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Sustainable multiple resonator sound absorbers made from fruit stones and air gap

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Abstract This article investigates the sound absorption coefficient of materials manufactured from natural wastes. Fruit stones from some crops are one of the most available natural wastes in the Mediterranean Region. Recycled and vegetable products are becoming an interesting alternative to traditional materials to be used as sound-absorbing panels.

Fruit stones can be profitable for a number of applications, such as biomass to produce energy. This research work intends to demonstrate that one of their applications can be ecological sound absorbers in building acoustics.

Different four fruit stone samples, with different air gap volume percentages, display similar behaviour to multiple Helmholtz resonators (MHRs). By adding a 40 mm-thick rockwool layer, the sound absorption coefficients are compared for each sample.

The experimental results allow establishing some analogies between MHRs and the new absorbing materials according to thickness, fruit type and the air gap volume. These fruit stones have been demonstrated as a good choice from acoustic and sustainable points of view.

1. Introduction

One of the causes of health problems in modern societies is noise pollution due to traffic, machines and crowded spaces [1–4]. Noise pollution problems often lead to hypertension, ischaemic heart disease, less efficiency in study and work positions, etc.

By observing these problems, which started in the 1960s, the noise regulations in the Architectural Acoustics field include restrictive conditions to limit noise pollution and to protect people inside buildings.

These problems caused by undesirable noise and reverberations can be reduced by sound-absorbing panels. Difficulties are significant at low frequencies (20–400 Hz), and absorbing sound is easier at medium and high frequencies.

Qiu Xiaojun [5] studied the literature on the principles of sound absorbers, and provides a wide range of works and researchers who investigate in the noise reduction field.

One of the most widely used resources are microperforated panels that absorb sound at particular frequencies depending on some geometric parameters [6–8]. These panels are applied

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in building acoustics, and also in the automotive and aerospace sectors [9,10]. Occasionally, natural, synthetic or mineral fibres are added to these microperforated panels to widen the frequency range within which a material absorbs sound [11–14]. Other researchers have conducted works with fibrous materials by determining the sound transmission loss (STL factor) [15], whose intended use is in sound insulation.

Another solution to absorb noise at particular frequencies is the Helmholtz resonator, which appears in a number of research works [16–21], as well as innovative solutions by means of metamaterials for the absorption of low-frequency sounds [22,23].

In the research conducted to improve sound absorption properties by reducing materials' thickness, some works are about employing metallic foams like 10-mm aluminium foams [24–26].

However, because of climate change and the need to minimise its effects, the use of natural materials has rapidly extended.

According to Arenas and Asdrubali, most ecomaterials are divided into four categories: natural materials; recycled materials; mixed and composite materials; green walls [27].

In the sound absorption field, porous materials made of natural fibres are the most widely studied, such as pineapple leaves [28], wood-based materials [29,30], tea leaves [31], wool [32], esparto grass [33], sugar cane [34], kenaf [35,36], hemp [37], coconut [38] and others [39].

Some other previous research works are related to acoustic panels made from natural grains [40,41]. Part of this research was conducted to develop empirical models based on the experimental results. Some authors have developed similar models to predict materials' acoustic properties [42,43].

The properties of natural and recycled materials influence the acoustic behaviour of their components. In the particular case of recycled materials, some works are available about crumbed end-of-life tyres with different granulometry [44].

In some applications, biomass is used as an additive to concrete but other applications to reduce noise imply a higher added value for the material [45,46]. Another field of interest regarding biomaterials is the biogenic waste generated worldwide. This case is explained by Casadesús et al. by manufacturing sound-absorbing non-woven materials with chicken feather waste [47].

In the present work, four fruit stone varieties are employed to manufacture sound-absorbing panels. The shapes of the different hard fruit stones result in distinct acoustic properties, as previously studied [48]. The acoustic performance of other types of natural fibres mixed with grains has been investigated with interesting results at low frequencies [49,50].

Fruit stones are waste materials that can be profitable in a number of applications. In line with the Spanish Ministry of Agriculture report "Fruta de Hueso: Análisis de la realidad productiva 2020" (Stone Fruit: Analysis of Productive Reality 2020), the percentages of the surface used to grow fruit with stones are represented in Fig. 1.

New peach plantations are directed towards mid-season and late varieties of yellow peaches by reducing the areas used for early varieties of peaches. This means that peaches with yellow skin already account for 45% of the total planted area. However, this crop's area has been reduced on the whole by 11% to almost 27,000 ha.

With apricots, although the total area has decreased by 1% because the production areas of traditional yellow varieties have disappeared, the areas with orange varieties have increased and now represent 58% of the total. The south-eastern part is Spain's main producer (34%) with almost 6000 ha.

The area where cherries are grown increased the most in 2020 while this study was underway, and has grown by 9% compared to the previous year and gone from 21,000 to 23,000 ha. Early (27%) and mid-season (25%) cherry varieties are the groups that occupy the most hectares.

The situation with olive stones is slightly different because the range of applications is wider than the other fruit stone types. Among others, olive stones are used to generate agrobiomass energy to produce heat. In Spain, 78% of the facilities that employ agrobiomass to generate thermal energy resort to olive stones.

This energy source is gaining a better reputation because it respects the environment. It also has a high calorie value (4500 calories per gram) and is very cost-effective (saves 70% more than if gasoline or diesel is used). With 2 kg of olive stones, it is possible to heat in an equivalent way to what a litre of gasoline achieves.

The present research allows to broaden the knowledge about these materials' acoustic behaviour and considering them offers the possibility of manufacturing sound-absorbing panels with air layers and rockwool.

2. Experimental

2.1. Materials and samples

The samples studied in this work are four different fruit stone types: olive, cherry, apricot and peach (Fig. 2). The physical properties of the raw materials and their preparation are explained in the previous research by the authors of this work [48].

The sample manufacturing process consists of mixing the fruit stones with the binder in the appropriate proportion so that the binder does not excessively influence acoustic performance. As a binder, cyanoacrylate adhesive is applied to glue the fruit stones. The samples were manufactured in cylindrical PVC tube moulds of 100 mm diameter.

Table 1 explains the terminology used for samples and their meaning:

The sequence is repeated for each thickness per sample, as indicated in Table 2.

2.2. Standing wave tube

In order to determine the sound absorption coefficient, a standing wave tube with an inner diameter of 100 mm was used.

The frequency range was determined by Standard ISO 10534-2 [51] which states that the lower frequency depends on the distance between microphones (80 mm for these tests) and the higher frequency is limited by the tube's inner diameter.

According to Standard ISO 10534-2, the equipment consists of an impedance tube with a circular section. The test specimen is located at one end of the tube and a sound source

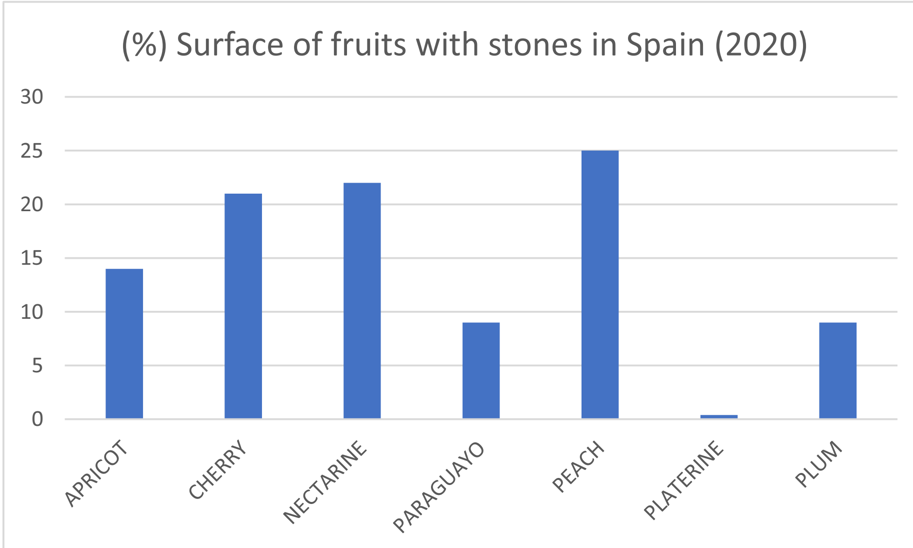

Fig. 1 Surface percentage of fruit stone in Spain (2020) according to the Spanish Ministry of Agriculture.

Fig. 2 Olive, cherry, apricot and peach stones (from left to right).

generates plane waves from the other end. Two microphones located close to the sample measure sound pressures.

The experimental setup to conduct tests is represented in Fig. 3. The microphones were G.R.A.S., model 40AO. The data acquisition card was National Instruments model NI-9233. The Matlab software was used for processing signals.

3. Theory

3.1. Sound absorption coefficient

Recommendations from Standard ISO 10534-2 were followed to evaluate these materials' sound absorption coefficient with an impedance tube by determining the reflection coefficient from the transfer function method.

According to this standard, specific acoustic impedance is calculated from:

$$\frac{Z}{\rho\hat{\mathrm{A}}\cdot c} = \frac{R}{\rho\hat{\mathrm{A}}\cdot c} + \frac{X}{\rho\hat{\mathrm{A}}\cdot c}j = \frac{(1+r)}{(1-r)} \quad (1)$$

where R, the real component of impedance; X, the imaginary component of impedance; $\rho\hat{\mathrm{A}}\cdot c$, the characteristic impedance (density multiplied by sound velocity); r, the reflection coefficient; Z, acoustic impedance. The reflection coefficient is determined from:

$$r = \frac{H_{12} - H_i}{H_R - H_{12}}\hat{\mathrm{A}}\cdot e^{2jk_o x_1} \quad (2)$$

and the sound absorption coefficient is given by:

$$\propto = 1 - |r|^2 \quad (3)$$

where: H_{12}, is the transfer function from microphone positions 1 and 2, H_R, is the real part of H_{12}, H_i is the imaginary part of H_{12}, k_0 is the wave number, x_1 is the distance between the sample and the first microphone.

The tests to determine the sound absorption coefficient were conducted on the apricot, cherry, olive and peach samples with their different thicknesses and air layers.

3.2. Multiple Helmholtz resonator

The obtained results allowed us to consider these samples' behaviour as if they acted as multiple Helmholtz resonators (MHRs). Resonators are basically tubes and cavities intended

Table 1 Terminology of samples with the first thickness (1).

Sample	Thickness (mm)	Air layer (cm)
Olive – 10	22	0
Olive – 11	22	1
Olive – 12	22	2
Olive – 13	22	3
Olive – 14	22	4
Olive – 15	22	5
Olive – 14lr	22	4 cm with rockwool
Cherry – 10	24	0
Cherry – 11	24	1
Cherry – 12	24	2
Cherry – 13	24	3
Cherry – 14	24	4
Cherry – 15	24	5
Cherry – 14lr	24	4 cm with rockwool
Apricot – 10	24	0
Apricot – 11	24	1
Apricot – 12	24	2
Apricot – 13	24	3
Apricot – 14	24	4
Apricot – 15	24	5
Apricot – 14lr	24	4 cm with rockwool
Peach – 10	20	0
Peach – 11	20	1
Peach – 12	20	2
Peach – 13	20	3
Peach – 14	20	4
Peach – 15	20	5
Peach – 14lr	20	4 cm with rockwool

Table 2 Thicknesses of samples.

Specimen	Thickness (mm)
Olive-1	22
Olive-2	43
Olive-3	55
Olive-4	77
Olive-5	98
Cherry-1	24
Cherry –2	42
Cherry –3	55
Cherry –4	77
Cherry –5	97
Apricot-1	24
Apricot –2	40
Apricot –3	55
Apricot –4	75
Apricot –5	95
Peach-1	20
Peach –2	35
Peach –3	55
Peach –4	75
Peach –5	95

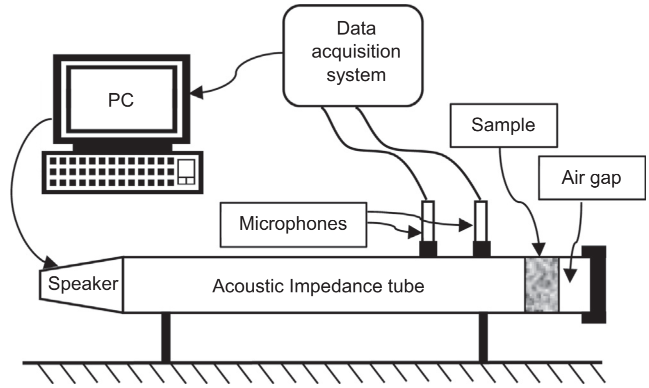

Fig. 3 Scheme of the acoustic impedance tube to measure the sound absorption coefficient.

to lower sound pressure levels. When a series of MHRs is used as a sound-absorbing surface, the resonant frequency is given by [52].

$$f_r = 5480\hat{A} \cdot \sqrt{\frac{\varepsilon}{T_s T_p}} \tag{4}$$

where: ε is the ratio between the area with holes and the area without holes in the cross-section; T_p is the sample's thickness (cm); T_S is the air gap's thickness (cm).

4. Results and discussion

4.1. Experimental results

The sound absorption coefficient for each fruit stone type was obtained by testing samples in the standing wave tube.

Figs. 4–7 represent the sound absorption coefficient for each sample depending on the frequency for thickness one.

With thickness one, the four stone fruits showed low acoustic absorption for the whole studied range of air gaps. All the values were below 0.6 except for Olive 11, whose maximum was between 1200 and 1400 Hz. However, all the fruit stones obtained high acoustic absorption values when rockwool was added. These values came close to 1 for cherry, olive and apricot within the frequency range of 600–800 Hz, and for peach within the frequency range of 800–1200 Hz.

Figs. 8–11 represent the sound absorption coefficient depending on the frequency for thickness two.

For thickness two, the acoustic absorption of the four fruit stones showed the same tendency when the air gap decreased and obtained the higher values with maximums within the frequency range of 1200–1600 Hz. All the values were below 0.8, except for Apricot 20. When the gap was filled with rockwool, all the acoustic absorption values of fruit stones were above 0.8 at certain frequencies. These values came close to 0.9 for cherry, olive and apricot within the frequency range around 500 Hz, and for peach within the frequency range of 600–800 Hz.

Figs. 12–15 represent the sound absorption coefficient depending on the frequency for thickness three.

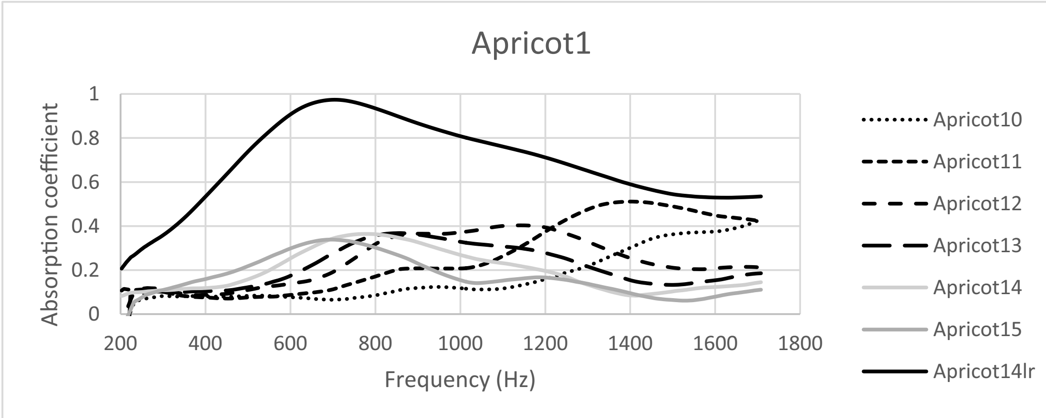

Fig. 4 Apricot samples, thickness 1 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

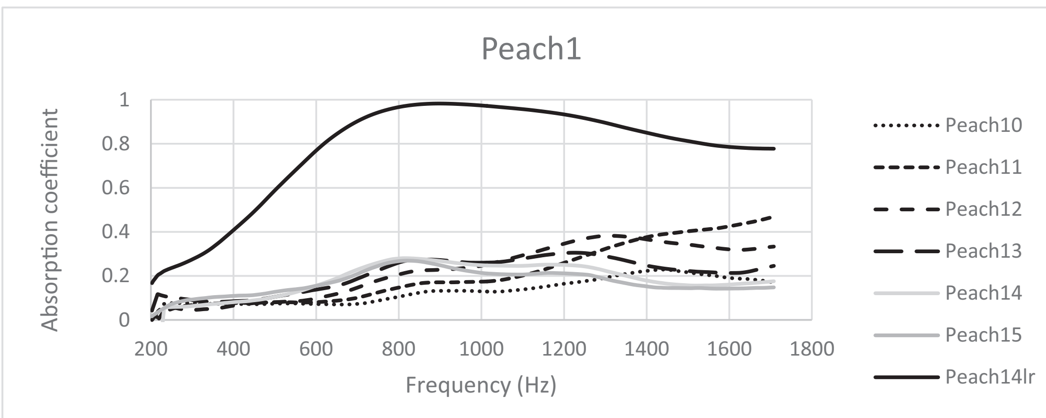

Fig. 5 Peach samples, thickness 1 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

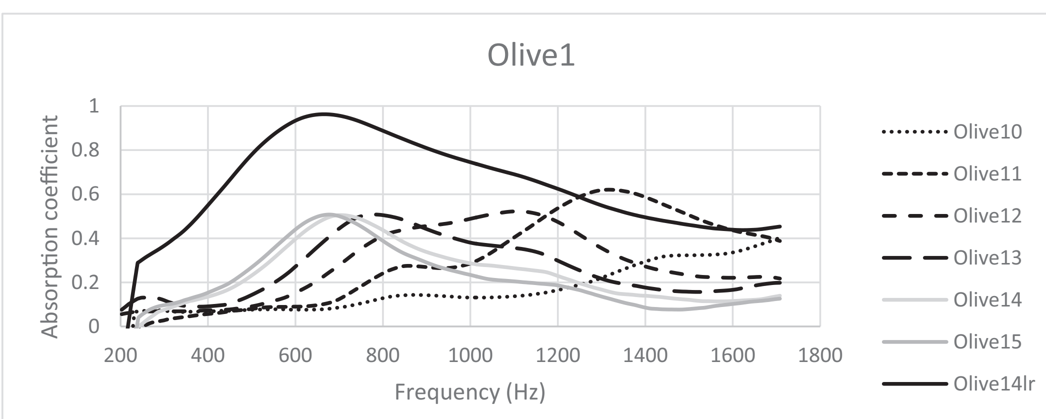

Fig. 6 Olive samples, thickness 1 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

With thickness three, the acoustic absorption of the four fruit stones showed significant differences. Their acoustic absorptions displayed the same tendency as thickness two, but with maximums within a lower frequency range of 800–1200 Hz. All the values were below 0.8, except for Apricot 30 and Cherry 30. When the gap was filled with rockwool, the acoustic absorption values for all the fruit stones was above 0.8, with a slight reduction in acoustic absorption compared to thickness two.

Figs. 16–19 represent the sound absorption coefficient depending on the frequency for thickness four.

With thickness four, the stone fruits' acoustic absorption showed the same tendency as thickness three but with maximums towards the frequency range of 600–800 Hz. In this case,

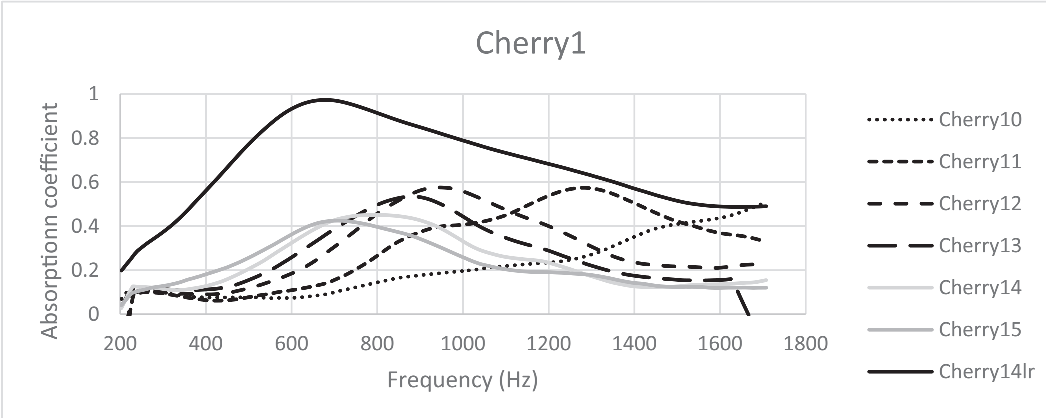

Fig. 7 Cherry samples, thickness 1 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

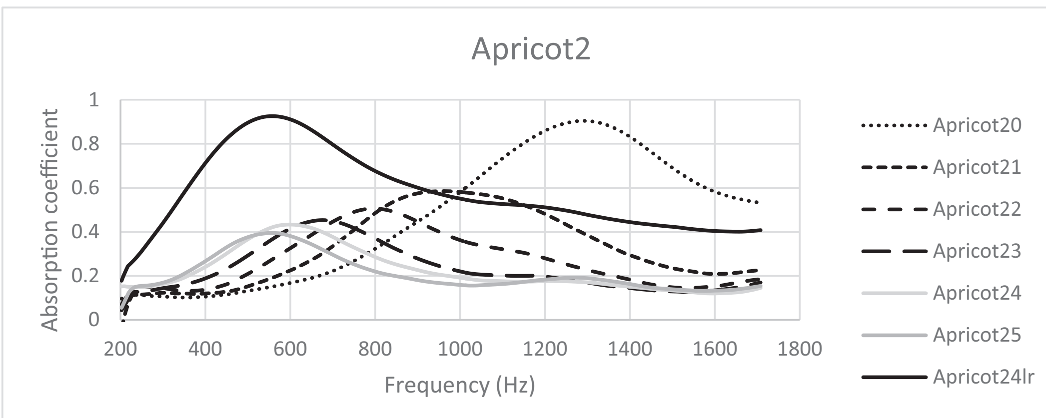

Fig. 8 Apricot samples, thickness 2 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

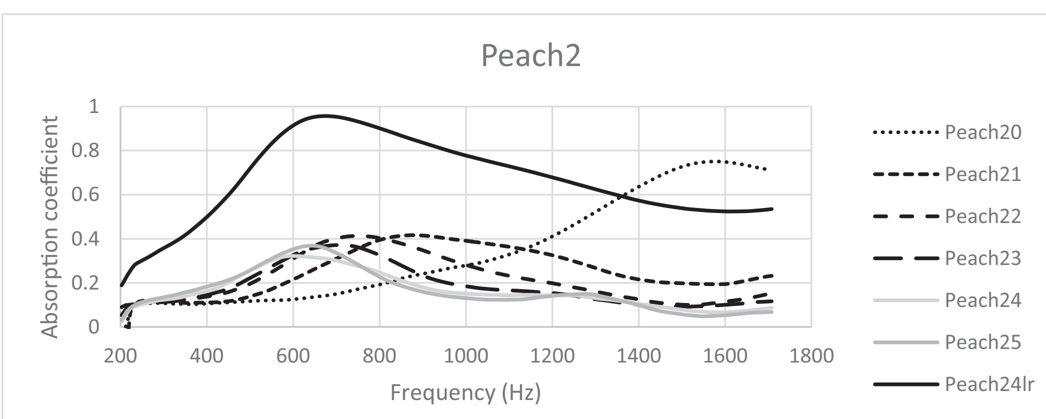

Fig. 9 Peach samples, thickness 2 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

the differences between the maximum values for each air gap were less significant. All the values were below 0.8, except for Cherry 40. When the gap was filled with rockwool, all the fruit stones obtained acoustic absorption values of around 0.8, which indicates a clearly declining tendency.

Figs. 20–23 represent the sound absorption coefficient depending on the frequency for thickness five.

With thickness five, all the fruit stones displayed two acoustic absorption peaks within the studied frequency range: the second one within the range of 1200–1600 Hz

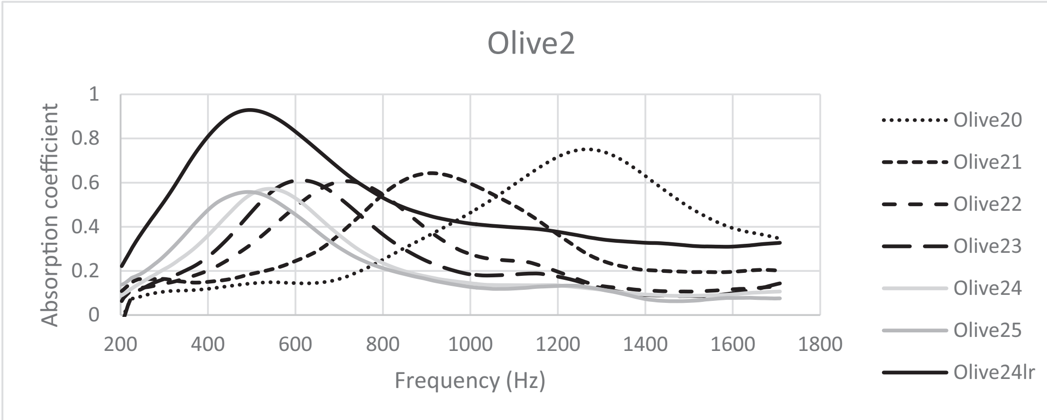

Fig. 10 Olive samples, thickness 2 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

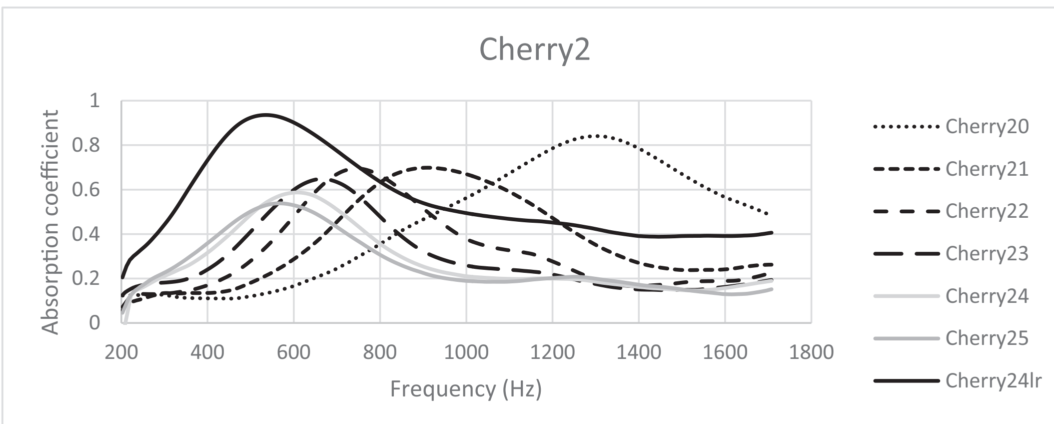

Fig. 11 Cherry samples, thickness 2 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

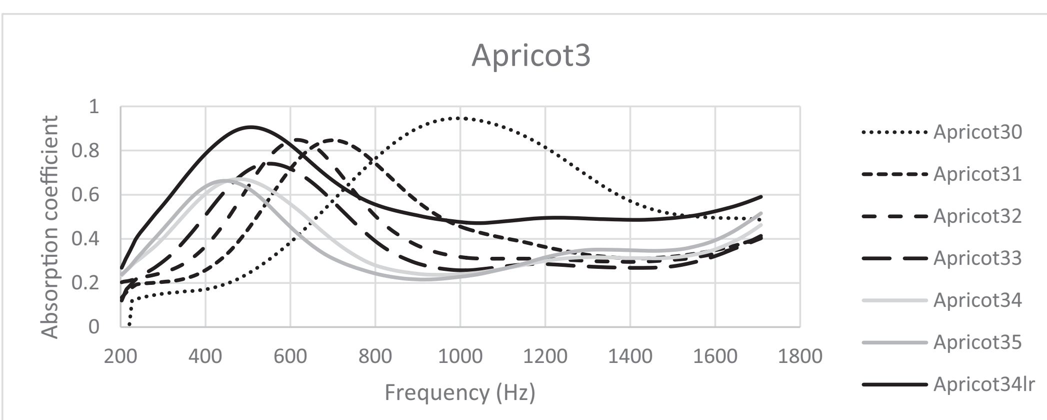

Fig. 12 Apricot samples, thickness 3 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

had the highest acoustic absorption values, which came close to or exceeded 0.8. When the gap was filled with rockwool, the acoustic absorption values of all the fruit stones were around 0.8, except for cherry whose value was 0.9 at around 500 Hz.

From the experimental results, we can conclude that the shapes of the stones have an influence on the sound absorption. Stones with a rougher surface absorb much more energy than fruit stones with a smooth surface, as happens in other known materials depending on their porosity.

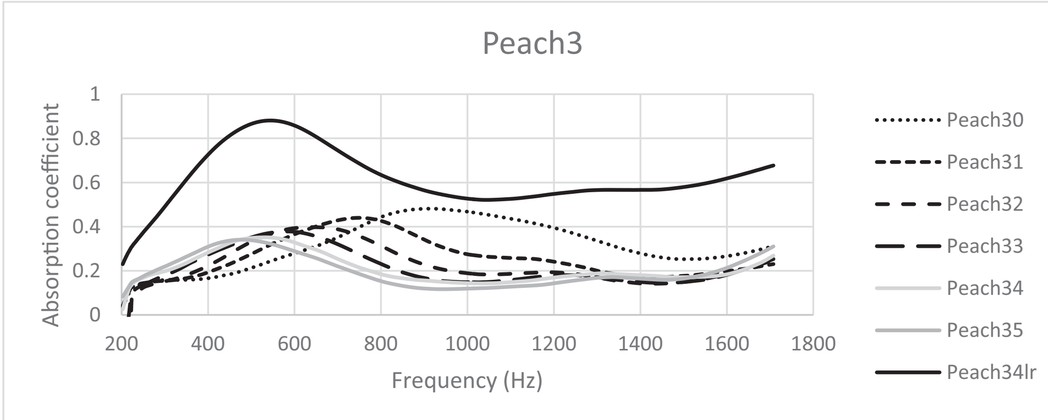

Fig. 13 Peach samples, thickness 3 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

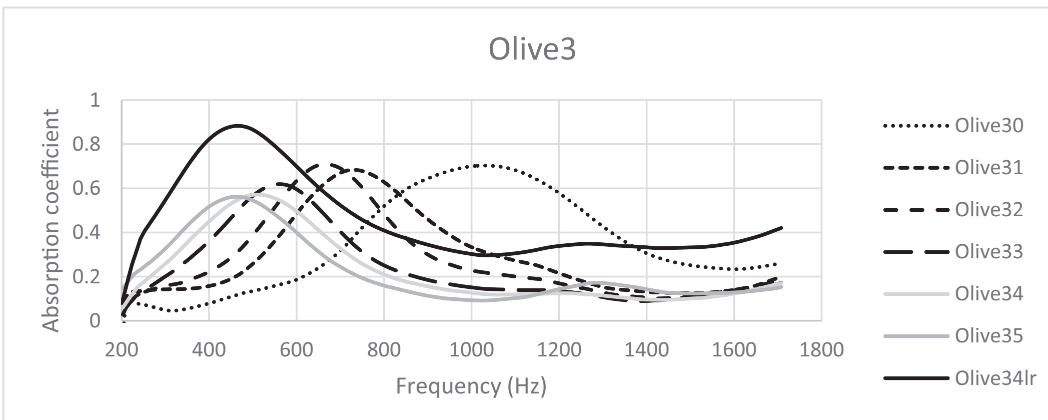

Fig. 14 Olive samples, thickness 3 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

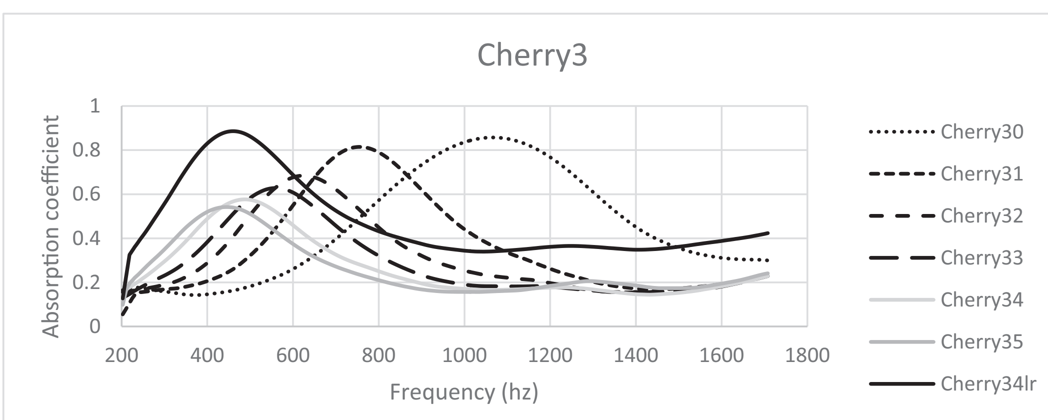

Fig. 15 Cherry samples, thickness 3 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

5. Conclusions

The sound-absorbing applications of fruit stone panels made of food industry waste represent a step towards environmental care. The use of such a product is a viable solution to manage the waste generated by consuming these fruits.

This work has been focused on the influence of the air gap between samples and the rigid wall. This influence was studied by varying the air gap thickness and adding a rockwool layer to one particular gap. The experimental results for the sound absorption coefficient presented the general tendency of having higher values at low frequencies by increasing the thickness. A

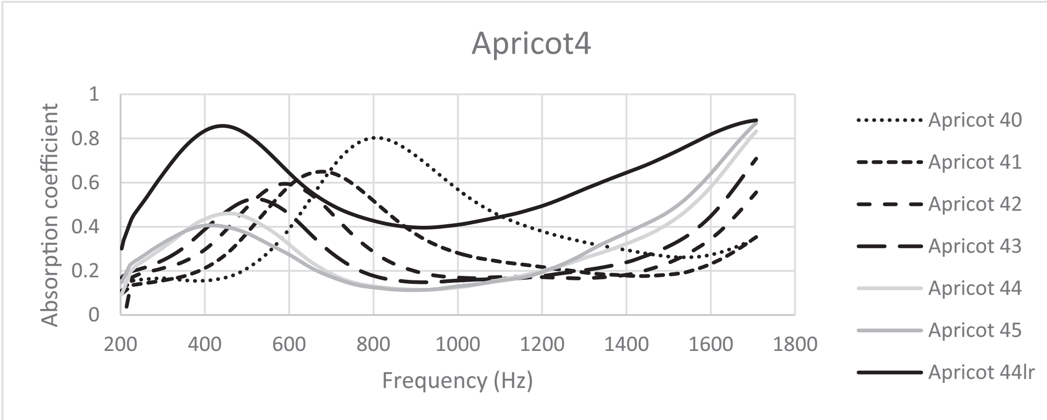

Fig. 16 Apricot samples, thickness 4 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

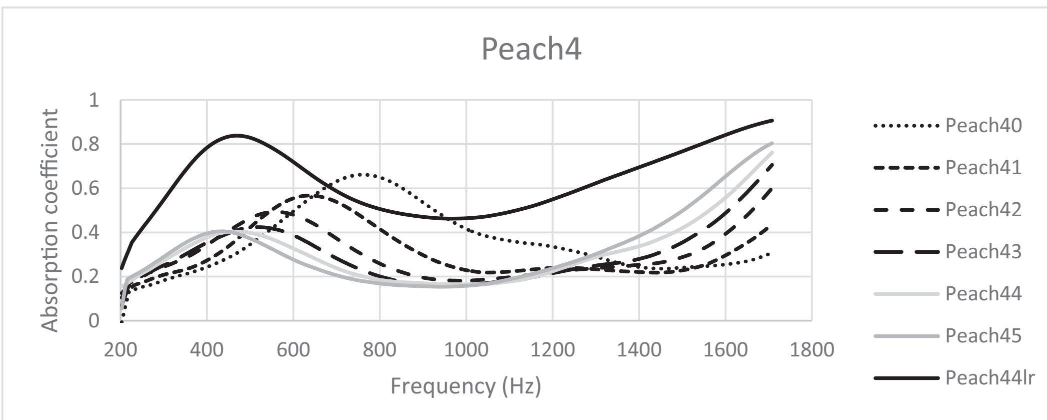

Fig. 17 Peach samples, thickness 4 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

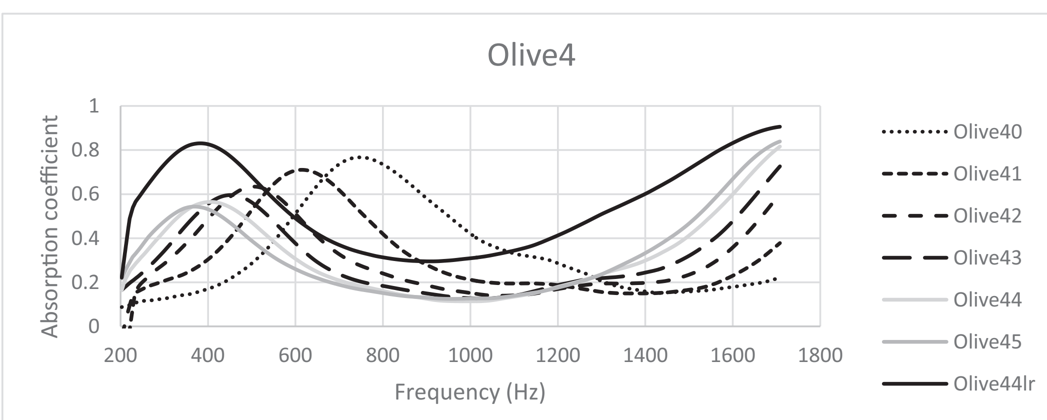

Fig. 18 Olive samples with thickness 4 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

similar tendency was observed when increasing the thickness of the air gap.

The porosity of the fruit stones and the air gap between the sample and the rigid wall influences the acoustic absorption, acting as a resonator at certain frequencies. The absorption is higher when the porosity increases since it depends on the surface roughness of the material, among other factors. Density also influences the absorption of the material, the less dense the material the higher the absorption.

With thickness one, the four stone fruits showed low acoustic absorption within the whole studied range of air gaps. For thickness two, the acoustic absorption of the four fruit stones showed the same tendency when the air gap decreased and obtained the higher values with maximums within the fre-

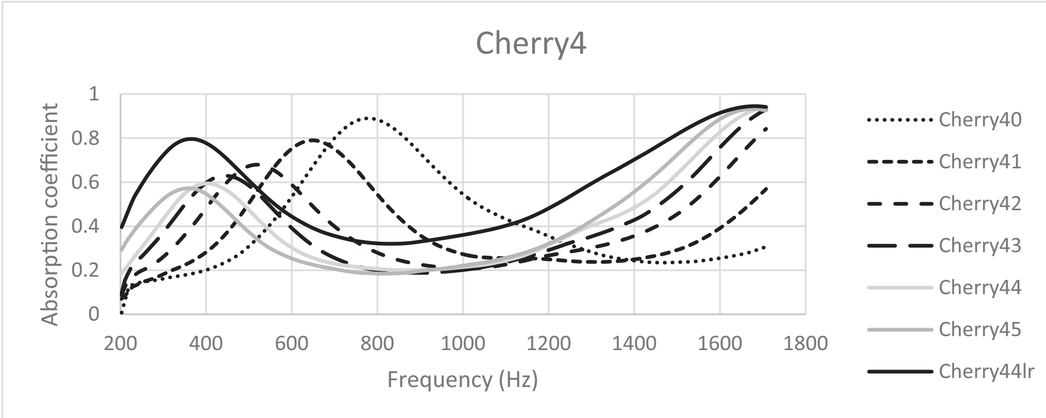

Fig. 19 Cherry samples, thickness 4 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

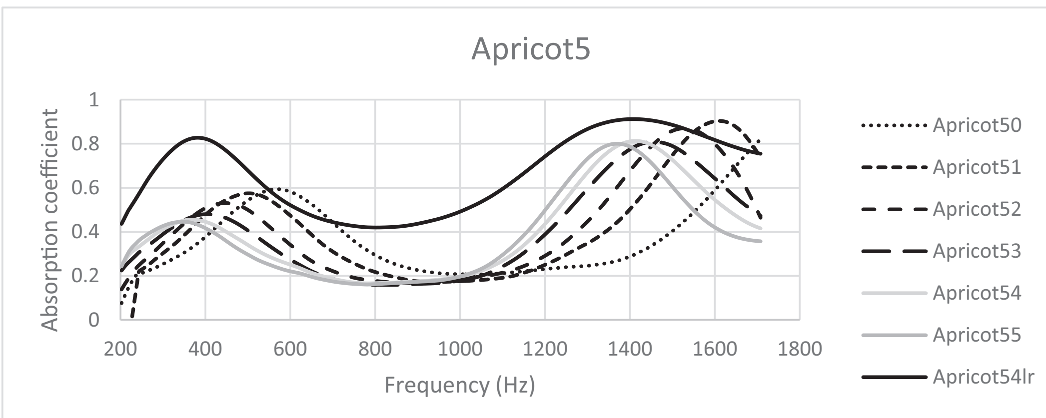

Fig. 20 Apricot samples, thickness 5 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

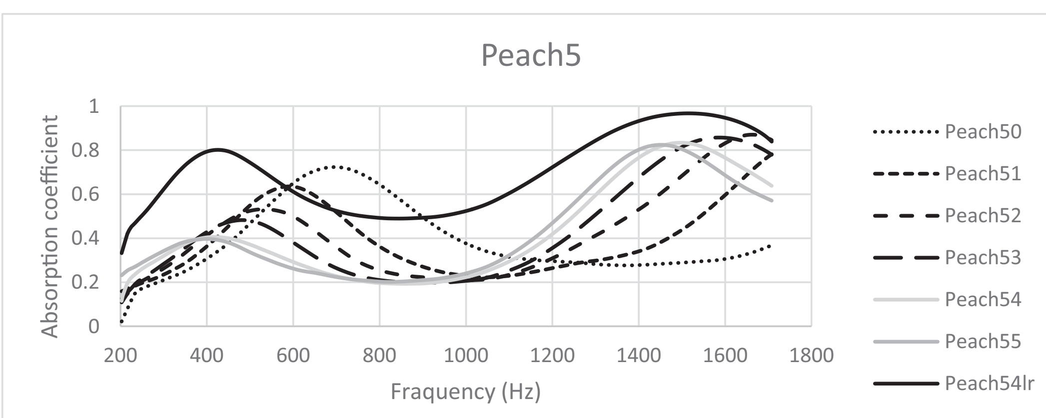

Fig. 21 Peach samples, thickness 5 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

quency range of 1200 to 1600 Hz. Regarding thickness three, the acoustic absorption of the four fruit stones showed significant differences. Their acoustic absorptions displayed the same tendency as thickness two, but with maximums within a lower frequency range of 800–1200 Hz. With thickness four, the stone fruits' acoustic absorption showed the same tendency as thickness three but with maximums towards the frequency range of 600–800 Hz. Finally, with thickness five, all the fruit stones displayed two acoustic absorption peaks within the studied frequency range: the second one within the range of 1200–1600 Hz had the highest acoustic absorption values.

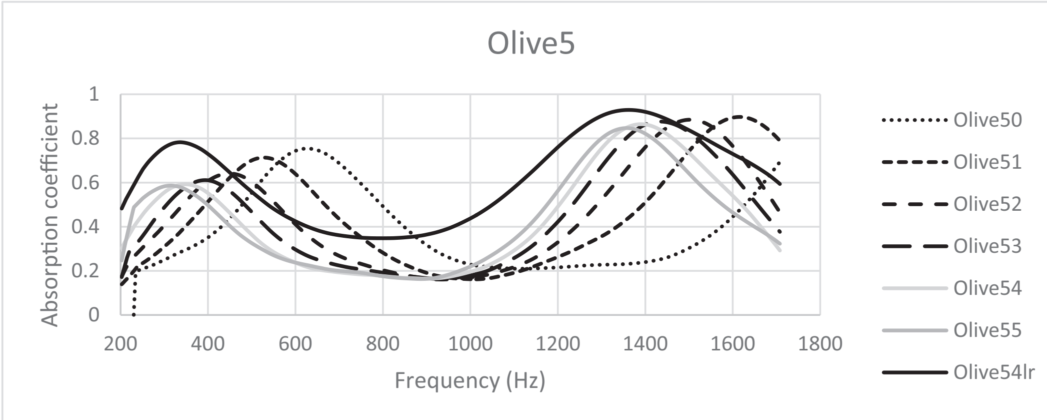

Fig. 22 Olive samples, thickness 5 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

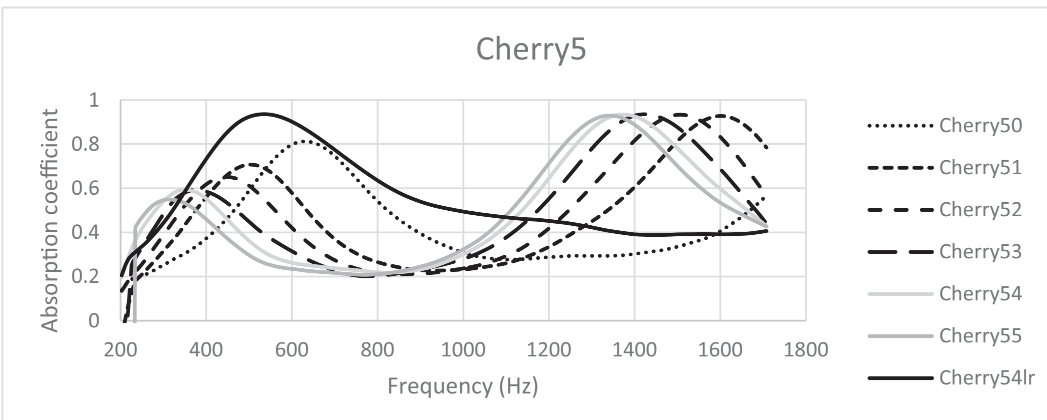

Fig. 23 Cherry samples, thickness 5 with 0, 1, 2, 3, 4 and 5 cm of air layer. And the sample with a 4 cm layer of rockwool.

The sound absorption results demonstrated that these materials‘ acoustic behaviour is like MHRs because higher sound absorption values appeared at specific points, which corresponded to resonant frequencies. This fact would allow an analytical model to be developed for each fruit stone panel by considering the thickness of both the sample and air gap.

The present research concludes that an air gap improves the sound absorption properties of these stone fruit panels and makes them more versatile to be used in the acoustics field by reducing the noise generated inside buildings, especially at some particular frequencies. These materials are convenient for specific acoustic applications, such as auditoriums, theatres, classrooms, among others, and offer the possibility of covering exposed surfaces with decorative effects given their organic appearance. This work extends previous research by offering the possibility of combining these materials with other traditionally used to manufacture multilayer panels for the acoustic conditioning of buildings.

Declaration of Competing Interest

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

References

[1] B. Berglund, P. Hassmén, R.F.S. Job, Sources and effects of low-frequency noise, J. Acoust. Soc. Am. 99 (5) (1996) 2985–3002, https://doi.org/10.1121/1.414863.
[2] G. Leventhall, A Review of Published Research on Low Frequency Noise and its Effects, 2003.
[3] G.H. Leventhall, Low frequency noise and annoyance, Noise Health (2004).
[4] W. Passchier-Vermeer, W.F. Passchier, Noise exposure and public health, Environ. Health Perspect. 108 (2000) 123, https://doi.org/10.2307/3454637.
[5] X. Qiu, Principles of Sound Absorbers, 2016. doi: 10.1007/978-981-10-1476-5_3.
[6] X. Cai, Q. Guo, G. Hu, J. Yang, Ultrathin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar Helmholtz resonators, Appl. Phys. Lett. 105 (12) (2014) 121901, https://doi.org/10.1063/1.4895617.
[7] S.H. Park, Acoustic properties of micro-perforated panel absorbers backed by Helmholtz resonators for the improvement of low-frequency sound absorption, J. Sound Vib. 332 (20) (2013) 4895–4911, https://doi.org/10.1016/j.jsv.2013.04.029.
[8] R. Tayong, On the holes interaction and heterogeneity distribution effects on the acoustic properties of air-cavity backed perforated plates, Appl. Acoust. 74 (12) (2013) 1492–1498, https://doi.org/10.1016/j.apacoust.2013.05.016.

[9] S.H. Park, A design method of micro-perforated panel absorber at high sound pressure environment in launcher fairings, J. Sound Vib. 332 (3) (2013) 521–535, https://doi.org/10.1016/j.jsv.2012.09.015.
[10] P.F. Soto, M. Herráez, A. González, J.A. de Saja, Acoustic impedance and absorption coefficient measurements of porous materials used in the automotive industry, Polym. Test. 13 (1) (1994) 77–88, https://doi.org/10.1016/0142-9418(94)90042-6.
[11] R. Zulkifli, M.J.M. Nor, M.F.M. Tahir, A.R. Ismail, M.Z. Nuawi, Acoustic properties of multi-layer coir fibres sound absorption panel, J. Appl. Sci. 8 (20) (2008) 3709–3714, https://doi.org/10.3923/jas.2008.3709.3714.
[12] R. Zulkifli, Zulkarnain, M.J.M. Nor, Noise control using coconut coir fiber sound absorber with porous layer backing and perforated panel, Am. J. Appl. Sci. (2010). doi: 10.3844/ajassp.2010.260.264.
[13] X.-L. Gai, T. Xing, X.-H. Li, B. Zhang, W.-J. Wang, Sound absorption of microperforated panel mounted with helmholtz resonators, Appl. Acoust. 114 (2016) 260–265, https://doi.org/10.1016/j.apacoust.2016.08.001.
[14] P.V. Bansod, T. Sai Teja, A.R. Mohanty, Improvement of the sound absorption performance of jute felt-based sound absorbers using micro-perforated panels, J. Low Freq. Noise Vib. Active Control 36 (4) (2017) 376–389, https://doi.org/10.1177/1461348417744307.
[15] K. Ghorbani, H. Hasani, M. Zarrebini, R. Saghafi, An investigation into sound transmission loss by polypropylene needle-punched nonwovens, Alex. Eng. J. 55 (2) (2016) 907–914.
[16] M. Yang, S. Chen, C. Fu, P. Sheng, Optimal sound-absorbing structures, Mater. Horiz. 4 (4) (2017) 673–680.
[17] Z. Liu, J. Zhan, M. Fard, J.L. Davy, Acoustic properties of multilayer sound absorbers with a 3D printed micro-perforated panel, Appl. Acoust. 121 (2017) 25–32, https://doi.org/10.1016/j.apacoust.2017.01.032.
[18] D.P. Jena, J. Dandsena, V.G. Jayakumari, Demonstration of effective acoustic properties of different configurations of Helmholtz resonators, Appl. Acoust. 155 (2019) 371–382, https://doi.org/10.1016/j.apacoust.2019.06.004.
[19] T. Dupont, P. Leclaire, R. Panneton, O. Umnova, A microstructure material design for low frequency sound absorption, Appl. Acoust. 136 (2018) 86–93, https://doi.org/10.1016/j.apacoust.2018.02.016.
[20] C. Cai, C.M. Mak, Noise attenuation capacity of a Helmholtz resonator, Adv. Eng. Software 116(November 2017) (2018) 60–66. doi: 10.1016/j.advengsoft.2017.12.003.
[21] C. Chen, Z. Du, G. Hu, J. Yang, A low-frequency sound absorbing material with subwavelength thickness, Appl. Phys. Lett. 110 (22) (2017) 221903, https://doi.org/10.1063/1.4984095.
[22] J. Mei, G. Ma, M. Yang, Z. Yang, W. Wen, P. Sheng, Dark acoustic metamaterials as super absorbers for low-frequency sound, Nat. Commun. 3 (1) (2012), https://doi.org/10.1038/ncomms1758.
[23] Y. Tang, S. Ren, H. Meng, F. Xin, L. Huang, T. Chen, C. Zhang, T.J. Lu, Hybrid acoustic metamaterial as super absorber for broadband low-frequency sound, Sci. Rep. 7 (1) (2017), https://doi.org/10.1038/srep43340.
[24] T.J. Lu, A. Hess, M.F. Ashby, Sound absorption in metallic foams, J. Appl. Phys. 85 (11) (1999) 7528–7539, https://doi.org/10.1063/1.370550.
[25] T.J. Lu, F. Chen, D. He, Sound absorption of cellular metals with semiopen cells, J. Acoust. Soc. Am. 108 (4) (2000) 1697–1709, https://doi.org/10.1121/1.1286812.
[26] F. Han, G. Seiffert, Y. Zhao, B. Gibbs, Acoustic absorption behaviour of an open-celled aluminium foam, J. Phys. D Appl. Phys. 36 (3) (2003) 294–302, https://doi.org/10.1088/0022-3727/36/3/312.
[27] J.P. Arenas, F. Asdrubali, in: Handbook of Ecomaterials, Springer International Publishing, Cham, 2019, pp. 3031–3056, https://doi.org/10.1007/978-3-319-68255-6_137.
[28] A. Putra, K.H. Or, M.Z. Selamat, M.J.M. Nor, M.H. Hassan, I. Prasetiyo, Sound absorption of extracted pineapple-leaf fibres, Appl. Acoust. 136 (2018) 9–15, https://doi.org/10.1016/j.apacoust.2018.01.029.
[29] J. Smardzewski, T. Kamisiński, D. Dziurka, R. Mirski, A. Majewski, A. Flach, A. Pilch, Sound absorption of wood-based materials, Holzforschung 69 (4) (2015) 431–439, https://doi.org/10.1515/hf-2014-0114.
[30] L. Ismail, M.I. Ghazali, S. Mahzan, A.M.A. Zaidi, Sound absorption of Arenga Pinnata natural fiber, World Acad. Sci. Eng. Technol. (2010).
[31] S. Ersoy, H. Küçük, Investigation of industrial tea-leaf-fibre waste material for its sound absorption properties, Appl. Acoust. 70 (1) (2009) 215–220, https://doi.org/10.1016/j.apacoust.2007.12.005.
[32] R. del Rey, A. Uris, J. Alba, P. Candelas, Characterization of sheep wool as a sustainable material for acoustic applications, Materials 10 (11) (2017) 1277, https://doi.org/10.3390/ma10111277.
[33] J.P. Arenas, R. del Rey, J. Alba, R. Oltra, Sound-absorption properties of materials made of esparto grass fibers, Sust. (Switzerland) 12(14) (2020). doi: 10.3390/su12145533.
[34] C. Othmani, M. Taktak, A. Zain, T. Hantati, N. Dauchez, T. Elnady, T. Fakhfakh, M. Haddar, Acoustic characterization of a porous absorber based on recycled sugarcane wastes, Appl. Acoust. 120 (2017) 90–97, https://doi.org/10.1016/j.apacoust.2017.01.010.
[35] Z.Y. Lim, A. Putra, M.J.M. Nor, M.Y. Yaakob, Sound absorption performance of natural kenaf fibres, Appl. Acoust. 130 (2018) 107–114, https://doi.org/10.1016/j.apacoust.2017.09.012.
[36] L.Z. Ying, A. Putra, M.J.M. Nor, N. Muhammad, Sound Absorption of Multilayer Natural Coir and Kenaf fibers, 23rd International Congress of Sound and Vibration, 2016.
[37] O. Kinnane, A. Reilly, J. Grimes, S. Pavia, R. Walker, Acoustic absorption of hemp-lime construction, Constr. Build. Mater. 122 (2016) 674–682, https://doi.org/10.1016/j.conbuildmat.2016.06.106.
[38] M. Jailani, M. Nor, N. Jamaludin, F.M. Tamiri, A preliminary study of sound absorption using multi-layer coconut coir fibers, Electron. J. Tech. Acoust. (2004).
[39] V. Gómez Escobar, R. Maderuelo-Sanz, Acoustical performance of samples prepared with cigarette butts, Appl. Acoust. 125 (2017) 166–172, https://doi.org/10.1016/j.apacoust.2017.05.001.
[40] M. Guo, Z.Y. Shang, H.W. Shi, Sound absorption measurements of various types of grain, Acta Acust. United Acust. (2005).
[41] H. Mamtaz, M. Hosseini Fouladi, M.Z. Nuawi, S. Narayana Namasivayam, M. Ghassem, M. Al-Atabi, Acoustic absorption of fibro-granular composite with cylindrical grains, Appl. Acoust. 126 (2017) 58–67, https://doi.org/10.1016/j.apacoust.2017.05.012.
[42] Z. Cai, X. Li, X. Gai, B. Zhang, T. Xing, An empirical model to predict sound absorption ability of woven fabrics, Appl. Acoust. 170 (2020) 107483, https://doi.org/10.1016/j.apacoust.2020.107483.
[43] R.D. Rey, J. Alba, J.P. Arenas, V.J. Sanchis, An empirical modelling of porous sound absorbing materials made of recycled foam, Appl. Acoust. 73 (6-7) (2012) 604–609, https://doi.org/10.1016/j.apacoust.2011.12.009.
[44] J. Segura-Alcaraz, J.E. Crespo-Amorós, E. Juliá-Sanchis, A. Nadal-Gisbert, J.M. Gadea-Borrell, Study of the acoustic absorption properties of panels made from ground tire

rubbers, Dyna (Spain) 89 (1) (2014), https://doi.org/10.6036/5796.

[45] D.J. Oldham, C.A. Egan, R.D. Cookson, Sustainable acoustic absorbers from the biomass, Appl. Acoust. 72 (6) (2011) 350–363, https://doi.org/10.1016/j.apacoust.2010.12.009.

[46] N. Holmes, A. Browne, C. Montague, Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement, Constr. Build. Mater. 73 (2014) 195–204, https://doi.org/10.1016/j.conbuildmat.2014.09.107.

[47] M. Casadesús, M.D. Álvarez, N. Garrido, G. Molins, J. Macanás, X. Colom, J. Cañavate, F. Carrillo, Environmental impact assessment of sound absorbing nonwovens based on chicken feathers waste, Resour. Conserv. Recycl. 149 (2019) 489–499, https://doi.org/10.1016/j.resconrec.2019.06.009.

[48] J.M. Gadea Borrell, E. Juliá Sanchis, J. Segura Alcaraz, I. Montava Belda, Sustainable sound absorbers from fruit stones waste, Appl. Acoust. 161 (2020) 107174, https://doi.org/10.1016/j.apacoust.2019.107174.

[49] R. Vijay, D.L. Singaravelu, Experimental investigation on the mechanical properties of Cyperus pangorei fibers and jute fiber-based natural fiber composites, Int. J. Polym. Anal. Charact. 21 (7) (2016) 617–627, https://doi.org/10.1080/1023666X.2016.1192354.

[50] H. Mamtaz, M.H. Fouladi, M. Al-Atabi, S. Narayana Namasivayam, Acoustic absorption of natural fiber composites, J. Eng. (United Kingdom) 2016 (2016) 1–11, https://doi.org/10.1155/2016/5836107.

[51] International Organization for Standardization, ISO 10534-2, Work, 2001.

[52] M. Long, Architectural Acoustics: Second Edition, 2014. doi:10.1016/C2009-0-64452-4.