



# STATE OF THE ART OF ACOUSTIC MATERIALS BASED ON ANIMAL WASTE

Marco A. Oliveira<sup>1</sup>, Julieta António<sup>2</sup>

<sup>1</sup>Itecons, Coimbra, Portugal  
{marco.oliveira@itecons.uc.pt}

<sup>2</sup>University of Coimbra, CERIS, Department of Civil Engineering, Coimbra, Portugal  
{julieta@itecons.uc.pt}

## Resumo

As preocupações ambientais têm sido a força motriz da investigação de materiais mais sustentáveis para aplicações acústicas. Alternativas aos materiais tradicionais, provenientes de recursos não renováveis, começam a surgir no mercado em linha com a agenda global de descarbonização e novas políticas de economia circular. Estas alternativas têm sido investigadas por vários autores para garantir propriedades equivalentes às dos materiais tradicionais. A maioria dos estudos centra-se na utilização de materiais reciclados e na utilização de resíduos ou de fibras de origem natural. Existem vários artigos de revisão de literatura em revistas científicas, focados neste tema, e que propiciam ao leitor uma perspetiva atual sobre as recentes investigações nesta área, particularmente no que diz respeito às fibras de origem vegetal e outros resíduos. No entanto, tanto quanto é do conhecimento dos autores, não há nenhum trabalho de revisão da literatura a abordar a aplicação de resíduos de origem animal para este fim, exceto uma publicação recente dos autores numa revista científica. O presente trabalho tem como objetivo apresentar um resumo desse artigo e comparar os resultados de simulações em software quanto ao desempenho de diferentes materiais acústicos de origem animal com materiais sintéticos.

**Palavras-chave:** resíduos de origem animal, material acústico alternativo, edifícios sustentáveis.

## Abstract

Environmental concerns have been the driving force for research into more sustainable materials for acoustic applications. Alternatives to traditional materials, originating from non-renewable and more energy-intensive resources, are beginning to appear on the market, in line with the global agenda for decarbonization and new circular economy policies. These alternatives have been investigated by several authors to guarantee properties equivalent to those of traditional materials. Most studies focus on the use of recycled materials, the use of waste or fibres of natural origin. There are several literature review papers that include these studies in scientific journals giving to the reader an informed and current perspective on research in this area, particularly regarding fibres of vegetal origin and other wastes. However, as far as the authors know, there was no literature review paper that addresses the application of waste of animal origin for this purpose, until a recent publication by the authors in a scientific journal. The present work aims to present a summary of that paper that fills this gap, and also presents software simulations to compare the performance of different acoustic materials of animal origin with that of synthetic materials.

**Keywords:** animal-based waste, alternative acoustic material, sustainable buildings.

PACS no. 43.55.Dt, 43.55.Ka

## 1 Introduction

Noise is classified as one of the three main pollutants of modern society, whose effects on health and well-being are well known and described in the literature [1,2,3]. It is therefore essential to assure acoustic comfort in the built environment. Synthetic sound-absorbing materials, such as mineral wool, are a common solution to control noise inside buildings. However, traditional materials often present environmental and energy concerns, as they derive from non-renewable resources (foams) or their manufacture involves energy-intensive processes (mineral wools). In addition, some of them are suitable for reuse at the end of their useful life due to some deterioration [4]. Ecological sound absorbers made from animal waste can replace synthetic ones and help reduce the carbon footprint of construction, a sector responsible for 40% of the world's energy and 1/3 of the planet's greenhouse gas emissions [5]. In addition, there is a growing public awareness of more sustainable solutions and products, which can be seen, for example, in some municipal tenders for services and works. A wide range of non-traditional sound absorbers, based on waste and natural fibres, have been explored by researchers in an attempt to replace synthetic acoustic materials with the same (or at least similar) performance. Most of the existing literature focuses on alternative acoustic materials made from plant waste and fibres, and a smaller number on animal waste. However, with the exception of a recent publication by the authors in a scientific journal [6], there is no review dedicated to animal waste for acoustic applications, so more clarification is needed on the subject. The aim of this article is to present a summary of this work [6] and to highlight the acoustic potential of the materials reviewed in comparison with synthetic absorbers, through acoustic simulations.

## 2 Systematic literature review

Natural fibres of plant and animal origin have played an important role in various applications since the dawn of civilization. Over the past few decades, natural materials have been revalued in order to cope with the reduction of non-renewable resources and reduce emissions of climate-changing gases. Figure 1 shows the temporal distribution of an in-depth search of electronic databases for high-quality, peer-reviewed articles on the use of plant and animal waste for acoustic applications, from 1970 to 2024.

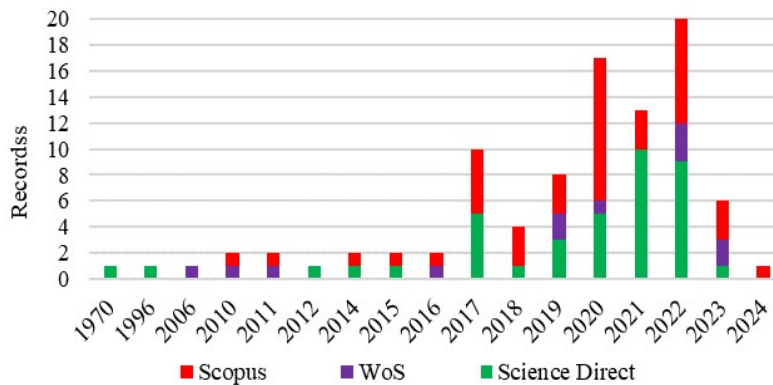


Figure 1 – Temporal distribution of the selected records from 1970 to 2024.

Wool is the material most intensively researched in acoustic applications, followed by chicken feathers (CFF) and leather scraps (rarer) found in articles which subject is animal waste recovery. Unlike plants, animal waste and fibres present a protein structure that gives it better elasticity and compressibility, characteristics that are useful, for example, in damping impact noise in flooring systems under concrete screeds [7]. In feathers, the presence of hollow structures (quills) greatly contribute to the thermoacoustic performance of biocomposites. In addition, the manufacturing method is a key factor in the final acoustic performance of these materials, as it strongly affects their thickness, bulk density and air permeability [8]. Despite the many favourable aspects of acoustic materials based on animal waste, it should be borne in mind that they have some vulnerabilities and disadvantages that need to be overcome before they can be used as a building material. For example, the great variability and heterogeneity of its physical properties, vulnerability to attack by pests and microorganisms, high sensitivity to humidity, moderate thermal stability and low resistance to fire can shorten the useful life of the material or even make it impractical. Table 1 shows some of the studies that have investigated the acoustic application of waste and fibres of animal origin. More information on articles and the acoustic properties of these materials can be found in [6].

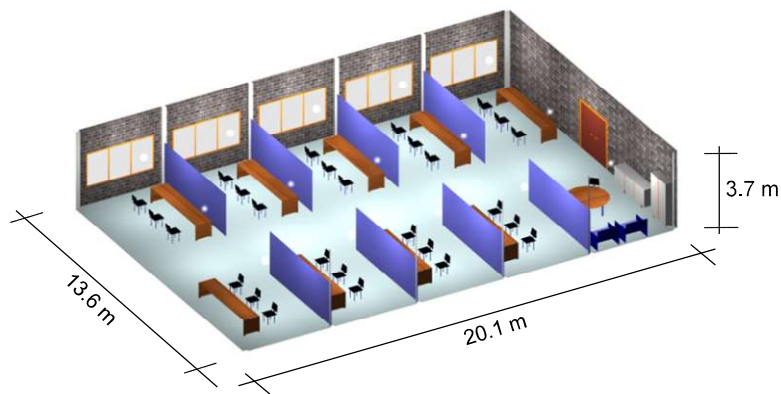
Table 1 – Applications of acoustic materials based on animal waste (adapted from [6]).

Animal waste/other components	Acoustic material	Ref.
Wool	nonwoven	[9]
Wool	wool boards	[10]
Low quality wool	hardboard panel	[11]
Sheep wool and hemp fibres	self-supporting panel	[12]
Wool + modified wool + concrete	concrete	[13]
CFF+cotton+polyethylene+polyester	nonwoven	[14]
Wool+plants+CFF	Nonwoven	[15]
Duck feather+EVA	Nonwoven	[16]
Wool+CFF	Nonwoven	[17]
Wool+CFF+polypropylene	Nonwoven	[18]
Feather flour+polypropylene	Nonwoven	[19]
CFF	Nonwoven	[20]
Goose feathers+cashmere+kapok+acrylic fibres	Nonwoven	[21]
CFF + Phase change material	PVC panel (filling the cavity)	[22]
CFF+jute	Nonwoven	[23]
CFF+epoxy	Nonwoven	[24]
CFF, wood chips, wood dust, Meldur H 97	Medium-density fibreboard	[25]
Finished leather scraps, PVA	Acoustic panel	[26]
Leather, semi-liquefied bamboo, polyurethane, silane	Composite plate	[27]
Natural leather collagen	Web foam	[28]
Leather scraps, silver coffee skin	Nonwoven	[29]
Human hair, epoxy, solid glass microspheres	Nonwoven	[30]
Wool, coconut fibres	Ceiling plasterboards (reinforce)	[31]
Camel wool, microperforated panel	Nonwoven	[32]
Leather scraps, coffee skin, polyacrylic, citric acid	Nonwoven	[33]

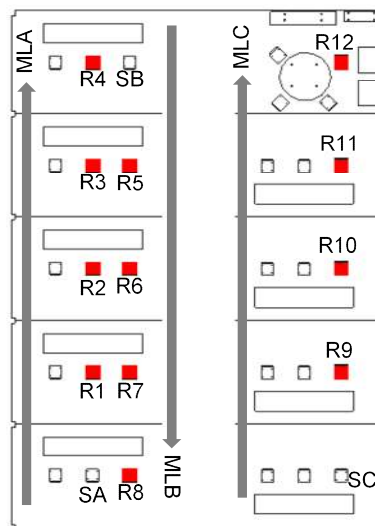
### 3 Software simulations

To compare the acoustic performance of synthetic and non-traditional sound absorbers, simulations of the sound field in a dummy-room were performed, using the software EASE® 4.4, to calculate the

descriptors of ISO 3382-3 [34]. VDI 2569 [35] was used as a benchmark for the analysis of the results. The room is an open plan office with dimensions 13.6 m x 20.1 m and 3.7 m (see Figure 2). Seven cases were computed, varying the sound absorption coefficients assigned to the ceiling while all other boundary conditions remained unchanged, as shown in Table 2. In Case 1 (initial condition), the room was calculated without sound absorption in the ceiling, with a highly sound-reflecting material (smooth concrete). In Case 2, the smooth concrete of the ceiling (273.20 m<sup>2</sup>) was replaced with a PU foam (50 mm and 28 kg/m<sup>3</sup>). In Case 3, glass wool tiles with plenum (25 mm and 100 kg/m<sup>3</sup>) were used in the ceiling [36]. Sheep wool [37] (75 mm and 12 kg/m<sup>3</sup>) was used in the ceiling for Case 4, while Cases 5, 6 and 7 correspond to the placement of Camel wool [32], CFF nonwoven [20], and leather scraps [33], respectively. The plan view of the room in Figure 2b) shows the omnidirectional sound sources SA, SB, SC and the listener seats R1 to R12. Three measurement lines, ML, (which direction is represented by an arrow) are selected following a straight path defined by the source and listeners: MLA (arrow SA-R1-R2-R3-R4), MLB (arrow SB-R5-R6-R7-R8), and MLC (arrow SC-R9-R10-R11-R12).



a)



b)

Figure 2 – Open plan office: a) perspective; b) plan view.

Table 2 – Surface areas and sound absorption coefficients of the materials used in the simulations.

Material	Area (m <sup>2</sup> )	Frequency (Hz)						
		125	250	500	1 k	2 k	4 k	
Floor – tile glazed	273.20	0.01	0.01	0.01	0.01	0.02	0.02	
Ceiling smooth concrete	273.20	0.01	0.01	0.02	0.02	0.02	0.05	
Walls – masonry	177.52	0.01	0.05	0.06	0.07	0.09	0.08	
Chairs - Upholstered	30 units	0.08	0.16	0.22	0.23	0.24	0.24	
Sofa – Upholstered	2 units	0.08	0.16	0.22	0.23	0.24	0.24	
Large door – wood	5.04	0.15	0.11	0.10	0.07	0.06	0.07	
Small doors - wood	5.52	0.15	0.11	0.10	0.07	0.06	0.07	
Rectangular table	33.84	0.12	0.12	0.13	0.13	0.11	0.11	
Circular table	2.70	0.12	0.12	0.13	0.13	0.11	0.11	
Resonant panel	142.49	0.60	0.42	0.35	0.12	0.08	0.08	
Windows – double glass	22.05	0.35	0.25	0.18	0.12	0.07	0.04	
Metal stud - steel	3.10	0.05	0.10	0.10	0.10	0.07	0.02	
Office cupboards - steel	7.24	0.05	0.10	0.10	0.10	0.07	0.02	
Ceiling	PU foam 50 mm	273.20	0.15	0.58	1.00	0.98	0.94	0.91
	Glass wool tile 25 mm [36]	273.20	0.17	0.53	0.84	0.99	0.99	0.97
	Wool 75 mm [37]	273.20	0.42	0.68	0.85	0.89	0.83	0.86
	Camel wool 50 mm [32]	273.20	0.10	0.36	0.79	0.99	0.99	0.89
	CFF nonwoven 50 mm [20]	273.20	0.13	0.41	0.84	0.88	0.83	0.80
	Leather scraps 50 mm [33]	273.20	0.05	0.15	0.49	0.83	0.98	0.95

Figure 3 and Table 3 show the results of the simulations for reverberation time and sound propagation. The shaded area in Figure 2 indicates the reverberation time limits associated with room acoustic class (RAC) A, B or C, as defined in VDI 2569 [35].

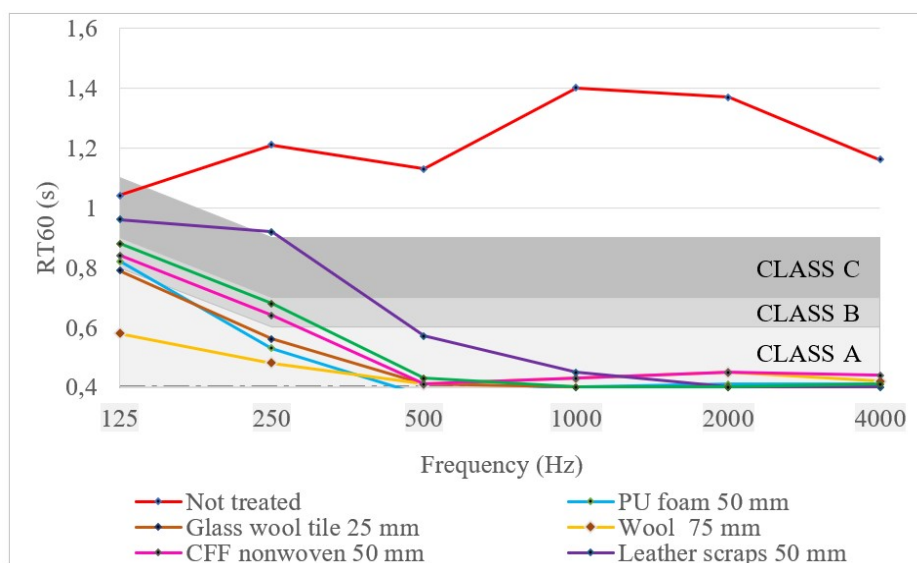


Figure 3 – reverberation time results.

Table 3 – Sound propagation results.

Ceiling Treatment	ML	$L_{p,Source,1m}$ dB(A)	$L_{p,A,S,4m}$ dB(A)	$L_{p,8m}$ dB(A)	$D_{2,s}$ dB(A)	ML Level
Not treated (Case 1)	A	62.5	55.0	51.0	4.0	---
	B	62.9	56.0	53.0	3.0	---
	C	62.8	55.0	51.0	4.0	---
PU foam 50 mm (Case 2)	A	59.2	48.0	39.0	9.0	L <sub>2</sub>
	B	60.9	46.0	42.0	4.0	L <sub>3</sub>
	C	59.7	45.0	41.0	4.0	L <sub>3</sub>
Glass wool tile 25 mm with plenum [36] (Case 3)	A	61.0	48.0	39.0	9.0	L <sub>2</sub>
	B	61.0	47.0	42.0	5.0	L <sub>3</sub>
	C	61.2	46.0	41.0	5.0	L <sub>3</sub>
Sheep wool 75 mm [37] (Case 4)	A	61.0	48.0	38.0	10.0	L <sub>2</sub>
	B	60.9	46.0	40.0	6.0	L <sub>2</sub>
	C	61.2	46.0	41.0	5.0	L <sub>3</sub>
Camel wool 50 mm [32] (Case 5)	A	61.2	49.0	41.0	8.0	L <sub>2</sub>
	B	61.2	49.0	44.0	5.0	L <sub>3</sub>
	C	61.4	48.0	43.0	5.0	L <sub>3</sub>
CFF nonwoven 50 mm [20] (Case 6)	A	61.1	49.0	41.0	8.0	L <sub>2</sub>
	B	61.2	48.0	43.0	5.0	L <sub>3</sub>
	C	61.3	47.0	42.0	5.0	L <sub>3</sub>
Leather scraps 50 mm [33] (Case 7)	A	61.5	51.0	45.0	6.0	L <sub>3</sub>
	B	61.6	51.0	47.0	4.0	L <sub>3</sub>
	C	61.7	50.0	46.0	4.0	L <sub>3</sub>

The Level in the last column of Table 3 refers to the propagation of sound along a measurement line (ML), and is classified into three categories L<sub>1</sub>, L<sub>2</sub> and L<sub>3</sub> [35]. Level L<sub>1</sub> is for  $D_{2,s} \geq 8$  dB(A) and  $L_{p,A,S,4m} \leq 47$  dB(A), Level L<sub>2</sub> is for  $D_{2,s} \geq 6$  dB(A) and  $L_{p,A,S,4m} \leq 49$  dB(A), and Level L<sub>3</sub> is for  $D_{2,s} \geq 4$  dB(A) and  $L_{p,A,S,4m} \leq 51$  dB(A).  $D_{2,s}$  is the rate of spatial decay of A-weighted sound pressure level of speech when doubling the distance between the receiver and the source, while  $L_{p,A,S,4m}$  is the sound pressure level in dB(A) of a receiver positioned 4 m from the source. According to VDI 2569 [35], an open plan office is grouped in a particular RAC if it fulfils the conditions displayed in Table 4.

Table 4 – Classification of open plan offices [35].

RAC	Classification of ML in levels	Reverberation time (s)		$L_{NA,Bau}$ dB(A)
		125 Hz	250 Hz to 4 KHz	
A	2/3 of ML in L <sub>1</sub> and rest in L <sub>2</sub>	≤ 0.8	≤ 0.6	≤ 35
B	2/3 of ML in L <sub>2</sub> and rest in L <sub>3</sub>	≤ 0.9	≤ 0.7	≤ 40
C	1/3 of ML in L <sub>2</sub> and rest in L <sub>3</sub>	≤ 1.1	≤ 0.9	≤ 40

Table 5 shows the room classifications obtained when different materials are assigned to the ceiling.

Table 5 – Simulated RAC of the open-plan office.

Open plan office treatment	ML level	RT60 (s)		$L_{NA,Bau}$ dB(A)	RAC
		125 Hz	4 KHz		
Not treated (case 1)	---	1.04	1.21 - 1.16	40.0	---
PU foam 50 mm (case 2)	1/3 L <sub>2</sub> , 2/3 L <sub>3</sub>	0.82	0.53 - 0.41	40.0	C
Glass wool tile 25 mm [36] (case 3)	1/3 L <sub>2</sub> , 2/3 L <sub>3</sub>	0.79	0.56 - 0.40	40.0	C
Sheep wool 75 mm [37] (case 4)	2/3 L <sub>2</sub> , 1/3 L <sub>3</sub>	0.58	0.48 - 0.42	40.0	B
Camel wool 50 mm [32] (case 5)	1/3 L <sub>2</sub> , 2/3 L <sub>3</sub>	0.88	0.68 - 0.41	40.0	C
CFF nonwoven 50 mm [20] (case 6)	1/3 L <sub>2</sub> , 2/3 L <sub>3</sub>	0.84	0.64 - 0.44	40.0	C
Leather scraps 50 mm [33] (case 7)	all in L <sub>3</sub>	0.96	0.92 - 0.40	40.0	---

## 4 Discussion

The literature review reveals a growing interest in animal-based waste for building acoustic use, with the predominance of publications on sound-absorbing applications to the detriment of airborne or impact sound insulation. In this context, wool waste is the main raw material for this purpose. The results of the acoustic simulations with synthetic absorbers and with animal waste sound absorbers are very close. The room with synthetic sound absorbers in the ceiling met VDI 2569:2019 [35] in acoustic class C, while sheep wool, camel wool and CFF nonwoven met acoustic classes B, C and C, respectively. The room with leather scraps (Case 7) did not meet the standard recommendations for any class [35], possibly due to the lack of sound absorption of the material between 125 Hz and 500 Hz. In general, synthetic materials were slightly more effective at reducing noise than non-traditional sound absorbers, with an average difference of around 2 dB(A). When the listener's distance from the sound source is doubled, the average value of the  $D_{2,s}$  descriptor for the untreated room is 4 dB(A), and 6 dB(A) for the room with the synthetic and non-traditional absorbers. Figure 3 confirms that synthetic and most animal-based waste sound absorbers analysed, due to their fibrous and porous nature, have similar acoustic behaviour, i.e. good sound absorption at medium and high frequencies and poor performance at low frequencies. When PU foam (Case 2), glass wool tiles (Case 3), camel wool (Case 5) and non-woven CFF (Case 6) are used in the room, there is a closeness between the RT60 values below 500 Hz. The greatest differences are found when using sheep wool (Case 4) or leather scraps (Case 7). In this range, the RT60 of the room with PU foam is slightly lower than with CFF non-woven and camel wool, probably due to the porous internal microstructure of the foam, which leads to greater resistance to airflow and therefore greater dissipation of sound energy. In addition, it is possible to obtain higher RAC indices with the use of sound absorbers based on animal fibres and waste, as in the case of sheep wool, where the room obtained the best RAC index (B) (see Table 5).

## 5 Conclusions

From an acoustic point of view, sound absorbers made from animal fibres and waste show equivalent performance to synthetic sound absorbers. However, for its scalability and widespread adoption in buildings, some technical barriers need to be overcome, such as its low durability and resistance to fire. Most of the materials found in literature are still at the prototype stage and need further development to meet certification requirements before they can be applied to buildings. The price of non-recycled acoustic materials tends to be lower than that of recycled materials of animal and synthetic origin. The fibrillar nature of most animal waste materials gives them good performance at

medium and high frequencies and poor performance at low frequencies. Future research could focus on this aspect, and broaden their scope of use, such as in acoustic panels and acoustic barriers. Other topics that deserve further research are new biopolymer matrices in composites, the combination of different types of animal fibres, and the mixture of animal fibres with vegetable and synthetic fibres.

## Acknowledgment

Acknowledgment: The authors would like to thank the HEAD-Genuit-Stiftung Foundation (Project n°: P-22/03-W) and the support of Itecons in Coimbra; they are also grateful for the Foundation for Science and Technology's support through funding UIDB/04625/2020 from the research unit CERIS (DOI: 10.54499/UIDB/04625/2020) and to Itecons in Coimbra.

## References

- [1] Montes González, D., Barrigón Morillas, J. M., & Rey-Gozaló, G. (2023). Effects of noise on pedestrians in urban environments where road traffic is the main source of sound. *Science of The Total Environment*, 857, 159406. <https://doi.org/10.1016/j.scitotenv.2022.159406>.
- [2] Ma, S., Chen, M., Liu, L., Dai, C., & Chen, Y. (2022). Preparation of Hu sheep wool/polyacrylonitrile oxidized fiber flame retardant and sound absorption material. *Journal of Industrial Textiles*, 52, 15280837221115068. <https://doi.org/10.1177/15280837221115067>.
- [3] Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. In *The Lancet*. [https://doi.org/10.1016/S0140-6736\(13\)61613-X](https://doi.org/10.1016/S0140-6736(13)61613-X).
- [4] Arruda, E. H., Melatto, R. A. P. B., Levy, W., & Conti, D. de M. (2021). Circular economy: A brief literature review (2015–2020). *Sustainable Operations and Computers*, 2, 79–86. <https://doi.org/10.1016/j.susoc.2021.05.001>.
- [5] United Nation Environment Programme, Environment for development. <https://www.unep.org/resources/factsheet/united-nations-environment-programme-unep-energy-finance>. [Online]. [Accessed: June 04, 2024].
- [6] Oliveira, M. A., & António, J. (2024). Animal-based waste for building acoustic applications: A review. *Journal of Building Engineering*, 84, 108430. <https://doi.org/10.1016/j.jobbe.2023.108430>
- [7] Ballagh, K. O. 1996. Acoustical properties of wool. *Applied Acoustics* 48 (2):101–20. Doi:10.1016/0003-682X(95)00042-8.
- [8] Broda, J., & Bączek, M. (2020). Acoustic Properties of Multi-Layer Wool Nonwoven Structures. *Journal of Natural Fibres*, 17(11), 1567–1581. <https://doi.org/10.1080/15440478.2019.1584078>.
- [9] Rubino, C., Bonet Aracil, M., Liuzzi, S., Stefanizzi, P., & Martellotta, F. (2021). Wool waste used as sustainable nonwoven for building applications. *Journal of Cleaner Production*, 278, 123905. <https://doi.org/10.1016/j.jclepro.2020.123905>
- [10] Qiu, H., & Enhui, Y. (2017). Effect of Thickness, Density and Cavity Depth on the Sound Absorption Properties of Wool Boards. *Autex Research Journal*, 18. <https://doi.org/10.1515/aut-2017-0020>.

- [11] Bosia, D., Savio, L., Thiebat, F., Patrucco, A., Fantucci, S., Piccablotto, G., & Marino, D. (2015). Sheep Wool for Sustainable Architecture. *Energy Procedia*, 78, 315–320. <https://doi.org/10.1016/j.egypro.2015.11.650>.
- [12] Pennacchio, R., Savio, L., Bosia, D., Thiebat, F., Piccablotto, G., Patrucco, A., & Fantucci, S. (2017). Fitness: Sheep-wool and Hemp Sustainable Insulation Panels. *Energy Procedia*, 111, 287–297. <https://doi.org/10.1016/j.egypro.2017.03.030>.
- [13] Alyousef, R. (2022). Enhanced acoustic properties of concrete composites comprising modified waste sheep wool fibres. *Journal of Building Engineering*, 56, 104815. <https://doi.org/https://doi.org/10.1016/j.jobe.2022.104815>
- [14] Dieckmann, E., Dance, S., Sheldrick, L., & Cheeseman, C. (2018). Novel sound absorption materials produced from air laid non-woven feather fibres. *Heliyon*, 4(9), e00818. <https://doi.org/https://doi.org/10.1016/j.heliyon.2018.e00818>.
- [15] Bousshine, S., Ouakarrouch, M., Bybi, A., Laaroussi, N., Garoum, M., & Tilioua, A. (2022). Acoustical and thermal characterization of sustainable materials derived from vegetable, agricultural, and animal fibres. *Applied Acoustics*, 187. <https://doi.org/10.1016/j.apacoust.2021.108520>.
- [16] Lv, L., Bi, J., Yu, X., Wang, X., Wei, C., & Cui, Y. (2016). Sound absorption properties of composites made of discarded duck feathers. *Tekstil ve Konfeksiyon*, 26, 153–158.
- [17] Casadesús, M., Álvarez, M. D., Garrido, N., Molins, G., Macanás, J., Colom, X., Cañavate, J., & Carrillo, F. (2019). Environmental impact assessment of sound absorbing nonwovens based on chicken feathers waste. *Resources, Conservation and Recycling*, 149, 489–499. <https://doi.org/https://doi.org/10.1016/j.resconrec.2019.06.009>.
- [18] Ilangovan, M., Navada, A. P., Guna, V., Touchaleaume, F., Saulnier, B., Grohens, Y., & Reddy, N. (2022). Hybrid biocomposites with high thermal and noise insulation from discarded wool, poultry feathers, and their blends. *Construction and Building Materials*, 345, 128324. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.128324>.
- [19] Constantin, M., Constantin, L. A., Aradoaei, S., Aradoaei, M., Bratu, M., & Vasile, O. (2022). Acoustic Properties of a New Composite Material Obtained from Feather Flour and Recycled Polypropylene. *Materiale Plastice*, 58, 84–93. <https://doi.org/10.37358/MP.21.4.5534>.
- [20] Kusno, A., Mulyadi, R., Sakagami, K., Okuzono, T., Toyoda, M., Otsuru, T., & Kamil, K. (2019). A pilot study on the sound absorption characteristics of chicken feathers as an alternative sustainable acoustical material. *Sustainability (Switzerland)*, 11(5). <https://doi.org/10.3390/su11051476>.
- [21] Yang, S., Yu, W., & Pan, N. (2010). Investigation of the sound-absorbing behavior of fiber assemblies. *Textile Research Journal*, 81(7), 673–682. <https://doi.org/10.1177/0040517510385177>.
- [22] Abdulmunem, A. R., Samin, P. M., Sopian, K., Hoseinzadeh, S., Al-Jaber, H. A., & Garcia, D. A. (2022). Waste chicken feathers integrated with phase change materials as new inner insulation envelope for buildings. *Journal of Energy Storage*, 56, 106130. <https://doi.org/https://doi.org/10.1016/j.est.2022>.
- [23] Saravanan, K., & C, P. (2019). Study of Acoustic Properties of Chicken Feather Fibre (CFF) and Its Hybrid Composites. *Journal of Natural Fibres*, 18, 1–8. <https://doi.org/10.1080/15440478.2019.1629560>.
- [24] Bessa, J., Souza, J., Lopes, J. B., Sampaio, J., Mota, C., Cunha, F., & Figueiro, R. (2017). Characterization of thermal and acoustic insulation of chicken feather reinforced composites. *Procedia Engineering*, 200, 472–479. <https://doi.org/https://doi.org/10.1016/j.proeng.2017.07.066>.

- [25] Safaric, R., Fras Zemljič, L., Novak, M., Dugonik, B., Bratina, B., Gubelj, N., Bolka, S., & Strnad, S. (2020). Preparation and Characterisation of Waste Poultry Feathers Composite Fibreboards. In *Materials* (Vol. 13, Issue 21). <https://doi.org/10.3390/ma13214964>
- [26] Barbanera, M., Belloni, E., Buratti, C., Calabrò, G., Marconi, M., Merli, F., & Armentano, I. (2020). Recycled leather cutting waste-based boards: thermal, acoustic, hygrothermal and ignitability properties. *Journal of Material Cycles and Waste Management*, 22. <https://doi.org/10.1007/s10163-020-01024-3>.
- [27] Pu, H., Shu, C., Dai, R., Chen, H., & Shan, Z. (2022). Mechanical, thermal and acoustical characteristics of composite board kneaded by leather fiber and semi-liquefied bamboo. *Construction and Building Materials*, 340, 127702. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.127702>.
- [28] Rämmal, H., & Lavrentjev, J. (2020). Acoustic study of novel eco-friendly material for vehicle NVH applications. *Materials Today: Proceedings*, 28, 2331–2337. <https://doi.org/https://doi.org/10.1016/j.matpr.2020.04.632>.
- [29] Abdi, D. D., Monazzam, M., Taban, E., Putra, A., Golbabaie, F., & Khadem, M. (2021). Sound absorption performance of natural fiber composite from chrome shave and coffee silver skin. *Applied Acoustics*, 182, 108264. <https://doi.org/https://doi.org/10.1016/j.apacoust.2021.108264>.
- [30] Nanda, B. P., & Satapathy, A. (2020). Thermal, acoustic, and dielectric behavior of epoxy-based hybrid composites using short hair fiber. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 42(6), 306. <https://doi.org/10.1007/s40430-020-02398-z>.
- [31] Guna, V., Yadav, C., Maithri, B. R., Ilangovan, M., Touchaleaume, F., Saulnier, B., Grohens, Y., & Reddy, N. (2021). Wool and coir fiber reinforced gypsum ceiling tiles with enhanced stability and acoustic and thermal resistance. *Journal of Building Engineering*, 41, 102433. <https://doi.org/https://doi.org/10.1016/j.jobbe.2021.102433>.
- [32] Beheshti, M. H., Khavanin, A., Safari Varyani, A., Yahya, M. N. Bin, Alami, A., Khajenasiri, F., & Talebitooti, R. (2022). Improving the Sound Absorption of Natural Waste Material-based Sound Absorbers Using Micro-perforated Plates. *Journal of Natural Fibres*, 19(13), 5199–5210. <https://doi.org/10.1080/15440478.2021.1875364>.
- [33] Abdi, D. D., Monazzam, M., Taban, E., Putra, A., Golbabaie, F., & Khadem, M. (2021). Sound absorption performance of natural fiber composite from chrome shave and coffee silver skin. *Applied Acoustics*, 182, 108264. <https://doi.org/https://doi.org/10.1016/j.apacoust.2021.108264>.
- [34] ISO 3382-3:2022, Acoustics - Measurement of room acoustic parameters – Part 3: Open plan offices, International Organization for Standardization. Geneva, Switzerland; 2022.
- [35] VDI 2569:2019, Sound protection and acoustical design in offices, The Association of German Engineers. Düsseldorf, Germany, 2022.
- [36] Hout, G.V., & Reeve, W. (2017). Effect of plenum absorption on ceiling attenuation. *New Zealand Acoustics*, 30, 10-21.
- [37] Ballagh, K. O. 1996. Acoustical properties of wool. *Applied Acoustics* 48 (2):101–20. Doi:10.1016/0003-682X(95)00042-8.