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ORIGINAL PAPER

Sound absorption performance of tea waste reinforced polypropylene and nanoclay biocomposites

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Abstract

Noise is the principal physical hazard in many workplaces that affects work efficiency and human health; consequently, reducing noise by utilization sound adsorbent is a major method for controlling noise. Synthetic materials such as fiberglass and rock wool are utilized as sound absorbers in developing countries are harmful to the environment and health. Thus, this has motivated the initiative to develop natural fibers and their reinforced composites as candidates to replace the synthetic materials utilization theoretical study and life cycle assessment (LCA). In addition to lightweight and low CO_2 emission advantages, the natural vegetable fibers are non-toxic and recyclable. The characterization of these green composites will develop for utilization in engineering applications. Nowadays, their sound absorption properties have been extensively studied and are applied in many components for airplanes and cars. This research aimed to study the sound absorption properties of tea waste fibers and their reinforced composites. It was observed that adding 5 wt% nanoclay in samples improved the sound absorption coefficients (SAC), especially at lower frequencies. A 60% increase in tea waste had a special role in absorbing sound waves at a frequency of 1000 Hz and a frequency range of 2500 to 6300 Hz. The Scanning Electron Micrographs (SEM) images showed that the different sound absorption properties of nanocomposites were due to the high porosity of tea waste.

Keywords Sound absorption coefficient · Nanocomposite · Tea waste · Nanoclay · Polypropylene

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Introduction

With the rapid urbanization and fast growth of transportation, noise pollution has been considered a major environmental problem [1, 2]. One of the most common problems in exposure to high-level noise is a hearing loss so that, 10% of hearing loss is due to exposure to noise in the work environment [3]. According to the World Health Organization (WHO), noise pollution can cause heart attacks and sleep disturbance [4]. Various techniques are suggested for controlling or minimizing excessive noise levels. For example, sound absorbers are utilized as an impressive noise control method in interior and exterior environments, and these are necessary to create convenient conditions for speech communication [5, 6].

Porous synthetic materials, such as rock wool, fiberglass, and plastic foams, are harmful to human health and cause global warming [7, 8]. Life cycle assessment has shown that natural materials have the lowest environmental damage [9]. In recent years, greater attention to human health and environmental protection has led to study for the utilization of natural fibrous material, such as rice husk [10], bagasse [11, 12], coir fiber [13], coffee chaff [14], sunflower [15], corn husk [16], date palm branches [17], coconut husk, and sugar cane fibers [18]. Natural fibers have positive mechanical properties [19] and are biodegradable [20], cost-effective, and environmental-friendly, and they can reduce noise pollution [21, 22]. For these reasons, the utilization of natural materials for noise reduction is gradually evolving [23–25].

Tea is a world popular drink that prepares from brewing tea leaves. About 4.5 million tons of teas are consumed annually in the world [26]. Tea leaves are resistant to fungi and termites and have high durability [27]. They are available in excess and can be utilized in enormous quantities without spending money. Ahsan et al. [28] worked on spent tea leaf fiber-filled polyurethane foam composite because tea leaves are resistant to fire, fungal, and termites. Ekici et al. [29] demonstrated that utilization tea-leaf fibers in polyurethane foams significantly improved sound absorption. Moreover, the results of previous studies indicate that polyurethane foams loaded with tea-leaf fibers have higher positive effects on sound absorption [30].

Recently, nanoscience and nanotechnology materials have been utilized for improving mechanical and physical properties in the manufacture of composites [31, 32]. Among the nanoparticles, nanoclays are utilized widely as a filler [33]. Gayathri et al. [34] demonstrated that adding nanoclays to the polyurethane foam improves sound absorption. Nanofibrous materials have a high surface area and effective airflow resistance; therefore, they can increase the absorption of acoustic energy [35].

Researchers have focused on the acoustic characterization of natural materials and published numerous studies. However, very few publications are available in the kinds of literature that discuss the issue of the sound absorption of tea waste fibers. This research aims to study the behaviors and characteristics of sound absorption of tea waste from the leftovers brewed reinforced polypropylene and nanoclay as a biomaterial that have not been utilized in previous studies. The

normal incidence absorption coefficients of samples were examined by an impedance tube, and the effect of nanoclay on the sound absorption coefficient was studied. The relation between the sound absorption coefficient and density, porosity, airflow resistivity, and thickness were investigated, too. The previous studies that have studied tea waste fiber have not investigated these variables exactly.

Materials and methods

Materials and preparation samples

The studied natural fibers are tea waste fibers. Tea wastes were taken from the tea residue of brewing Iranian tea to eliminate the variable of tea type. They were spread under the sun for three days and dried frequently into an oven at 80 °C for 20 minutes. The relative humidity is calculated by utilization Eq. (1) based on the wet weight that was less than 2%. Finally, size 1 to 5 mm of dried tea wastes were separated.

$$M_w = \frac{W_w - W_d}{W_w} \times 100 \tag{1}$$

Polypropylene (PP) was produced by a company in Iran. It was in the form of homopolymer pellets whit grade HP552R, a density of 0.9 g/cm^3, Vicat-softening point (10 N) of 152.

The 2% Maleic Anhydride (MA) was utilized for improving the connection between tea wastes and polypropylene. It was a product of German Merck with a density of 1.48 g/cm^3.

Nanoclay montmorillonite (MMT) was obtained from SIGMA-ALDRICH whit particles sizes 1–2 nm and moisture content 1–2%.

Firstly, polypropylene granules were melted at a temperature of 250 °C. In the second stage, tea waste, maleic anhydride, and nanoclays were mixed for 120 min by a magnetic stirrer with a 10 rpm at the temperature of 152 °C. Then prepared combination was blended with melted polypropylene for 15 min at 152 °C. Different mixtures were prepared with a diameter of 28 mm for subsequent testing (Table 1).

Table 1 The blend weight percentage of nanocomposite and composite samples

Sample code	Tea waste (%)	MA (%)	MMT (%)	PP (%)
TW_0	0	2	0	98
TW_{30}	30	2	0	68
TW_{40}	40	2	0	58
TW_{60}	60	2	0	38
TW_0N_5	0	2	5	93
$TW_{30}N_5$	30	2	5	63
$TW_{40}N_5$	40	2	5	53
$TW_{60}N_5$	60	2	5	33

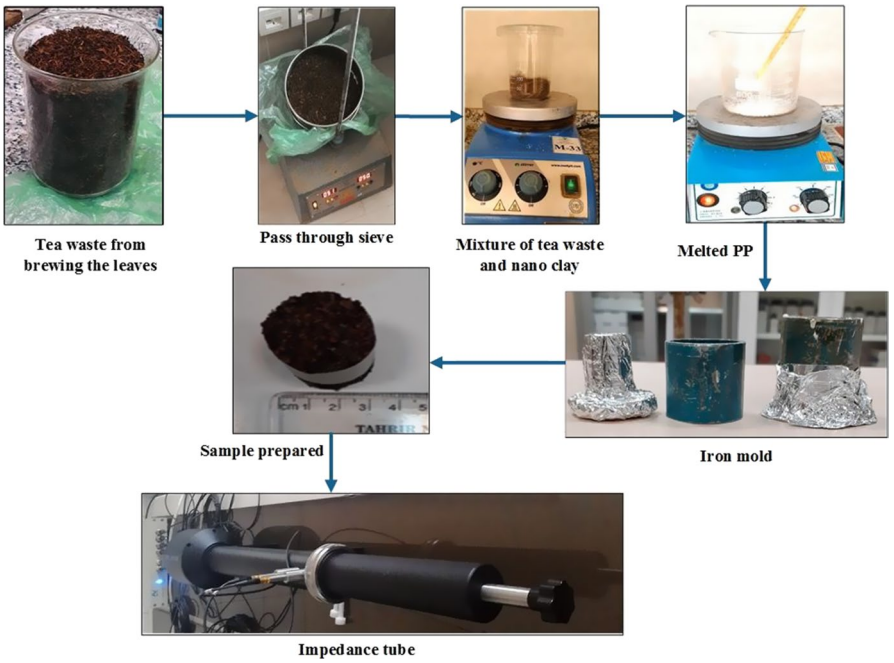

Fig. 1 Nanocomposite samples preparation process for sound absorption experiment

From each mixture, two samples were obtained, one in the thicknesses of 3 cm and one in the 4 cm, to examine the effect of the thickness in the sound absorption. Figure 1 illustrates the sample preparation process.

Sound absorption measurement

Acoustic absorption coefficient measurement is performed by the two microphones impedance tube BSWA SW477 and based on the standard of ISO10534-2. During the measurement, the ambient temperature, atmospheric pressure, and relative humidity were T = 20 °C, Pa = 101.4 kPa, and $\phi = 50\%$, respectively. The microphones are calibrated with a calibrator at a frequency of 1000 Hz. The sample is held tightly by the holder and the end of the impedance tube. The sound absorption coefficient of the samples was measured by utilization VA-Lab4 software at frequencies of 1/3 octave bands. The precision and accuracy of the experimental measurements were verified by conducting three times repeated.

The density

According to ASTM 1622-08, Eq. (2) is utilized to determine the bulk density. Where m is the mass of the sample measured by precision of 0.0001 and V is the volume of the sample.

$$\rho_{\text{bulk}} = \frac{\text{m}}{\text{V}} \tag{2}$$

Airflow resistivity and porosity

The diameter of natural fiber, thickness, and mass of samples affect the amount of flow resistance and porosity [9]. The flow resistance of each sample is calculated by utilization Eq. (3) and having a density of sample (ρ_{bulk}) and diameter of fiber (d_{fiber}) [36]. SEM pictures are utilized by the SEM device AIS-2100 model to obtain the diameter of tea waste fiber. The samples were immersed in liquid nitrogen for a few minutes to reduce the possibility of deformation when they were broken. All fractured surfaces of samples were prepared by sputtering with gold before the examination.

$$\sigma = 3.18 \times 10^{-9} \times \frac{\rho_{\text{bulk}}^{1.53}}{\text{d}_{\text{fiber}}^{2}} \tag{3}$$

Porosity represents the ratio of the total pore volume to the total volume of the sound-absorbing material and can vary between 0 and 1 [37]. The porosity of each sample can be defined using Eq. (4). Where ρ_{fiber} is fiber density and ρ_{bulk} is bulk density [38].

$$\varphi = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{fiber}}} \tag{4}$$

Water absorption

The water absorption experiment is performed by the ASTM-D1037 standard [39]. The weight of all samples was measured before being immersed in distilled water. The nanocomposite samples were immersed in distilled water for 2, 24, and 72 hours and then taken out and weighed again. The percentage of water absorption is determined by using Eq. (5).

$$\text{WA}_t = \frac{\text{W}_t - \text{W}_0}{\text{W}_0} \times 100 \tag{5}$$

where W_t is the weight of the sample after immersion in distilled water at time t and W_i is the dry weight of the sample [40, 41].

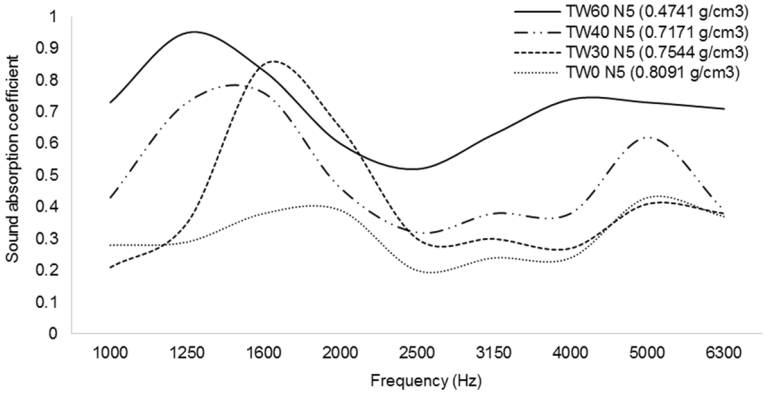

Fig. 2 The sound absorption coefficient of tea waste nanocomposites with nanoclay

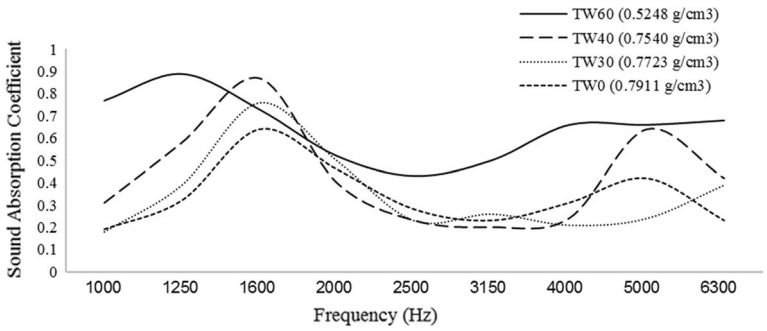

Fig. 3 The sound absorption coefficient of tea waste composites without nanoclay

Results and discussion

Sound absorption coefficient

Figure 2 shows the curves of the SAC of samples with different weight percent of tea waste and 5 wt% nanoclay, and Fig. 3 shows variations of the SAC without nanoclay in 3 cm thickness.

In composites without nanoclay, increasing the weight percentage of tea waste to 30% does not make a noticeable change in the sound absorption coefficient compared to samples without tea waste, while the samples treated with 60% tea wastes have the highest value of the SAC, especially at frequencies of 1000, 1250, and 4000 to 6000 Hz. The composite porous structure has an excellent sound absorption coefficient at higher frequencies, especially above 4000 Hz [42].

Fibrous material is one particular type of porous material that is composed of an assembly of continuous filaments. As the sound waves travel through the material, they provide resistance to acoustic wave motion and lose energy by the frictional

forces [43]. Thus, an increase in the amount of natural fiber leads to an increase in the sound absorption coefficient, and the highest sound absorption coefficient is in the range of 1000 to 2000 Hz. When the weight of tea waste in composites without nanoclay is increased from 30% to 40%, the peak absorption coefficient is shifted from 1600 Hz to 1250 Hz.

When the sound waves pass through the pores, the air in the pores is forced to vibrate and causes the pore wall to vibrate. The diminutive pore size makes more contact area for sound waves to get dampened that consequently attenuating the wave strength [44–46].

The comparison between curves of Figs. 2 and 3 demonstrates that adding nanoclay to samples causes the sound absorption coefficient to increase; for instance, at the frequency of 1250, the SAC of $TW_{60}N_5$ is equal to 0.95, while the SAC of TW_{60} is 0.89.

Hajizadeh et al. [47] demonstrated that adding nanoclay partially can improve the sound absorption coefficient at all frequencies, especially at low frequencies. Nanoparticles act as fillers inside the composites and cause the creation of tortuous paths for the sound transmission and increased contact area; thus, the sound energy loss in the form of heat and the sound absorption coefficient increases.

Effect of density

The previous studies indicate that the increase in the amount of natural fibers in the samples decreases the density and subsequently enhances the sound absorption coefficient [48]. When the amount of tea waste increases and the percentage of polypropylene decreases, the bulk density decreases, and the sound absorption coefficient also increases. As shown in Fig. 2 at the same thickness, the SAC of sample $TW_{60}N_5$ with a density of 0.474 g/cm^3 is higher than sample TW_0N_5 with a density of 0.809 g/cm^3 at all frequencies.

The denser sample can reduce the porosity of the sample and significantly increase the airflow resistance; therefore, the sound reflection increases from the surface of the sample, which causes the sound wave to penetrate the sample difficulty, and as a result, the sound absorption coefficient reduces at high frequencies [49]. Thus, the decreasing density of samples increases the sound absorption coefficient at the frequency range of 4000 to 6300 Hz; for example, The SAC recorded by 0.474 g/cm^3 $TW_{60}N_5$ achieved 0.74 at 4000 Hz, while for 0.524 g/cm^3 TW_{60} sample achieved 0.66 at 4000 Hz. On the other hand, the samples with nanoclay have lower bulk density compared to samples without nanoclay; therefore, nanoclay affects the bulk density value, which results improvement of the sound absorption properties.

When sound waves are absorbed at middle and low frequencies, with an increase in the bulk density, the flow resistance becomes stronger; thus, the inner voids become smaller, and sound waves have friction with fibers and the frequent interaction between air and voids. Then, sound waves reflect in the inner part of the sample and become impermeable, which causes sound energies to lose, and the sound absorption properties improve at middle and low frequencies [50]. As shown in the measurement result, that the SAC for the 0.754 g/cm^3 $TW_{30}N_5$

sample is 0.65 at 2000 Hz, while the 0.717 g/cm^3 $TW_{40}N_5$ sample achieves the SAC value of 0.46 at the same frequency.

Based on the result, it is found that if the thickness of the samples is preserved constant, density imports much in sound absorption.

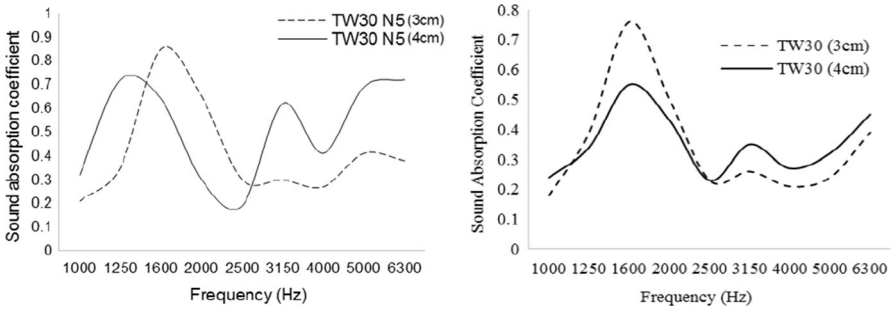

Fig. 4 The effect of thickness on the sound absorption coefficient of nanocomposite and composites samples with 30% tea waste

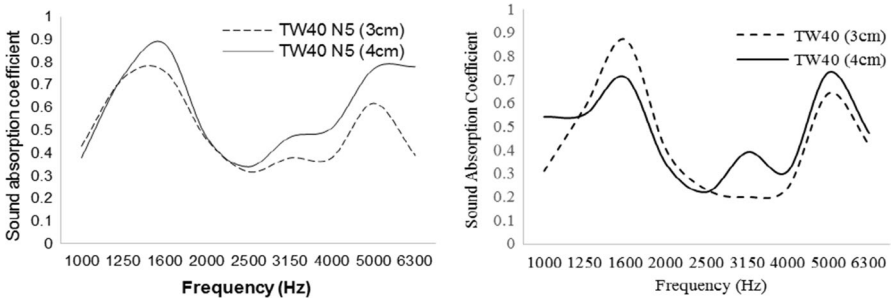

Fig. 5 The effect of thickness on the sound absorption coefficient of nanocomposite and composites samples with 40% tea waste

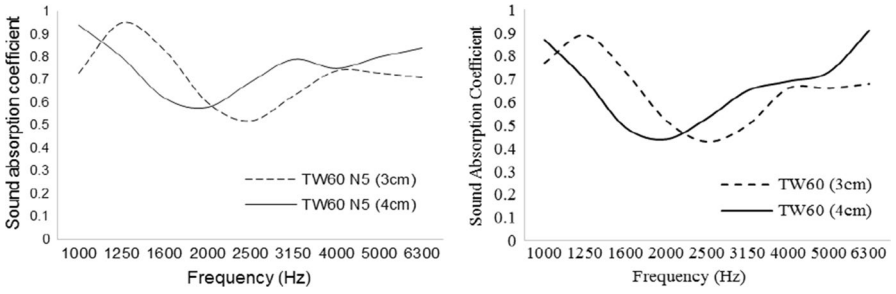

Fig. 6 The effect of thickness on the sound absorption coefficient of nanocomposite and composites samples with 60% tea waste

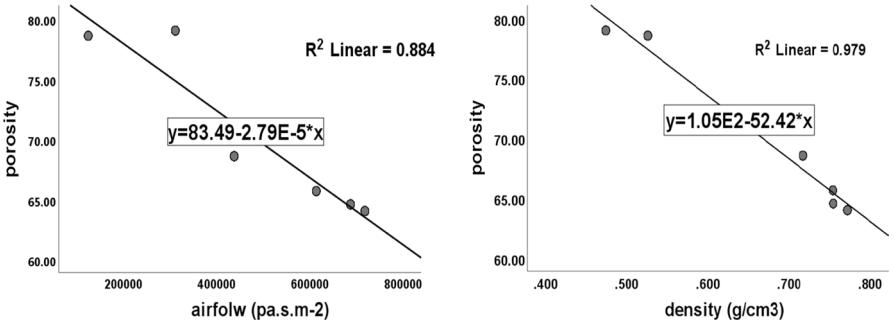

Fig. 7 Relations between the density and the porosity and flow resistivity

Table 2 The physical characterizer of samples with different weight percentages tea waste

Sample code	ϕ (%)	Fiber diameter (μm)	σ (Pa s m^{-2})
TW_{30}	64	10.48	758,156
TW_{40}	65.66	11.44	613,695
TW_{60}	78.57	9.37	524,233
$TW_{30}N_5$	64.55	10.81	687,311
$TW_{40}N_5$	68.56	13.04	437,437
$TW_{60}N_5$	79	10.62	350,041

Effect of thickness

For effective sound absorption, the thickness of the samples should be at least one-tenth of the incident sound wavelength. Under similar conditions of density and the amount of tea waste with thicknesses of 3 and 4 cm as a variable, the sound absorption coefficients are illustrated in Figs. 4, 5, and 6.

In thicker samples, the peak sound absorption coefficient moves toward lower frequencies (1000 Hz and 1250 Hz), and the SAC increases at higher frequencies, too. For instance, the first peak value of the SAC of the sample $TW_{40}N_5$ is 0.95 at 1600 Hz for the 3 cm thick, but an increased thickness (4 cm) the first peak value of the SAC is 0.94 at 1000 Hz.

Qui et al. [1] demonstrated that the thickness affects the sound absorption coefficient positively at high and low frequencies. An increase in the sample thickness creates more pore channels, which allow acoustic waves to pass through tortuous passages. Thus, the kinetic energy of the incident sound wave is converted to heat energy because of frictional loss between sound waves and fiber [42]. In addition, when the thickness of the material increases, the time and the distance for passing sound through the composite will be longer, and the sound could be reflected and refracted multiple times. Consequently, the sound energy losses, and the sound absorption coefficient increases [51].

Effect of airflow resistivity and porosity

Figure 7a shows a linear regression between porosity and density. It is completely clear that density has a reverse effect on the porosity; furthermore, it is observed in Table 2 that a decrease in the density increases the porosity percentage of composite samples. Fouladi et al. [38] demonstrated that the blend of natural fibers with binder makes the binder and fiber that acts as a part of the material, and the porosity is decreased; thus, increasing the natural fibers compared to binder cause the porosity increase.

According to the results, the TW_{60} N_5 sample has the lowest density and airflow resistivity and the highest porosity. Figure 7b illustrates a reverse linear regression between porosity and airflow resistance. Therefore, porosity alone cannot provide a perfect picture of the structure of a porous material; thus, other physical properties like airflow resistance must be investigated to determine the sound absorption coefficient [52]. Flow resistivity is the principal parameter influencing the sound absorption coefficient [53].A reducing of the fiber diameter of tea waste increased airflow resistance, however it was not a linear regression (Table 2).

Regression analysis showed the highest Re-square values ($R^2 = 0.999$) were observed between the porosity and airflow resistance and density, and there is a significant correlation between these variables. Equation (6) illustrates the measured regression line that indicates the relation between the porosity and airflow resistance, and density in composite and nanocomposite samples.

$$\text{porosity} = 99.867 - (38.299 \times \text{density}) - (9.001E^{-6} \times \text{airflow}) \tag{6}$$

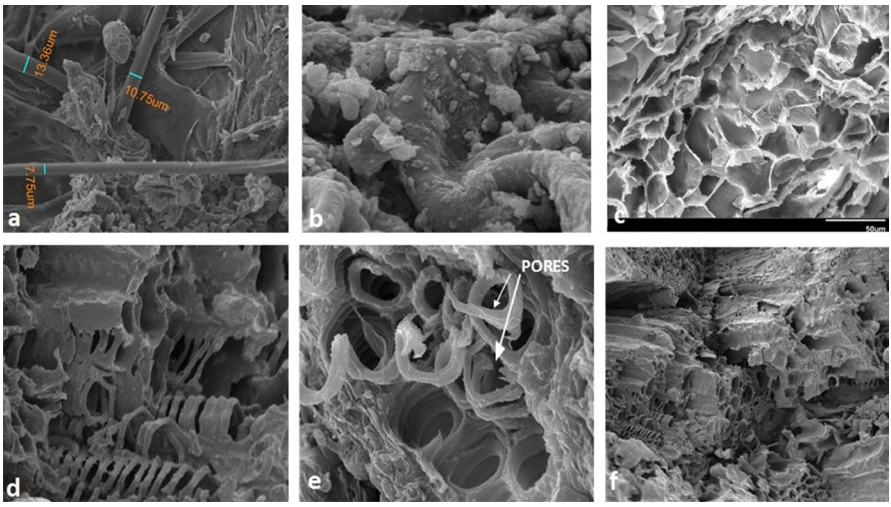

Fig. 8 Scanning electron micrographs (SEM) of **a** dispersion of Tea waste fiber among polypropylene and nanoclays, **b** dispersion of nanoclays among polypropylene × 10,000, **c** the cell structures of tea waste, **d–f** porosity of tea waste respectively × 2000, × 10,000, × 500

SEM and FTIR

Figure 8 shows the SEM micrographic of the open-cell structures, the size, and the shape of the porous cells of tea waste. As shown in Fig. 8d–f, TW_{60} made of 60 wt. % tea waste has the structure of connected open pores that completely have formed; consequently, the disposition of fibers is caused by a longer path for the sound waves, so the internal path (tortuosity) increases which energy loss and the sound absorption coefficient is increased significantly [54]. The structure of open pores is one of the most important factors for achieving a great sound absorption coefficient. In Fig. 8c, the cell structures of tea waste are almost uniform.

In Fig. 8a is shown the morphology of the TW/PP (60–33 wt%) material where it is possible to see the stretching of the PP between the tea waste fibers, and in Fig. 8b, images suggest that the surface of the nanoclays interacted well with the polypropylene since voids or vacant spaces between the two phases were not detected. There is a significant difference in polarity of utilization components, tea waste and nanoclay are hydrophilic, and polypropylene is the hydrophobic matrix. This is related to MAPP coupling agent that results in a more homogeneous mixture of tea waste

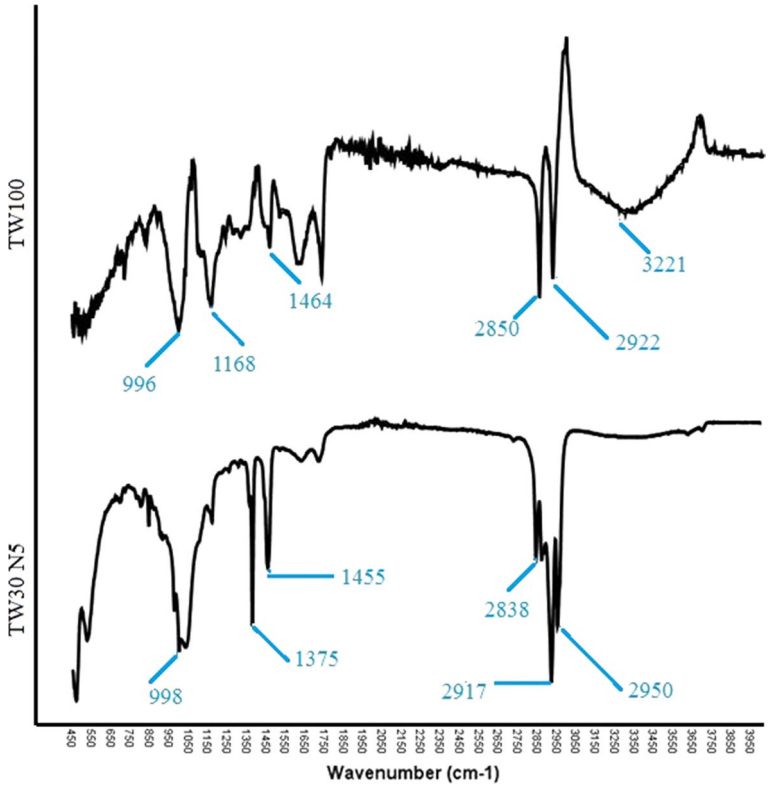

Fig. 9 FTIR spectra of the prepared samples

fibers, nanoclays, and PP together. Reddy et al. [55] demonstrated that the surface modifications with the addition of a coupling agent improve the adhesion between fibers and polymer matrix interface.

Figure 9 shows the FTIR spectra for TW_{30} N_5 and untreated TW_{100} samples that were scanned at a range of 400–4000 cm^{-1}.

In Fig. 9, the region of the broad absorption band at 3500 cm^{-1} to 3000 cm^{-1} for the tea waste fibers are characterized with O–H stretching and H– bonding structure that contains phenols, alcohols and water functional group [56]. The O–H stretching and H– bonding broad absorption band in the regions is absent in TW_{30} N_5; it is likely for taking 63 wt% PP that causes breaking of O–H bond to eliminate waterish (hydroxide) structure [36].

The region of 1500–1200 relates to the deformation modes of the CH_3/CH_2 species [57]. Absorption at 1455 cm^{-1} is attributed to the scissor vibrations of C–H bonds in CH_2 groups of aliphatic chains. The presence of absorption bands at 1455 cm^{-1} is related to asymmetric methyl bending modes [58]. The signal at 1375 cm^{-1} is associated with C–H bonds in CH_3 end groups. FTIR analysis provides insight into the interactions between the fibers and polymer because of the existence of these two new spectrums.

Water absorption behavior

The results in Fig. 10 show that WA is increased 11–27% by adding tea waste of about 40–60 wt% compared to boards made without tea waste after immersion in water for 24 hours. Natural fibers have hydroxyl groups that interact between water molecules and hydrogen bonds that predispose them to water absorption. However, the water absorption of natural fibers surrounded by thermoplastic composites is less than that of lignocellulose materials because thermoplastic materials have hydrophobic plastics [59, 60].

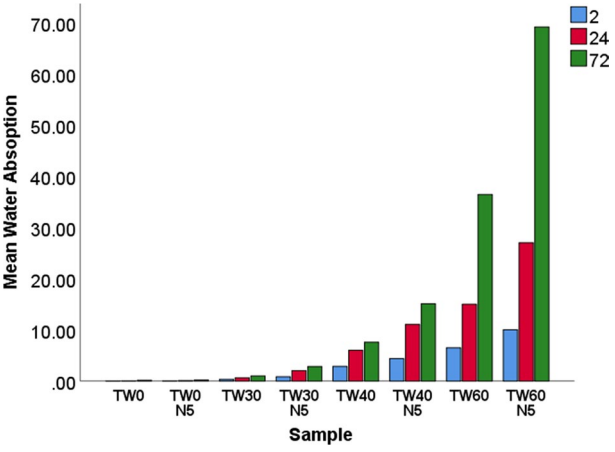

Fig. 10 Water absorption behavior of tea waste

When water retention time increases, water absorption is also increased; for example, water absorption of sample $TW_{60}\,N_5$ after 2 hours immersion in water is equal to 10.42%, while after 72 hours, water absorption is equal to 69.127%.

The water absorption of sample $TW_{60}\,N_5$ is higher than TW_{60}. The water absorption of samples with nanoclays increased compared to samples made without nanoclays. According to the SEM analysis, it can be supposed that a significant increase in the water absorption ability of nanocomposites in the case of materials containing 5 wt% of the nanoclay happens as a result of structural changes. According to the previous literature, composites that formed hybrid nanocomposites have increased the water absorption capability, and this effect is related to the hydrophilic particles of the filler [61].

Conclusion

The results indicated by increasing the tea waste weight percent compared to the polypropylene, the sound absorption coefficient increased. In addition, the sound absorption coefficient was increased by adding nanoclays to composite samples. Another important point is that an increase of tea waste percentage decreased the density of samples and increased the porosity, which can effectively enhance the high-frequency sound absorption coefficient, however the effect of density at middle and low frequencies is slightly low. Increasing the thickness can improve the high and low-frequency sound absorption coefficient, and the sound absorption peak moves towards the frequency of 1000 Hz. In the SEM analysis was observed that the presence of pores in tea waste fibers allows to air to flow into the cellular structure, and the sound energy converts into thermal energy. The decrease in sound intensity by utilization of tea waste biocomposites discloses that they can be utilized as a great sound absorber especially controlling noise at high and medium frequencies.

With proper design, it can meet a variety of applications, from small to enormous items. This application has the potential to reduce the noise level in the vehicle, automotive, road noise, and engine noise; other than that, it can be utilized in the interior design of aircraft. The materials that have been utilized in this study are safer compared with the traditional absorbing materials produced in the market. Furthermore, they are devoid of harmful effects on human health and environmentally friendly substances. However, a limitation might exist for the tea waste reinforced nanoclay and polypropylene; for example, providing tea waste in enormous quantities could be difficult.

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