) = k \rho_o \left( k - (k - 1) \left[ 1 + \frac{\sigma' \phi}{i \omega \rho_o \alpha_\infty N_{pr}} \left( 1 + \frac{4i \alpha_\infty^2 \eta N_{pr} \omega \rho_o}{(\sigma' \Lambda' \phi)^2} \right)^{\frac{1}{2}} \right]^{-1} \right)^{-1} \quad (19)$$

$$\sigma' = \frac{8 \eta \alpha_\infty}{\Lambda'^2 \phi} \quad (20)$$

$$Z_c = \sqrt{\rho(\omega) \cdot K(\omega)} \quad (21)$$

$$K_c = \omega \sqrt{\frac{\rho(\omega)}{K(\omega)}} \quad (22)$$

where the effective density  $\rho(\omega)$  and bulk modulus  $K(\omega)$ .

### Empirical models for thermal conductivity

Alambeta device (Sensora s.r.o, Czech Republic) was used to test the thermal conductivities of produced nonwoven fibrous materials. A copper block inside the Alambeta's measuring head has been electrically heated to a temperature of about 32 °C to mimic that of human skin (Hes and Dolezal 2018). The fabric is kept between the hot and cold plates (i.e., 200 Pa) in this device. At a pressure of 200 Pa, the hot plate contacts the cloth sample. Heat flux sensors measure the quantity of heat flow from the hot surface to the cold surface via the fabric. Five measurements for each sample were taken to determine the averages, which were then used to plot the graphs.

$$K_{eff} = \left( \frac{Q \cdot t}{A \Delta T} \right) \quad (23)$$

where  $Q$  is the heat flow,  $A$  is the surface area,  $t$  is the thickness of web and  $\Delta T$  is the temperature difference.

In this work, two models (i.e., Herman (1957) and Bhattacharyya (1980)) that are often used to forecast the thermal conductivity of fibrous materials with fibers perpendicular to the heat flow will be used. Herman (1957) first suggested this approach for textile materials in 1957. The Herman model presents the following thermal conductivity for fibrous material with fibers (Bhattacharyya 1980) parallel to the heat flow:

$$k = \frac{k_f k_a}{k_a v_f + k_f v_a} \quad (24)$$

where  $k$  is the thermal conductivity of nonwoven fibrous materials and  $k_a$ ,  $k_f$  is the thermal conductivity of air, and fiber respectively;  $v_a$ , and  $v_f$  is the volume fraction of air and fiber respectively. Thermal conductivities and volume fractions of air and fiber should be known in these two models. Except for the thermal conductivity of the fiber, all of the parameters are extremely simple to get. To predict the thermal conductivity of nonwoven fibrous materials with



fibers randomly arranged and perpendicular to the heat flow, Bhattacharyya (1980) developed a model shown below.

$$k = \left[ 1 - \frac{1 - k_a/k_f}{1 + \frac{2(k_a/k_f)(v_f/v_a)}{(1+k_a/k_f)}} \right] k_f \quad (25)$$

The values of thermal conductivity of natural fibers including cotton lie between 0.026 and 0.065 W/mK (Chen et al. 2003; Morton and Hearle 2008; Majumdar et al. 2010; Mamtaz et al. 2017).

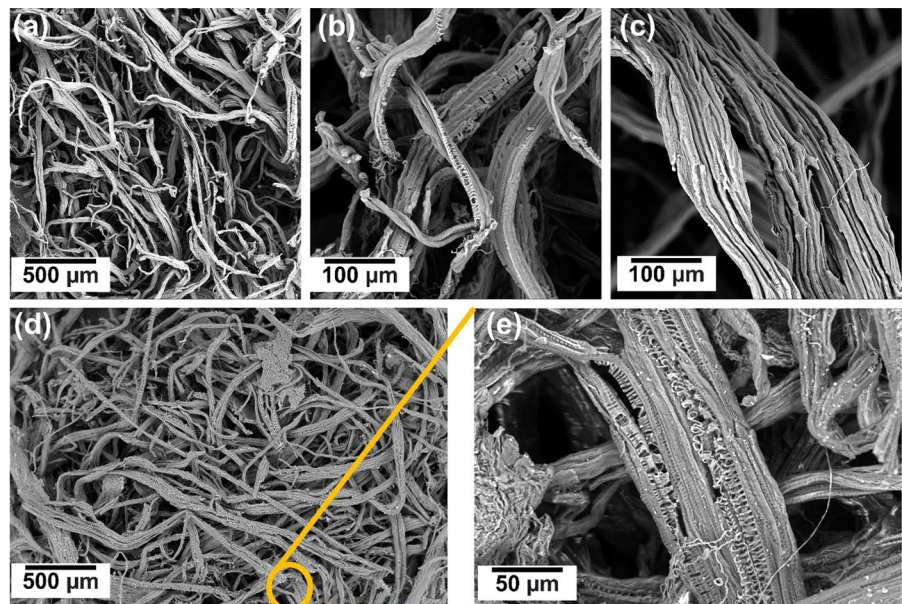
## Result and discussion

### Surface morphology of extracted cellulosic materials

The scanning electron microscope (SEM) was used to characterize the surface morphology of the produced nonwoven, and the results are depicted in Fig. 3. Overall, the produced nonwoven fabric shows the rough surface and especially, serrated surface can be observed in CH fibers. It is clear from the pictures that the CH fibers and the CO fibers were together to form an integrated structure of the fabric (see Fig. 3a), also the CH fibers show high roughness and voids as it significantly contributes to enhanced sound

absorption and thermal properties. For instance, the delignification process increases the surface roughness of CH fibers, and the surface roughness promotes sound absorption property by increasing the friction between the sound waves (Fig. 3b). Furthermore, the surface area of rough fibers is considerable, which is another cause for the sound-absorbing property of the material (Fig. 3c). In addition to this, it has been established that the CH fibers contain helix, and that it assembled in an organised manner (see Fig. 3c). The individual CH fibers appear elliptical and slightly oval in shape with a length (11–24 mm) and diameter of 28–78  $\mu\text{m}$  respectively. In accordance to this, the scanning electron microscopy analysis reveals that the coffee husk fibers include bundles of fibrils, which results in fibrillation. Generally, fibrillation creates a higher surface areas in the nonwoven structure that increases the sound absorption property (Fig. 3d, e). Surface roughness maximizes the likelihood of the incident acoustic wave being dampened, resulting in increased sound absorption. Microscopic pockets of air are formed by the helix and rough surfaces of the fibers to develop on the fiber surface, resulting in excellent thermal insulation and it can be seen in “[Thermal and acoustic properties](#)” section. The thermal and acoustical characteristics of the samples will be addressed in more depth in the following sections. In the case of cotton and its fineness resulting the increase in the quantity of fiber per unit area is

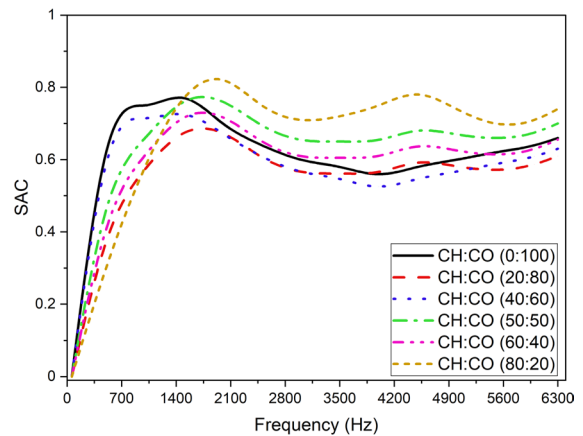
**Fig. 3** Microscopical images of nonwoven fibrous materials (a); CH:CO(80:20) (b); CH:CO(50:50) (c); porous structure of coffee husk fibers (d); CH fibers having the voids and fibrillation (e)



directly proportional to the higher surface area resulting in increased sound absorption (i.e., as compared to the coffee husk). The findings showed that increasing the amount of cotton in nonwoven fibrous materials improves sound absorption capabilities.

#### Results for sound absorption coefficient

The impedance tube method was applied in order to determine the sound absorption coefficient of CH/CO nonwoven fabrics. The sound absorption coefficient is a key indicator for the acoustic materials, and it is frequently used to examine sound-absorbing capacities and it measured in decibels (dB). Overall, the results of sound absorption coefficient of CH/CO nonwoven fabrics are dependent on their blend proportion. As per the results, the sound absorption coefficient typically increases as frequency increases to somewhere between 1600 and 2800 Hz. Then, when the sound frequency continues to rise, a minor diminution can be observed, along with an increase in the sound absorption coefficient. The blend proportion of (CH:CO (0:100) and CH:CO (80:20)) has the highest sound absorption coefficient throughout the whole frequency range, owing to the increased percentage of cotton and coffee husk fibers responsible for sound absorption in both cases. Perhaps, a higher proportion of CO fibers in the blend provides promising sound absorption coefficient values due to the higher fineness as compared to coffee husk fibers. The increased proportion of coffee husk fibers influenced the higher sound absorption since this fiber has helix and is assembled orderly (Fig. 3c). The presence of fibril bundles causes the fibrillation of coffee husk fibers results in a porous structure with better sound absorption. There is also a peak of about 1400–2200 Hz (i.e., for all blend proportions), which might be related to the intrinsic characteristic of fibers and their morphological structure. Low-frequency noise is more hazardous to human health than high-frequency noise, and coffee husk nonwoven fibrous materials may be an effective absorber of low-frequency noise (Waye 2011). According to the data presented in Fig. 4, the frequency range of 1400–2200 Hz is where the sound absorption coefficients reach their maximum value. The observed peak of sound absorption coefficients for CH:CO (80:20) nonwoven fabrics occurs at approximately 2100 Hz. The peak of sound absorption coefficients appears at 1600 Hz for the nonwoven



**Fig. 4** Influence of blend proportion on the sound absorption coefficients (SAC) values

samples of CH:CO (0:100) and drifts towards the low-frequency bands as the proportion of cotton fibers increases. As a consequence of this, one may say that increasing the amount of cotton components in samples improves the low-frequency sample absorption behavior of the samples.

Perhaps, the sound absorption coefficient has a significant influence by frequency, according to the researchers (Liu and Chen 2014; Oliveira 2021), the increasing frequency has been reported to cause an increase in sound absorption. It is noteworthy to see that the sound absorption increased at a high rate between 50 and 1000 Hz, but that this trend eventually decreased. Additionally, the sound absorption predominance changes between 50 and 6300 Hz for each sample.

From the Table 3, it is noteworthy that, the CH:CO (80:20) has higher sound absorption coefficients values in mid and high frequency range, this is due to their structural and morphological properties of coffee husk fibers, as it contains small fibrils which leads to the porous structure, as a resulting better sound absorption. Noise with a low frequency poses a greater threat to human health than noise with a high frequency, since the coffee husk proportion has a major effect on sound absorption coefficients at low frequency range, for example, CH:CO (40:60) and CH:CO (50:50) produces a sound absorption coefficients of 0.43 and 0.37 respectively, which is quite an excellent sound absorption coefficient. The CH:CO (80:20) blend proportion has a better sound

**Table 3** Measured values of the mean sound absorption coefficients

Sample	Low frequency 80–1000 (Hz)	Middle frequency 1000–3000 (Hz)	High frequency 3000–6300 (Hz)
CH:CO (0:100)	0.45	0.67	0.60
CH:CO (20:80)	0.31	0.63	0.58
CH:CO (40:60)	0.43	0.64	0.57
CH:CO (50:50)	0.37	0.71	0.67
CH:CO (60:40)	0.33	0.67	0.62
CH:CO (80:20)	0.29	0.76	0.73

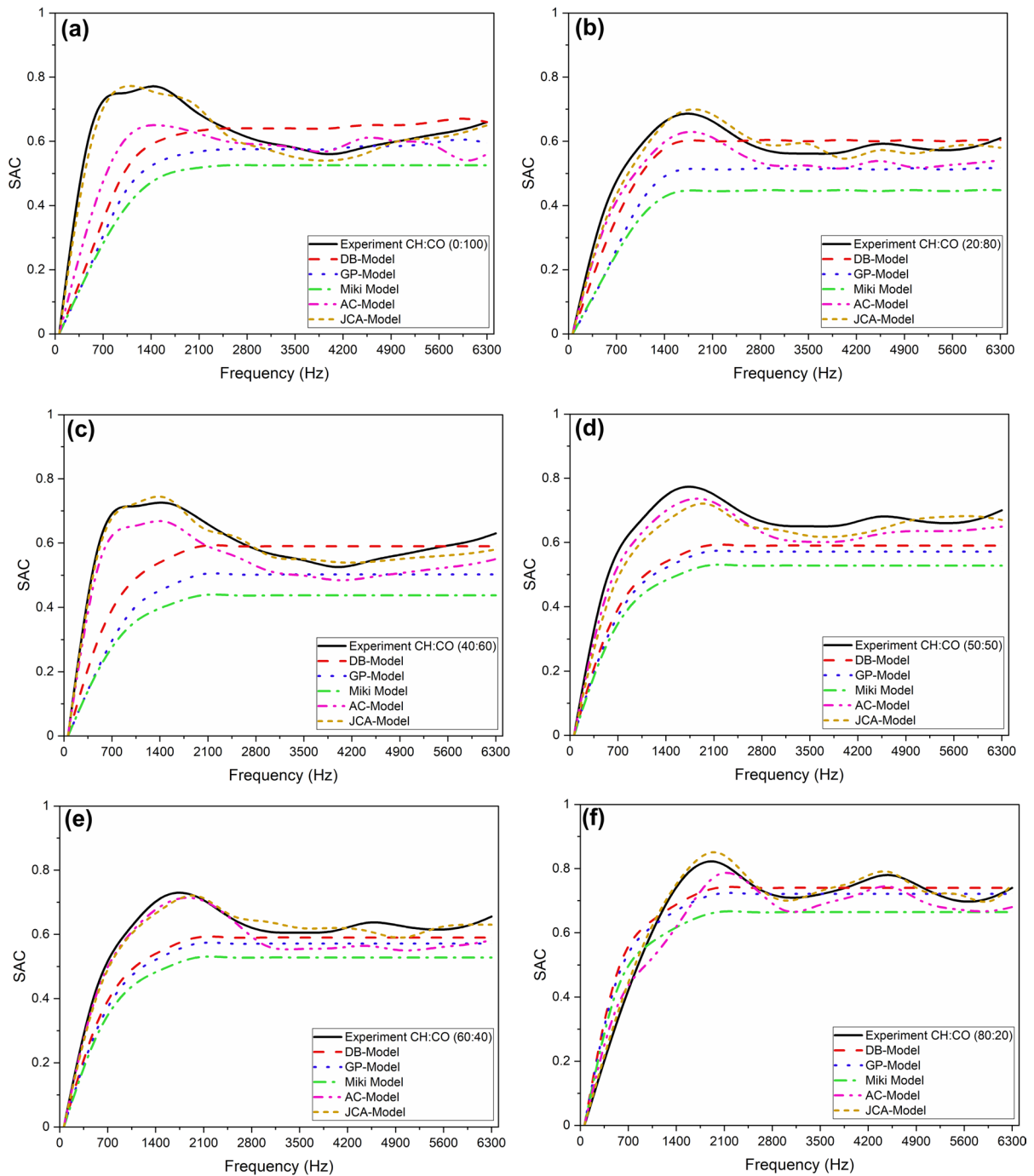
absorption coefficient that falls within the range of 0.76–0.82, making it superior to the other blend proportions when measured above the frequency range of 1000–3000 Hz, there is no significant reduction even in high frequency range (i.e., 0.73 at 3000–6300). As a result, it has been demonstrated that a higher proportion of coffee husk fibers demonstrates an excellent sound absorption coefficient at middle and high frequencies. On other hand, CH:CO (50:50) has the second highest sound absorption coefficients values in mid & high frequency range.

The sound absorption coefficients for the produced nonwoven materials constructed from a combination of coffee husk and cotton can theoretically be predicted using one of five well-known mathematical prediction models, namely DB, GP, Miki, AC, or JCA. Comparisons between the experimentally measured sound absorption coefficient values and the theoretically anticipated values were made and the results are shown in Fig. 5. The figure makes it clear that the empirical models of DB, GP, and Miki exhibit poor computational accuracy at frequencies below 2500 Hz, while their accuracy increases at higher frequency bands between 2500 and 6300 Hz. For all samples, the JCA and AC models accurately reproduce the trend of the experimental data in the frequency range of 80–6300 Hz. According to Mamtaz et al. (2017), and Samson et al. (2017), the results of theoretical and experimental studies exhibit good agreement at low and mid-range frequencies or frequencies below 2500 Hz. The results from the JCA and AC models are the most similar to the sound absorption coefficient values that were obtained from experimentation when contrasted with the results from the other empirical models of DB, GP, and Miki. This is because the nonwoven fabrics have more porosity and higher tortuosity than the other models. As already established, the models take four additional parameters into account in addition to

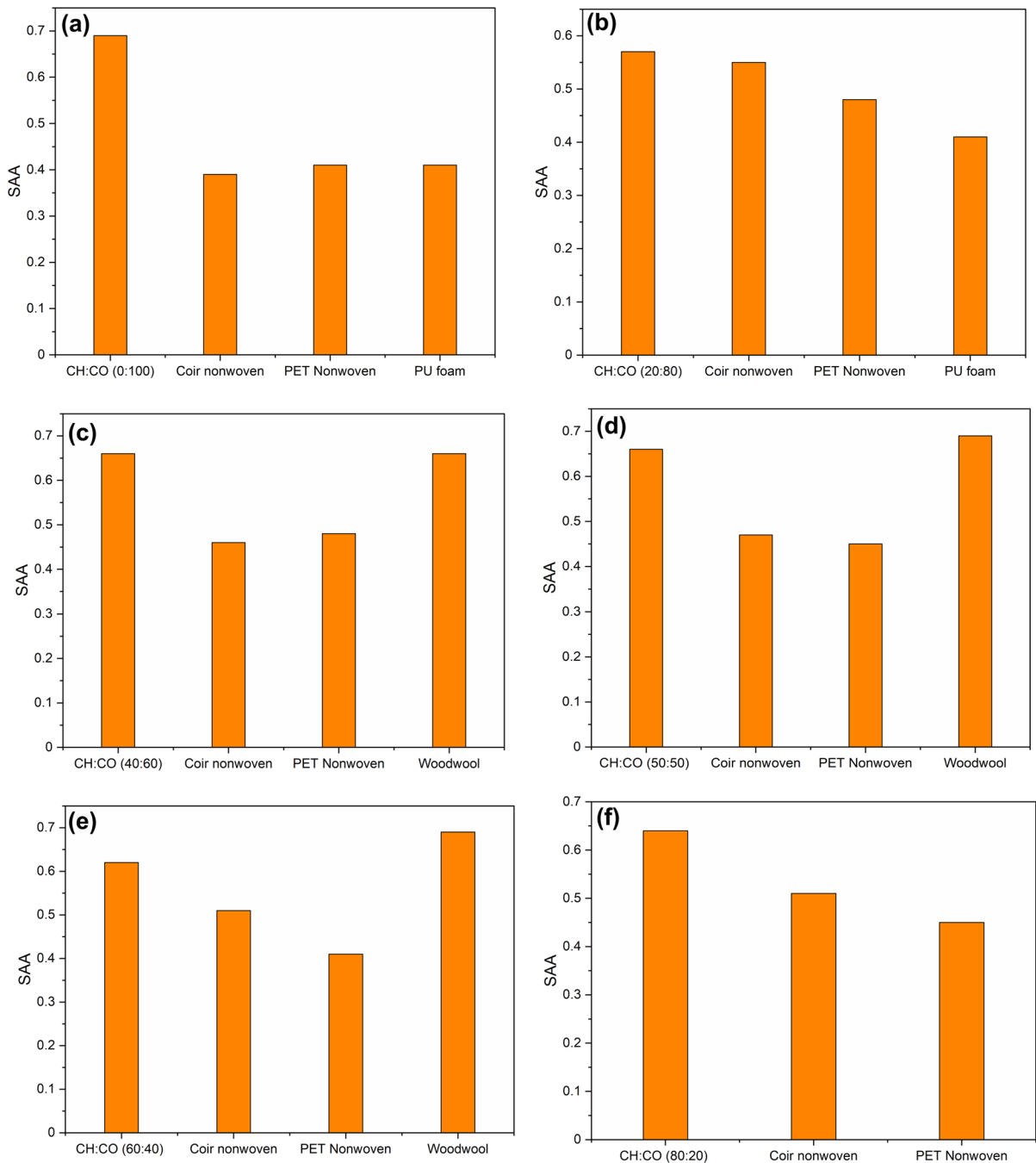
the flow resistivity, whereas the empirical models just take this into account when estimating the absorption coefficient.

#### Comparison with some commercial products

The average sound absorption values of CH/CO nonwoven fabrics are compared with that of other acoustic nonwoven materials that are currently available on the market, the results are shown in Fig. 6. In order to do a comparison with available commercial sound-absorbing nonwoven fabrics, similar thickness samples are being evaluated. On this particular occasion, needle felted coir nonwoven fibrous materials were supplied by the Central institute of coir technology (India), woodwool board was supplied by Jayswal agency (India), and Dynamic nonwovens supplied PU foam and PET nonwoven fibrous materials (India). Therefore, the thickness of the nonwoven fibrous materials that were developed with this study ( $t=2, 3$ , and 4 cm) were compared to their performances with the samples that are commercially available, and the results are presented in Fig. 6. In Fig. 6a, the sample CH:CO(0:100) ( $t=2$  cm) is compared with commercial sound absorption materials that have the same thickness. When compared to other sound absorption materials that are available commercially, the CH:CO(0:100) offers significantly improved the values of average sound absorption. In Fig. 6f, sample CH:CO(80:20) ( $t=4$  cm) is evaluated in comparison to commercial sound absorption materials such as coir nonwoven fibrous materials ( $t=4$  cm) and PET nonwoven fibrous materials ( $t=4$  cm). In general, the sound absorption provided by the CH:CO(80:20) is far better than that provided by any of the other sound absorbent materials that are currently on the market. Therefore, the fibers that can be extracted from coffee husk have the potential to be scaled up for the development of environmentally friendly nonwoven



**Fig. 5** Sound absorption models for different blend proportion of CH/CO nonwoven fibrous materials; CH:CO(0:100) (a); CH:CO(20:80) (b); CH:CO(40:60) (c); CH:CO(50:50) (d); CH:CO(60:40) (e); CH:CO(80:20) (f)



**Fig. 6** Results of SAA on the CH/CO nonwoven fibrous materials with commercial available sound absorption materials (i.e., a:t=2 cm; b:t=2 cm; c:t=3 cm; d:t=3 cm; e:t=4 cm and f:t=4 cm)

fibrous materials that can be used for sound-absorbing materials.

The comparison was carried out by utilizing the results of the current work in combination with

the work of other researchers; the findings are displayed in Table 4. The CH:CO (0:100; thickness of web is 2 cm) has high values of average sound absorption as compared to the other sound

**Table 4** The sound absorption average (SAA) values versus other works

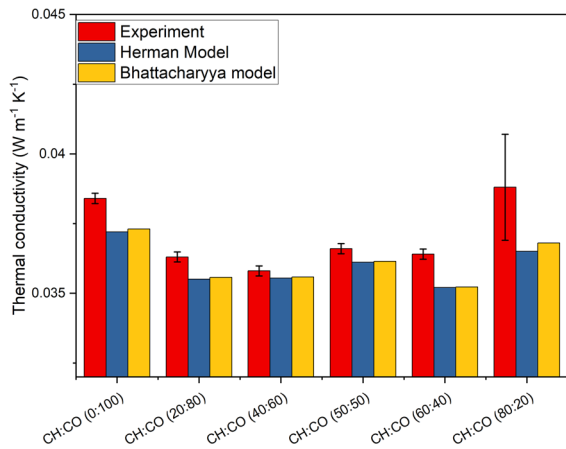
Thickness (cm)	Acoustic material	SAA	References
2	CH:CO (0:100)	0.69	Current work
	Composite made from date palm fibers	0.38	Taban et al. (2019)
	Post-consumer and discarded denim wastes	0.37	Hassani et al. (2021)
	Composite made from kenaf fibers/rice husk	0.39	Ehsan Samaei et al. (2021)
2	CH:CO (20:80)	0.57	Current work
	Post-consumer and discarded denim wastes	0.38	Hassani et al. (2021)
	Composite made from flax/polypropylene	0.31	Huang et al. (2019)
3	CH:CO (40:60)	0.66	Current work
	Composite made from date palm fibers	0.43	Taban et al. (2019)
	Composite made from kenaf fibers/rice husk	0.50	Ehsan Samaei et al. (2021)
	Areca nut leaf sheath nonwoven	0.52	Raj et al. (2020)
3	Nonwoven from recycled facemask	0.58	Maderuelo-Sanz et al. (2021)
	CH:CO (50:50)	0.66	Current work
	Composites made from kenaf/PVA	0.50	Taban et al. (2020)
4	Nonwoven from recycled facemask	0.56	Maderuelo-Sanz et al. (2021)
	CH:CO (60:40)	0.62	Current work
	Composite made from date palm fibers	0.58	Taban et al. (2019)
	Composite made from kenaf fibers/rice husk	0.65	Ehsan Samaei et al. (2021)
4	Areca nut leaf sheath nonwoven	0.51	Raj et al. (2020)
	CH:CO (80:20)	0.64	Current work
	Composites made from kenaf/PVA	0.53	Taban et al. (2020)

absorption materials like palm fibers, post-consumer and discarded denim wastes and composite from flax/ polypropylene. On the other hand, the CH:CO (80:20) nonwoven fibrous materials with a thickness of 4 cm have average values of sound absorption is 0.64, but the composite manufactured from kenaf/PVA has a an average values of sound absorption is 0.53 at the same thickness. In general, the fact that the CH/CO nonwoven fibrous materials demonstrate improved sound absorption capabilities while maintaining the same thickness segment confirms that these are promising materials for scale up. The values of average sound absorption for the composite built from kenaf fibers and rice husk are slightly higher than the web of CH:CO (60:40) (i.e., 0.62). This is may be the composite made from kenaf fibers and rice husk has high flow resistance, porosity, and tortuosity.

### Thermal and acoustic properties

Thermal conductivity is a characteristic of a substance that allows heat to flow through its interior structure (Militky and Kremenakova 2007). There is a correlation between a material's sound absorption and its heat conductivity. Porous fiber networks, such as those made of coffee husk fiber nonwoven, create vibrations when sound waves pass through their structure. Because of the friction, the vibration of the fibrous structures generates heat, which in turn is absorbed by the fibers leading to viscous behavior. As a result, the thermal energy of sound waves is absorbed by a good absorbent material, and less heat is created.

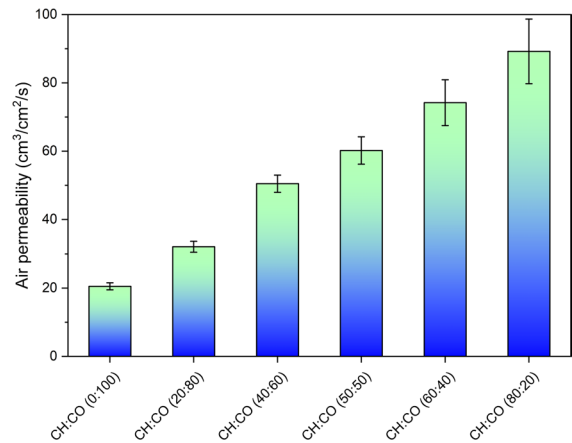
In Fig. 7, the measured and predicted thermal conductivities of nonwoven fibrous materials are displayed. Fabrics of CH:CO (80:20) and CH:CO (40:60) had the highest and lowest thermal conductivities, respectively. Every sample, except for CH:CO (80:20),



**Fig. 7** Influence of blend proportion on the thermal conductivity

displays an acceptable standard deviation. This is caused on by the considerable thickness, measurement inaccuracies, and variations in the fiber homogeneity of the sample CH:CO (80:20). Figure 7 shows that there is a large discrepancy between the predicted and experimental thermal conductivity values. It is noteworthy that, when compared to the Herman model, the Bhattacharyya model's results showed slightly greater thermal conductivities. The Herman model was chosen because it took into account both the fiber volume fraction and the fiber orientation fraction. Thus, it can be concluded that, in the Herman model, the fiber volume fraction has a greater impact on the thermal conductivity of nonwoven fibrous materials than the fiber orientation. From this work, both the models developed by Herman and Bhattacharyya cannot be used with very porous nonwoven fibrous materials.

The thermal conductivity of nonwoven fibrous materials does not always remain constant. The density, moisture content, and ambient temperature of the nonwoven fibrous materials are the key elements that influence thermal conductivity. Additional scattering mechanisms, such as voids and cell borders of natural fibers such as coffee husk and cotton might have an impact on the thermal conductivity of dense and porosity-rich materials. The thermal conductivity rises as the density, moisture, and temperature of the environment rise. Sound absorption and heat conduction were aided by the helix structure of CH fibers, which was arranged orderly in the framework. As a result, it was established that heat conduction via the voids and helical structure is the primary mode of



**Fig. 8** The air permeability of produced nonwoven fabrics

heat transmission across the CH/CO nonwoven fibrous materials. In general, the density is the most important component in heat transmission through textiles.

#### Effect of air permeability on sound absorption coefficient

In this work, the air permeability of produced non-woven observed to increase with increasing the web ariel density and thickness (see Table 2). Overall results shows that the samples CH:CO (0:100), and CH:CO (20:80) have the lowest air permeability, while samples CH:CO (60:40) and CH:CO (80:20) have the highest air permeability values was observed (Fig. 8). The larger portion of coffee husk fiber in the structure causes there to be a higher number of substantial gaps between the fibers, which in turn enables the majority of air to pass through these gaps. On the other hand, the thickness and the ariel density of the nonwoven material has a significant affect on how well it allows air to pass through it. The main structural characteristics of the nonwoven fibrous materials, such as the web ariel density and thickness, have a significant impact on the acoustic performance and air permeability of CH/CO nonwoven fibrous materials. CH/CO nonwoven fibrous materials with reduced air permeability generally demonstrates superior sound absorption capability if the nonwoven structure has a higher percentage of cotton fibers in it. In contrast, when the nonwoven structure has higher proportion of coffee fibers, CH/CO

nonwovens with improved air permeability also display improved sound absorption capability.

## Conclusion

Noise pollution has gone up as a result of the fast growth of the industrialization, construction, and transportation sectors in the twenty-first century. The most efficient method for reducing the amount of noise is to make use of materials that absorb sound. In this study, the acoustic behavior of blended nonwoven fibrous materials as a new environmentally friendly and sustainable sound-absorber material was investigated. The blended nonwoven fibrous materials was produced by extracting fibers from coffee husk (CH) and waste from the cotton (CO) spinning industry. Experiments were carried out to explore the sound-absorbing properties of fiber blends consisting of CH and CO fibers with various mass ratios, including 0:100, 20:80, 40:60, 50:50, 60:40, and 80:20 respectively. Overall, the CH fibers produce the higher sound absorption than the CO fibers, since the CH fibers contains the bundles of fibrils/fibrillation which creates the porous structure resulting the improved sound absorption property. In case of CO fibers, the fineness of the fibers plays a vital role in the sound absorption. Overall, the results shows that the sound absorption performance of CH/CO nonwoven fibrous materials was inconsistent with respect to their thickness. Therefore, the sound absorption coefficient value is strongly dependent on the blend proportion, thickness of the nonwoven web. The fibrillation of CH fibers is caused by the presence of bundles of fibrils. Fibrillation produces a porous structure with improved sound absorption. There is also a peak of about 1400–2200 Hz (i.e., for all blend proportions), which might be related to the intrinsic characteristic of fibers and their morphological structure. Low-frequency noise is more hazardous to human health than high-frequency noise, and coffee husk nonwoven fibrous materials may be an effective absorber of low-frequency noise.

Additionally, the sound absorption behavior of the samples was also investigated using the Delany-Bazley, Garai-Pompoli, Miki, Allard and Champoux and Johnson-Champoux-Allard models. In general, it has been demonstrated that this model provides a technique that is both straightforward and effective in the investigation of the acoustic properties of CH/CO

nonwoven fibrous materials. When compared with the experimental data, it was discovered that the JCA and AC model is the most acceptable model for predicting the absorption behavior of CH/CO nonwoven fibrous materials. This finding suggests that the JCA and AC model is able to satisfactorily predict the SAC of CH/CO nonwoven fibrous materials.

In this work, the thermal insulation of nonwovens made from CH/CO have been experimentally and numerically studied. It is noteworthy that, when compared to the Herman model, the Bhattacharyya model's results showed slightly greater thermal conductivities. The Herman model was chosen because it took into account both the fiber volume fraction and the fiber orientation fraction. Thus, it can be concluded that, in the Herman model, the fiber volume fraction has a greater impact on the thermal conductivity of nonwoven fibrous materials than the fiber orientation. From this work, both the models developed by Herman and Bhattacharyya cannot be used with very porous nonwoven fibrous materials.

In conclusion, the results of this research presented an innovative approach to the production of environmentally friendly sound-absorbing materials from agricultural and industrial waste. The research used a more environmentally friendly method of production to turn waste material into a valuable product, which contributed to the achievement of the United Nations (UN) sustainability development goals.

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**Data availability** The data that support this research and other findings of this paper are available from the corresponding author upon reasonable request.

**Declarations**

**Conflict of interest** All authors declare that they have no conflict of interest.



**Ethics approval and consent to participate** Not applicable.

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