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Animal-based waste for building acoustic applications: A review

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ABSTRACT

Acoustic comfort is essential to human health and well-being in both natural and built environments. In the workplace, for example, ensuring a better sound environment is of paramount importance because noise impacts communication, task completion, and productivity. Traditional porous and fibrous sound-absorbing materials have long been widely used as a possible passive acoustic technique to address noise control in buildings. More recently, however, acoustic product manufacturers are beginning to set their sights on eco-friendly sound absorbers to replace some of the conventional materials, since most of the latter are petroleum-based or require large amounts of energy to manufacture, which is at odds with the global agenda for decarbonisation and the new circular economy directives. Moreover, the end consumer feels that certain established sound absorbers are not affordable. In this scenario, the emergence of alternative, carbon-neutral, and cheaper materials is a trend with growing resonance in the acoustic insulation market. Natural materials and composites have therefore been investigated worldwide by a number of authors as a valid option for noise reduction in buildings. However, to the best of our knowledge, no literature review has specifically focused on animal-based waste for this purpose, and a paper is needed to fill this gap. In addition, this work presents software simulations to compare the performance of different acoustic materials of animal origin with that of synthetic materials.

1. Introduction

Noise is classified as one of the three main pollutants in modern society [1,2]. As an acoustic and psychoacoustic phenomenon at the level of the highly sophisticated biological structures of the auditory system and cerebral cortex, noise above regulatory limits can damage human health and the quality of life [3]. Therefore, it is crucial to ensure acoustic comfort in the built environment, where people spend most of their time. Traditional porous and fibrous sound absorbing materials have been widely used as one of the possible and preferred passive acoustic techniques to tackle the problem of noise in buildings. However, most of these materials are harmful to the environment at both the production and disposal stages, since they are derived from petroleum (foams), consume a lot of energy during manufacture (mineral wool), and present problems for reuse and recycling at the end of their useful life [4]. The construction industry is a gigantic consumer of natural resources and raw materials. According to the United Nations Environment Programme, this sector drains about 40 % of the world's energy, 25 % of its water, 40 % of global resources, and is responsible for 1/3 of the planet's greenhouse gas emissions [5]. However, as part of the same complexity, the worldwide sound absorption materials market is promising and expected to reach €23.6 billion by 2025 in emerging countries such as Brazil, China, India, and Mexico, driven by population

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growth and industrialisation [2]. Therefore, green building materials can play an important role in reducing the carbon footprint in the construction sector, since (usually) less energy is involved in their production [6–8]. For example, processing 1 m^3 of glass wool releases about 130 kg more CO_2 into the atmosphere than is released to produce a wool sound absorber [9–11]. Furthermore, local recommendations, building regulations, and increased public awareness of environmental protection and biodiversity have also encouraged this paradigm shift towards ecologically safer products [12]. A wide range of sound absorbers based on discarded and recycled materials have been subjected to research in a major effort to replace non-sustainable materials. Some of this work has led to products being launched on the market. However, despite the significant number of papers on the subject, to the best of the authors' knowledge, the literature lacks a review specifically focused on animal-based waste for building acoustic applications, so work is needed to shed more light on it. The motivation for this work stemmed from the need to fill this gap and it has the following objectives: i) to conduct a state of the art review on animal-based waste materials and composites with potential to reduce noise in buildings, and ii) to compare the acoustic performance of such materials with that of synthetic materials, using room acoustic simulations. The paper has six sections: Section 2 describes the review method; Section 3 presents the results of the systematic literature review; Section 4 shows the acoustic simulations; Section 5 is a discussion of the results; and Section 6 concludes the paper and proposes suggestions for future developments.

2. Methodology

To achieve the first objective, an exhaustive search of the electronic databases of Web of Science, Scopus, and Science Direct was carried out, looking for as many high-quality, peer-reviewed research articles as possible. The resulting data consists of eligible documents in the form of "reviews", "articles", "conference papers" and "books/book chapters", all written in English. The search engines used were Google Scholar, Google Books, Microsoft Academic, PubMed, Refseek, and Semantic Scholar, focusing on the terms "fibre", "absorption", "animal", "waste", "sound", "acoustics", "noise", "absorption coefficient", "natural" and "insulation". The following Boolean operators were considered in the search:

- AND: to inform the database that ALL search terms must be present in the resulting records;
- OR: to inform the database that ANY of the search terms can be present in the resulting records;
- NOT: to inform the database to ignore concepts that may be implicit in the search terms.

Documents were included in the review if they met the following eligibility criteria:

a. Publication in a scientific or peer-reviewed journal in English;
b. Sample preparation described in detail and sound absorption coefficient curves clear and identifiable;
c. Sound absorption coefficients measured under laboratory test conditions, and in one octave or 1/3 octave frequency band;
d. Published between January 1970 and January 2024.

Documents published before the period of 1970–2024 were exclude from the review.

For the second objective, software calculations were used to evaluate a hypothetical open plan office with respect to acoustic quality improvement, considering the room without acoustic treatment, the room with synthetic sound absorbers (PU foam and glass wool), and the room with different categories of animal waste sound absorbers. To assess the effectiveness of the sound absorbers in each situation and compare the results, VDI 2569:2019 [13] was used as a reference. The standard [13] deals with the acoustic protection and acoustic design of offices and defines three classes of room acoustics A, B and C, depending on the value of certain parameters of ISO 3382–3 [14], specifically the reverberation time (RT60) in seconds, the sound pressure level of in situ noise $L_{NA,Bau}$ in dB(A), the A-weighted sound pressure level of speech at 4 m from the sound source $L_{p,A,S,4m}$ and the spatial decay rate of the A-weighted sound pressure level of speech $D_{2,S}$ in dB(A), when doubling the distance between the receiver and the source.

3. Systematic literature review

The literature review resulted in the selection of 94 full-text records. Fig. 1 shows distribution patterns of the selected records after they had been filtered and duplicates removed.

Fig. 2 illustrates the temporal distribution of the selected records from 1970 to 2024.

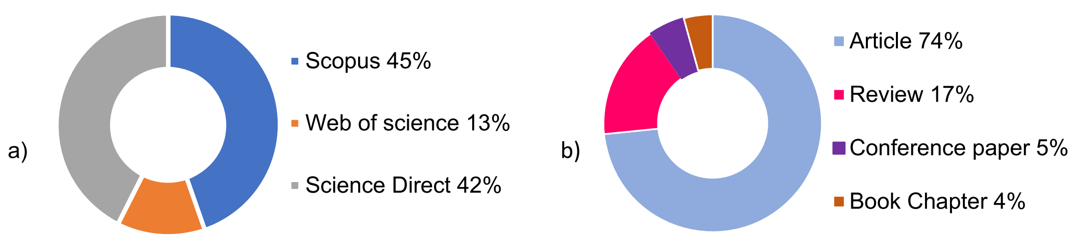

Fig. 1. Distribution patterns of the selected records of the review: a. by electronic databases; b. by record typology.

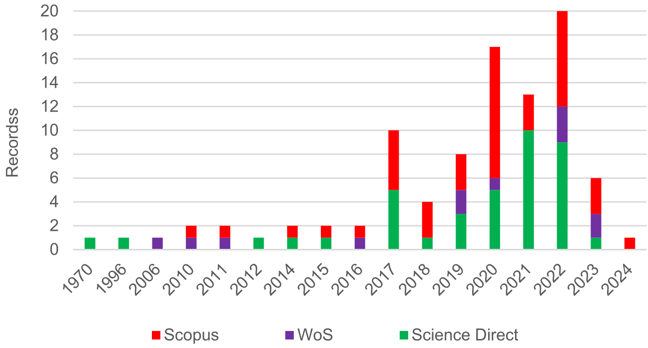

Fig. 2. Temporal distribution of the selected records from 1970 to 2024.

3.1. Natural fibres as sustainable building materials

Since the dawn of civilization, natural materials have played an important role in society in the manufacture of utensils, hunting tools, ropes, carpets, and fabrics [15]. With the advance of scientific knowledge and the mastery of new construction techniques, natural materials are being revalued to cope with the scarcity of non-renewable raw materials and reduce greenhouse gas emissions. In building acoustics, high-quality, bio-sourced materials are becoming increasingly common [16–28]. The choice to use environmentally friendly acoustic materials is supported by benefits such as their biodegradability in marine and terrestrial environments, thereby preventing microfibre pollution [34]. However, it is easy to see that synthetic materials are still predominant in our buildings and that there is still a long way to go to completely decarbonize the construction sector. Fig. 3 shows a classification of natural materials of animal and vegetal origin for acoustic applications in buildings (mineral sources have not been considered in this work).

Looking at Fig. 3 and analysing the subjects in the technical literature, it can be inferred that most of the research into alternative acoustic construction solutions is based on fibrous and non-fibrous plant materials, to the detriment of those of animal origin. One explanation for this may be the huge variety and easy availability of fibrous and non-fibrous raw materials of plant origin, compared to those of animal origin [31,32]. In addition, the reuse and revalorisation of certain animal waste, such as chicken feather fibres (CFF) for building applications, is at an early stage and is still little explored [70]. The two types of animal waste most used in the manufacture of acoustic absorption and sound insulation materials are wool and chicken feathers. However, there has been much less research on leather waste from the tanning industry for this purpose, for example. Regarding plants, there is a good amount of research on fibres, for example, from hemp [20], palm fibres [106], kenaf [43], sugarcane bagasse [17,19] and rice husk [23] composites.

Animal and plant fibres are natural materials with markedly different physical, chemical, and morphological characteristics, which determine many of their physical and mechanical properties in relation to their general behaviour in buildings.

Unlike plants, fibrous and non-fibrous animal materials have a protein structure, essentially composed of keratin but also including fibroin, collagen chitosan and lipids [33]. Plant fibres have cellulose, hemicellulose, pectin, lignin, wax, and moisture, joined by hydrogen bonds that give them rigidity and strength [15]. The keratin found in feather fibres has an environmental durability, like that of nylon, and its absorbent nature allows it to be used to prevent corrosion by microbial agents [70,72]. The protein structure of animal

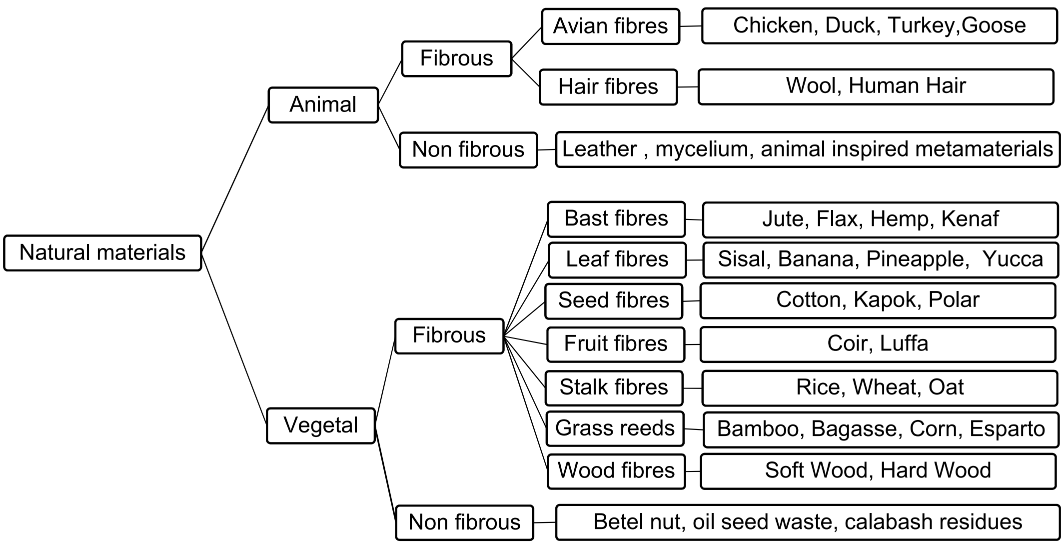

Fig. 3. Natural materials for acoustic applications in buildings [30,79].

fibres gives them better elasticity and compressibility than vegetable fibres, characteristics that are used, for example, to dampen impact noise in wool-based floating floor systems [54].

An important morphological difference between CFF, wool and vegetable fibres is the presence of quills on the feathers. Quills are hollow structures that greatly contribute to the thermoacoustic performance of CFF-based composites, as they trap air inside [35]. Interestingly, in hybridization, where feathers and other types of fibres (natural or not) are combined, the porous structure of the quills is maintained [70].

A key factor affecting the acoustic performance of porous and fibrous composite sound absorbers is the diameter of the fibre reinforcement content [79]. Unlike synthetic fibres, which are obtained under more controlled manufacturing conditions, and therefore have less diametrical variation, animal and plant fibres have a significant heterogeneous distribution in diameter, depending on anthropological factors related, for example, to plant cultivation and animal husbandry methods, the geography and climate of the region, and socio-economic determinants. It is therefore not surprising that animal fibres extracted from the same animal or from two animals of the same breed show variations in diameter or other physical and morphological attributes. For the same density of material and the same manufacturing parameters, albeit with different thicknesses, a composite whose reinforcement has smaller diameter fibres will tend to have a higher sound absorption performance than one whose fibres have a larger diameter. This is because smaller diameter fibres, whether of animal, plant, or synthetic origin, will form compounds with a greater number of pores, greater tortuosity and greater resistance to air flow, parameters intrinsically linked to the potential improvement in the material's sound absorption behaviour. Pure and crossbred sheep wool has fibre diameter around 22–34 μm, while CFF, excluding the quill, present generally smaller diameter than that of the wool fibres [33,70,72]. Table 1 shows a comparison between the diameters of some common types of synthetic, vegetable and animal fibres. The diameter of the fibres in Table 1 is expressed in micrometres (μm).

Acoustic and composite materials made from plant and animal waste are studied and evaluated using experimental and/or theoretical predictive models about their morphological, physical, and mechanical properties. More specifically, the properties most frequently evaluated in scientific studies of both types of acoustic materials (of plant and animal origin) are morphological analysis, fibre density and diameter, appearance, bulk density, thermal conductivity, flammability, sound absorption, sound insulation, impact noise, flow resistivity, porosity, tortuosity, and compressive and tensile strength [15,37,39].

It is difficult to generalise about which type of alternative material (of plant or animal origin) will perform best in terms of these properties, since each material has these parameters in a specific form and therefore each situation must be analysed separately, based on performance and test evidence.

3.2. Animal-based waste building acoustic materials

The meat and tanning industries play an important role in the world economy in terms of protein consumption and the production of high-quality articles in the clothing, footwear, furniture, and automobile sectors [41,83,84].

However, as a side effect, thousands of tons of coarse wool, chicken feathers and leather by-products are generated, posing a real threat to the environment, with the potential to trigger an increase global warming. In the European Union alone, there are 3.1 million tons of chicken feathers per year as waste [68].

The same is true of leather waste. Globally, 25 % of all solid leather waste comes directly from the cutting phase in tanneries, while the remaining 75 % comes from used leather goods that are thrown away after their useful life [85,86].

The various methods for managing animal waste, for example incineration, landfill, animal feed and bioenergy production, end up consuming more energy and lead to the release of toxic gases during processing, causing more damage to the environment [69,70]. Several initiatives are underway to transform animal waste into value-added products, such as sound absorbers and acoustic insulation materials, to alleviate the pollution burden on the environment and lower the costs associated with waste disposal [31,71,72].

Table 1
Diameter of synthetic, plant and animal fibres. Adapted from Refs. [12,33,40].

Type	Fibre	Diameter (μm)
Synthetic	Ceramic	2–6
	Mineral wool	3–10
	Glass wool	3–7
	Graphite	5–10
	Basal	7–13
	Kevlar	1
Plant	Cotton	8–33
	Kenaf	21
	Hemp	22
	Wood	16–38
	Flax	19
	Bagasse	23
	Jute	20
Animal	Sheep wool	20
	Camel wool	16
	Goat wool	78
	Chicken feather (barbs)	15–110
	Chicken feather (barbules)	5
	Chicken feather (quills pulverized)	10–40

Table 2
Summary of studies on animal based acoustic materials.

Material component	SAA	e (mm)	ρ (kg/m^3)	σ (Rayls/m)	Test type	Key findings	Ref.
Wool	0.81	75.0	12.0	1200.0	IT	Improve STL in double and triple wall systems by 6 dB	[54]
Wool underlayer	n.a.	8.6	186.0	n.a.	RR	$\Delta L_w = 18$ dB under concrete screeds	[55]
Multilayer wool nonwoven	0.47	15.0	22.0	198.0	IT	Multilayer wool structures improve sound absorption	[41]
Tufted wool fabric	0.41	16.0	219.0	n.a.	IT	In tufted wool fabrics α_{Sabine} depends on pile's height	[57]
Wool, PET fibres	0.78	55.0	30.0	5950.0	IT + RR	The quality of the wool is irrelevant to sound absorption	[58]
Wool cutoffs, PET, co-PET	0.74	50.0	91.0	33200.0	IT	Manufacturing affects porosity and sound absorption	[59]
Wool, hydrate lime, rice, flour (multi-layer panel)	0.53	50.0	546.0	n.a.	IT	Maximum sound absorption between 0.70 and 0.90 and $R_w =$ 38 dB	[60]
Wool board	0.60	24.0	249.5	n.a.	IT	Cavity's deep helps absorb low-frequency sounds	[61]
Wool, soy protein, glycerol	0.78	60.0	n.a.	n.a.	IT	Soy protein isolate used as a biopolymeric matrix	[53]
Wool mat	0.61	50.0	100.0	n.a.	IT	The sound absorption of wool mats is better for hot compression and lower moisture content	[11]
Wool, hemp fibres, fabric	0.78	45.0	142.0	n.a.	IT + RR	$\alpha w = 0.75$ for wool and hemp composites	[62]
Hu sheep wool, PANOF	0.14	4.8	92.0	n.a.	IT	Sound absorption improves with increasing PANOF content in the material	[2]
Wool, polyamide fibres	0.19	15.0	229.0	n.a.	IT	$\alpha_{max} = 0.91$ for optimal manufacturing conditions	[63]
Wool stiff panel	0.60	50.0	130.0	n.a.	RR	The keratin in the wool acts as a natural glue in the composite	[64]
Wool fibres, modified wool fibres, concrete	0.44	100.0	2400.0	n.a.	IT	Wool fibres in concrete composites improve sound absorption at medium and high frequencies	[65]
Camel wool, 2 mm microperforated plate	0.78	50.0	150.00	n.a.	IT	Sound absorption increases with the thickness of the microperforated panel and the fibrous content	[66]
Wool, CFF, PP web	0.10	6.0	796.0	n.a.	IT	Highest sound absorption for 50 % wool and 50 % CFF	[35]
Wool, coir fibre, gypsum	0.14	10.0	1220.0	n.a.	IT	Samples with a higher content of coir fibres compared to wool fibres have better sound absorption	[67]
Human hair, epoxy, glass microspheres	0.31	3.0	3500.0	n.a.	IT	Increasing the human hair fibre content improves the sound insulation behaviour of the hybrid composite	[50]
CFF, cotton,PET	0.68	50.0	32.0	n.a.	IT	CFF nonwovens can outperform sound absorption of cellulose and mineral wool	[73]
CFF nonwoven	0.68	50.0	60.0	1124.0	IT	The sound absorption of the CFF samples was comparable to that of glass wool	[74]
CFF	0.66	80.0	51.37	n.a.	IT	Similar sound absorption performance to glass wool	[24]
Duck feathers	0.54	20.0	70.0	n.a.	IT	Increasing the depth of the air cavity between the composite and a rigid wall improves low-frequency sound absorption	[75]
CFF, PVA, water	0.41	25.0	350.0	n.a.	IT	Concave surfaces performed better than flat surfaces	[78]
Goose down fibres	0.37	30.0	1140.0	n.a.	IT	For the same mass, goose down performed acoustically better than kapok, cashmere, and synthetic fibres	[79]
Duck feathers, cellulose aerogel, glutaraldehyde	0.30	3.0	80.0	n.a.	IT	New method to reinforce cellulose composite aerogels	[76]
CFF, sheep wool	0.46	45.0	20.0	n.a.	IT	Better sound absorption for 50 % CFF and 50 % wool	[70]
CFF flour, PPR	0.11	20.0	n.a.	n.a.	IT	Best sound absorption for 20 % of CFF flour content	[77]
CFF, PCM, PVC panel	n.a.	7.0	838.0	n.a.	FI	Panels with 75 % CFF +25 % PCM reduced noise by 9 %	[80]
CFF (75 %), jute fibres (25 %)	0.11	3.9	1010.0	n.a.	IT	Best sound absorption for 100 % of CFF content	[81]
CFF, epoxy resin	n.a.	n.a.	n.a.	n.a.	RR	NR of 6.7 dB at 500 Hz for 70 % CFF +30 % resin	[72]
CFF, wood residues, Melamine-urea-formaldehyde	n.a.	10.0	734.0	n.a.	IT	STL values depends more on the structural density of the fibreboard than on the CFF content	[82]
Leather scraps, PVA*	0.46	28.0	640.0	n.a.	IT	Higher average sound absorption compared to other glued wood-based fibre panels (30 mm); STL from 25 dB to 42 dB	[87]
Leather fibre, bamboo fibre, TPU, KH550*	n.a.	4.3	957.3	n.a.	IT	STL values from 25 dB to 45 dB in the range of 500 Hz-1.4 KHz	[88]
Leather trimmings, PVA, PAN*	n.a.	0.19	n.a.	n.a.	IT	Nanofibre multilayers have better sound absorption from 800 Hz to 2.5 kHz compared to individual nanofibre layers	[89]
Chrome leather scraps, PA, CA, coffee silver skin*	0.63	50.0	150.0	14781.0	IT	Average absorption coefficient of 0.95 above 1 kHz, for sample thicknesses of 30 mm and 50 mm	[90]
Leather collagen foam*	0.31	10.0	120.0	n.a.	IT + RR	Good performance at high frequencies and noise level reduction up to 20 dB	[91]
Leather waste, cement, gypsum, wood glue, latex*	0.34	n.a.	750.0	n.a.	IT	Trend of sound absorption peaks from 1.2 kHz-2.0 kHz	[92]
Mycelium foam*	0.40	38.0	n.a.	n.a.	IT	Have potential to replace traditional sound absorbers	[93]
Spider web-inspired metamaterial*	n.a.	2.0	2050.0	n.a.	IT	Low-frequency range sound suppression with a lightweight compact device	[94]
Crossbreed wool waste	0.07	5.73	325.0	42992	IT	Fibres with greater fineness have better sound absorption	[33]
Wool and PVA	0.73	50.0	150.0	n.a.	IT	Camel wool performed better (NRC = 0.74)	[99]

IT: Impedance Tube; RR: Reverberation Room; n.a.: not available; *: non-fibrous animal waste.

The European guidelines on the circular economy and some of the properties of these materials, such as good porosity and elasticity for thermoacoustic applications, are additional and positive variables that also require attention [2,52,56]. However, as any other solution aimed for construction, using these materials must be preceded by specific tests and evaluations to characterize their safety, overall performance, and durability in the building.

Understanding their sound absorption and insulation properties, as well as their manufacturing methods, advantages, and limitations, allows us to broaden their application in construction.

The next section presents the acoustic properties of these materials in the context of the articles reviewed.

3.2.1. Acoustic properties

This section looks at the most recent scientific studies on the use of acoustic materials of animal origin to improve the acoustic comfort in buildings.

Active, passive and hybrid acoustic strategies, used alone or in combination, can eliminate or reduce the noise problem in buildings to acceptable levels [107]. In active noise control, an electroacoustic device generates a second sound wave, in phase opposition to the incoming noise, to cancel it out. Acoustic building materials made from animal waste belong to the category of passive acoustic strategies, which can be applied to contribute to sound absorption and/or sound insulation.

Sound absorption is frequency dependent and is intrinsically associated with the thickness, density, and airflow resistance of the material [40,41]. The more efficient the material is at dissipating sound energy, the better it performs as a sound absorber [12,38]. Sound-absorbing properties of materials made from animal waste can be properly characterised by means of laboratory tests in which their sound absorption coefficients are obtained in 1/3 octave frequency band (from 100 Hz to 5000 Hz) [29]. For this, two main laboratory methods are applied, which are the measurement of the normal incident sound absorption coefficient with an impedance tube [44], and the measurement of the random sound absorption coefficient in a diffuse sound field, in a reverberation room [45]. Impedance tube is generally used for preliminary studies, such as prototypes, as it is less expensive, faster and requires only small samples. Most of the studies analysed in this review used this method to characterize the sound absorption properties of the samples. The reverberation room test method requires larger samples (around 12 m^2), consumes more time and resources. The data from this method is more realistic than that obtained with the impedance tube, since sound waves come from random directions.

In addition to these experimental methods, empirical and theoretical models are also useful to predict sound absorption in the material's prototype phase. Empirical models rely on the macroscopic geometry of the material while theoretical models rely on its microscopic characteristics [42]. The empirical model of Delany and Bazley and the phenomenological model of Johnson-Champoux-Allard are the most widely used [43,48,49]. Sound absorption measured in reverberation room allows to calculate acoustic descriptors such as α_w (weighted sound absorption coefficient) [46] and SAA (sound absorption average) [47]. The material then can be rated based on these single number quantities or acoustic descriptors. In section 4 of this review (software simulations) the acoustic descriptor SAA was used to analyse and compare the sound absorption of the materials considered. In the materials of the articles analysed, some materials were only tested in an impedance tube and others were only tested in a reverberation chamber and the SAA descriptor is not always given. Thus, the SAA descriptor was also calculated from the data obtained with the impedance tube measurements, as a way to compare the performance of the different materials. The acoustic descriptor SAA is calculated using Equation (1) [47].

$$SAA = \frac{1}{12} \sum_{i=200Hz}^{i=2500Hz} SACi \tag{1}$$

where SACi is the sound absorption coefficient of the material in each frequency band.

Scientific research focusing on sound insulation materials made from animal waste is less usual than sound absorption applications. Those materials can be applied to control airborne noise or impact noise. Unlike porous and fibrous materials, airborne noise reduction requires the use of denser, more airtight materials, while impact noise reduction is obtained with elastic dampening materials.

In the case of airborne sound insulation, acoustic materials can be simple partitions, or multilayer panels, mass-spring-mass partitions, such as sandwich panels. Single layer partition systems using animal fibres will only be effective against airborne noise if the fibre content is combined with denser building materials to form a composite, such as concrete composites incorporating wool [65]. This is because animal fibres alone, due to their low density and porous structure, do not offer sufficient resistance to incident sound waves, resulting in a low sound transmission class (STC) for the material. However, in double or triple wall systems, animal fibre nonwovens can absorb standing waves in the cavities between the rigid elements of the system and contribute to improving its overall acoustic performance [54]. In this case, wool can provide a noise reduction of around 6 dB [54]. There are products based on recycled wool on the market which are suitable for use in buildings as acoustic-decorative wall panels [110,115], underlayers, or for filling the cavities of double-walled systems [109]. However, in the case of wool in the cavity of a double wall, it is necessary to consider using an anti-vapour membrane barrier to prevent damp and condensation in the cavity, and thus ensure the durability of the building.

Structural noise in buildings annoys their occupants as it is transmitted through vibrations in solid structural elements such as slabs, beams, and columns and is quite common on floors between different levels (floor impact noise). Some acoustic materials from animal waste can help to mitigate this problem, such as wool in flooring systems under concrete screeds that can reduce impact noise (ΔL_w) by up to 18 dB [55].

Broda et al. [41] investigated the sound absorption properties of monolayer and multilayer wool nonwovens, manufactured by the needle-punching and stitch-bonding methods, and concluded that sound absorption increases with thickness, this being more noticeable in nonwovens with a small number of layers than in nonwovens with a larger number of layers.

Rey et al. [58] studied nonwoven composites of first and second quality sheep's wool mixed with polyester fibres (PES), manufactured by thermo-fusion, and reported good sound absorption at medium and high frequencies. They also concluded that the quality of sheep's wool (whether it is coarse wool or not) has no significant influence on the sound absorption coefficient.

Rubino et al. [59] produced nonwovens for acoustic applications, consisting of 100 % wool waste fibres thermally bonded to bicomponent polyester/copolyester fibres, and found that the production technique and the use (or not) of binders affect the sound absorption of the material. Thermal bonding was used to prepare the samples.

Qiu & Enhui [61] used the thermal bonding manufacturing method to produced wool boards from coarse wool and heat binding fibres, and explored the effects of thickness, density, and cavity depth (from the board to a rigid wall) on the sound absorption performance of the material. According to these authors, increasing the thickness of the wool board and increasing the depth of the cavity between the board and a rigid wall helps to improve sound absorption at low frequencies, while increasing the density has an insignificant effect.

Urdanpilleta et al. [53] developed a new fully biodegradable biocomposite from wool waste, soy protein isolate and glycerol, using the freeze drying method. Acoustic tests revealed sound absorption coefficients similar to those of conventional sound absorbers on the market.

The use of black Merino sheep wool as an alternative building material was explored by Borlea et al. [11]. Samples without binders were studied with respect to the influence of different manufacturing parameters on sound absorption. The manufacturing methods for the samples were hot and cold pressing. The results obtained by Borlea [11] indicated that sound absorption increases with thickness, lower fibre compression rate, lower moisture content, and the hot compression method, rather than the cold compression method.

Bosia et al. [64] developed a hardboard wool panel with low-quality wool and no synthetic fibres, using an innovative manufacturing method in which the keratin of the wool was partially degraded to act as a natural glue with the other fibres. The authors evaluated the sound absorption properties of the acoustic panel in a reverberation room, which revealed good sound absorption at medium and high frequencies, with $\alpha_w = 0.55$. Using the same manufacturing method as Bosia [64], i.e. the partial degradation of keratin as a binding natural-element, Pennacchio et al. [62] developed a self-supporting panel (with and without cover fabric) based on sheep wool and hemp technical fibres. They measured the absorption coefficient of the composite in a reverberation room and obtained a value of $\alpha_w = 0.65$ for the panels without fabric, and $\alpha_w = 0.75$ for the fabric-covered panels.

Alyousef et al. [65] investigated the effect of wool fibres and modified wool fibres on the acoustic and mechanical properties of concrete and concluded that the addition of the reinforcing fibres improves the sound absorption of the concrete composite. The preparation method consisted of adding the wool fibres during the preparation of the concrete using a normal concrete mixer. Adding wool fibres to the mix improved the sound absorption of the composite concrete, with absorption coefficients at 2000 Hz equal to 0.66 for mixtures with 2.5 % wool, and 0.75 for mixtures with the same amount of modified wool.

Dieckmann et al. [73] manufactured nonwovens from CFF, cotton, polyethylene (PE) and polyester (PET) using the air laid manufacturing method. They explored the sound absorption properties of the composite and concluded that CFF nonwovens can outperform cellulose and mineral wool for a given thickness and lower density.

Kusno et al. [74] also prepared CFF sound absorbent samples of various densities and thicknesses to experimentally investigate the sound absorption properties of the samples with measurements in an impedance tube. To prepare the samples the wool fibres were compacted in a mould, but not by cold pressing method, and then wrapped in a porous fabric to ensure the integrity of the sample during the tests. No adhesives were used in the preparation. The measured results show that the acoustic performance of the samples evaluated was equal to or better than the sound absorption of glass wool.

Bousshine et al. [24] studied plants, wool and CFF waste as alternative thermoacoustic solutions, and found that CFF is a relevant acoustic material, competing with glass wool in terms of sound absorption. To make the samples, the wool and CFF were first cleaned and left to dry, then ground to carry out the tests. Among the samples tested, wool and CFF showed acoustic performance results comparable to those of glass wool, with sound absorption coefficients between 0.6 and 0.9 at medium frequencies. The manufacturing method consisted of crushing and testing the fibres in loose form.

Lv et al. [75] used predictive models and experimental tests to investigate the acoustic performance of discarded duck feather nonwovens with an EVA polymer matrix, prepared using the lay-up and hot-pressing method. They concluded that for an air cavity depth between the composite and a rigid wall, there is an improvement in sound absorption at low frequencies and a shift of the sound absorption peak towards those frequencies.

In another study [76], down feather fibre reinforcement was dispersed in a hydroxyethyl cellulose (HEC) matrix. Freeze-drying manufacturing methods were used to produce the composite. In this work, the authors found sound absorption coefficients of up to 0.93 at frequencies above 4000 Hz.

Discarded wool and CFF can also be combined to obtain improved composite sound absorbers with desirable properties and unique characteristics. This approach is synergistic, since the final composite inherits the individual properties of the reinforcements, resulting in a new material capable of overcoming some of the limitations associated with these fibres, such as their lack of plasticity and homogeneity required, for example, in extrusion manufacturing processes. In these hybridised composites, the morphological structure of the reinforcement and the matrix, as well as the proportion between the materials involved in the mixture, are relevant factors. The acoustic characterisation of these materials in the few studies carried out on this topic shows that samples incorporated with 50 % CFF and 50 % wool have better sound absorption than samples with other mixture proportions [35,70].

In addition, after hybridization the feathers retain their porosity in the quills, which helps to improve the sound absorption of the composite. The presence of scales on the surface of the wool fibres, in turn, promotes better interaction with the matrix and this also helps to dissipate sound energy [35,70].

Casadesús et al. [70], using carding and needle-punching manufacturing techniques, created sound-absorbing nonwoven composite based on different proportions of CFF and wool. They measured the sound absorption coefficients (α) of the nonwoven using an impedance tube. Based on the results of the acoustic tests they concluded that nonwovens incorporated with 50 % CFF and 50 % wool had better sound absorption compared with the other mixture proportions, across the frequency range. The sound absorption profile of the composites revealed the same acoustic behaviour as glass wool and rock wool, increasing proportionally with frequency up to a maximum. For frequencies below 2.2 kHz, the composites performed even better than mineral wool materials.

Ghermezgoli et al. [33] used fabric weaving techniques (knitting) to manufacture and analyse the sound absorption properties of woven fabrics made from crossbred wool. The results of the impedance tube measurements showed good agreement with the Mechel predictive model used by the authors and revealed that crossing the Ghezel and Arkharmerino sheep breeds improves fibre fineness with positive effects on the sound absorption performance of the material and the appearance of the wool.

Ilangovan et al. [35] investigated the combined use of wool, CFF and polypropylene in composite sound absorbers produced by the hot-pressing method. The authors explored the acoustic and fire resistance performance of the composites and came to the same conclusion as Casadesus [66] regarding the influence of the ratio between the reinforcements, i.e. there is an ideal ratio for the reinforcements (50/50 wool and CFF) that leads to better sound absorption performance in the composite. They found a sound absorption coefficient of up to 0.55 and peaks in the 1000–6000 Hz range, depending on the proportion of wool and feathers.

Constantin et al. [77] prepared a new biocomposite based on feather flour and recycled polypropylene (PPR), with and without additives, using the hot-pressing technique. After acoustic tests with the impedance tube, maximum sound absorption was found for the samples containing 20 % feather flour and no additives, as well as for samples with 10 % feather flour and additives.

A CFF panel for architectural applications, with flat or concave surfaces, was developed by Baharuddin et al. [78]. They used the bonding method to produce the samples, in which polyvinyl acetate (PVA) was used as a binder, and clean water as a solvent. Acoustic tests with an impedance tube showed that samples with concavities on their surface had better sound absorption.

Yang & Pan [79] investigated the sound absorption behaviour of four different sets of animal, plant, and synthetic fibres (goose feathers, cashmere, kapok, and acrylic fibres) and concluded that, for the same mass, goose feathers had the best sound absorption. The samples were produced by simply assembling the fibres.

Abdulmunem et al. [80] melted a phase change material (PCM) and mixed it with different mass fractions of CFF, leaving the mixture to cool inside a commercial hollow PVC plastic panel with a thickness of 7 mm. The manufacturing method was thermal-bonding. The authors found a 9 % improvement in noise reduction for the composite incorporated with 75 % CFF.

Hybrid composites with CFF and jute were investigated by Saravanan [81] regarding the effect of processing parameters and fibre loading on sound absorption. It was concluded that processing conditions have a significant impact on sound absorption, with the highest value for composites with a 100 % CFF content. The manufacturing method used by Saravanan [81] was hot-compression molding.

Bessa et al. [72] used the compression molding manufacturing method to develop and evaluate the potential application of CFF and epoxy in composites. The authors reported an airborne sound insulation of 6.7 dB at 500 Hz for a mixture containing 70 % CFF and 30 % epoxy.

In a study using CFF to produce medium-density fibreboard for sound insulation, carried out by Safaric et al. [82], CFF were mixed with wood chips and wood dust and then bonded with melamine-urea-formaldehyde MELDUR H 97. After testing the samples for their soundproofing properties, the results showed that the STL of the panels depends more on their structural density than on the CFF content. Unlike the previously mentioned studies of Casadesús [70] and Ilangovan [35], the concentration of CFF played a secondary role in the sound insulation performance of the fibreboards proposed by Safaric [82]. A reasonable explanation for this could be that the CFF have lower density than the other components (wood chips, wood dust and melamine-urea-formaldehyde).

Barbanera et al. [87] developed an innovative acoustic panel from finished leather scraps and PVA. Two panels were produced with thicknesses of 18 mm and 28 mm, using the bonding and mechanical pressing methods. The characterisation of the acoustic properties of the panels revealed noise reduction coefficients of 0.46 and 0.20 and sound transmission loss of around 25–33 dB and 25–42 dB for the 18 mm and 28 mm panels, respectively. In addition, compared with glued wood fibre panels with a similar thickness (30 mm), the panels had a higher average sound absorption.

Pu et al. [88] also created a composite plate kneaded with leather fibre, semi-liquefied bamboo (SLB), thermoplastic polyurethane elastomer (TPU), and silane coupling agent (KH550). They found STL values between 25 dB and 45 dB in the range of 500 Hz to 1.4 KHz. The composite plate was prepared using the response surface method.

Rämmal & Lavrentjev [91] studied an environmentally friendly material for noise, vibration and harshness applications (NVH), using a web foam based on natural leather collagen. They validated the innovative material through experimental tests with a motorcycle helmet, obtaining good sound absorption performance at high frequencies and noise cancellation up to 20 dB. The manufacture method used was polymeric bonding.

Selvaraj et al. [89] proposed a novel multilayer nanofibre sound absorber based on PVA and collagen hydrolysate from leather scraps (nanofibre interlayer), sandwiched between polyacrylonitrile (PAN) nanofibre layers. They found that in the frequency range of 800 Hz to 2.5 kHz, the sound absorption of the nanofibre multilayer was better than that of the individual nanofibre layers, because of the variation in pore size and the hierarchical structure of the layers. The multiple layers of nanofibres were manufactured using electrospinning.

Abdi et al. [90] investigated composite materials made from chrome leather scraps mixed with silver coffee skin, bonded with polyacrylic (PA) and citric acid (CA). The samples were manufactured using bonding and cold pressing. An average sound absorption of 0.95 at 1 kHz was reported for sample thicknesses of 30 mm and 50 mm.

Nanda et al. [50] studied the thermal, acoustic, and dielectric behaviour of epoxy-based hybrid composites with short human hair fibres and solid glass microspheres. They noticed that increasing the content of human hair fibres improved the sound absorption behaviour of the composite. The manufacturing method consisted in casting the solution in a cylindrical mould.

Guna et al. [67] proposed a mixture of wool and coconut fibres, to reinforce ceiling plasterboards, and found that samples with a higher coconut fibre content had better sound absorption than samples with wool fibres. The manufacturing method consisted of mixing the components and letting them dry in a mould.

Beheshti et al. [66], in an attempt to improve the sound absorption performance of fibrous and porous materials at low frequencies, proposed a multilayer resonant sound absorber consisting of a thick microperforated panel (MPP) with a soft camel wool mat inside. They observed that as the thickness of the MPP and the fibrous absorbent layer increased, the low-frequency sound absorption also increased. The multi-layer system was manufactured by manually overlapping and assembling the components.

Kobiela et al. [57] investigated felts and tufted pile fabrics from ring spun and core rug yarns made from the coarse wool of mountain sheep (felting and tufting manufacturing methods). For the felt material the authors found that sound absorption was most affected by packing density and the fibre thickness of the felts, while in the case of the fabric the crucial parameter influencing sound absorption was the pile fabric height, regardless of whether ring yarns or core rug yarns are used. Another finding was that the sound absorption of coarse wool corresponds well with the performance of better-quality wool, such as that of Merino sheep [57].

Tamas-Gavrea et al. [60] proposed a sheep wool multilayer sandwich panel for sound absorption and airborne sound insulation. The authors obtained a sound reduction index of $R_w = 38$ dB, and maximum sound absorption coefficients between 0.70 and 0.90. The sandwich structure was assembled by hand in the laboratory by joining the components together.

Vidaurre-Arbizu et al. [92] explored the use of leather waste in the manufacture of acoustic panels, using cement, gypsum, latex, and wood glue as binders. The authors reported a trend of sound absorption peaks from 1.2 kHz to 2.0 kHz (maximum value of 0.73), higher than that shown by other materials such as cork (0.60) and carpet (0.27).

3.2.2. *Manufacturing methods*

This section gives an overview of the main methods, conventional and more recent, in the manufacture of acoustic composites of animal origin, and the influence that these methods have on the acoustic properties of these materials.

The manufacturing method is a relevant consideration in the development of a building acoustic material made from animal waste. This is a key factor, as it strongly affects the physical parameters of these materials such as their thickness, bulk density, and air permeability [41]. In addition, different manufacturing methods will have different impacts on equally crucial aspects of the final material's life cycle, which are associated with its production, appearance, use, sustainability, and final cost. It is not just a question of looking at the best acoustic profile to achieve for the material; another extremely important consideration is that, depending on the manufacturing method or process, toxic and non-toxic waste may be generated and that, at the end of the material's life cycle, components and parts of the material will have to be reused to meet the criteria of circularity and environmental safety.

Sound absorption and insulation materials are made from a single constituent, or more often, as a combination of several materials with distinct physical and mechanical properties. The most common forms in which these materials can be manufactured are as non-woven, woven, and knitted structures, which means that the choice of the most appropriate manufacturing method reflects what needs to be produced.

Various techniques or methods can be applied to produce these materials, the most common being needle punching, felting, knitting, tufting, thermal bonding, bonding, cold and hot pressing, air laid and freeze-drying [37,53].

In needle punching, the fibres are compressed into a pre-formed fibrous web and then needles with barbs punch some of the fibres through the body of the material several times, so that the fibres end up mechanically entangled and interlocked [41,54]. The bulk density of the finished material, and therefore its sound absorption performance, is controlled by the degree of compression of the fibres, the number of needles and the depth to which the needles penetrate the fibrous web. The higher the compression rate and the greater the interlacing between the fibres of the material, the more its porosity is reduced and its resistance to air flow increases, altering its acoustic impedance and favouring the dissipation of sound energy in its interstices. According to Ballagh [54], materials with densities from 40 kg/m^3 to 100 kg/m^3 can be obtained by needle punching.

In the felting method, animal fibres with felting properties (such as wool) are consolidated by the application of heat, humidity, or mechanical action, causing the fibres to interlock in the material. Knitting is another method of producing textile structures by interlacing loops of yarn with loops of the same yarn or other yarns [33,57,98]. Tufting is a manufacturing technique used to produce mainly woven and knitted wool materials [57]. The fibres of the material are entangled and interwoven to form a highly porous structure with numerous micron and submicron capillary channels where sound waves enter and are dissipated by viscous effect. Sound absorption in tufted wool fabrics is mainly influenced by the height of the fabric's pile [57].

The thermal bonding method involves a mix of a base fibre (for example wool or CFF) and a thermoplastic polymeric matrix that works by binding the reinforcements (for example polyester fibres). The thermoplastic polymer is melted by heating and then cooled to solidify the bonding area with the base fibre. The type of fibres and their proportion in the mix determine the bulk density and airflow resistivity of the final composite, providing different sound absorption profiles for the material [59,81].

Bonding simply involves applying a dispersion of a binder or polymer, either biodegradable or not, followed by curing and drying the impregnated animal waste fibre [59]. The polymer holds the fibres and provide dimensional stability [15]. Asdrubali [51] points out that from the point of view of environmental impact the more natural and less treated the fibres are, the better their ecological performance will be. In bonding, the type and quantity of the polymer determine the porosity of the composite material and therefore its acoustic performance [59]. Typical densities for composites manufactured by this method are within the range of 10 kg/m^3 to 30 kg/m^3 [54].

Cold and hot pressing are manufacturing techniques for preparing pressed felts with low energy consumption. In hot pressing, the animal fibre waste is placed in a cylindrical aluminium mould with upper and lower heating plates. The cylinder with the fibres is fitted with thermocouples and when heated, compressed, and agitated, it forms the felt [11]. In the cold pressing method, the mould where the samples are cold-pressed and agitated has a lid and is made of steel [11]. In these methods (cold and hot pressing), the working conditions of pressure, temperature, and moisture are controlled and manipulated to produce materials with different physical characteristics.

Borlea [11] observed that wool materials obtained by hot pressing had higher sound absorption properties than those obtained by cold pressing, thanks to the greater density and compaction of the fibres caused by the action of heat. Thick materials produced under the same boundary conditions as thin materials generally have better sound absorption. According to Borlea [11], excess water in a wool sample plasticises the surface of the material and makes it difficult for sound waves to penetrate the porous structure, thereby reducing its acoustic performance.

In the air laid manufacturing process, a mixture of fibres is subjected to the action of gravity and forms a bed of fibres that is continuously moved to another part of the manufacturing device, where it is heated and pressed to obtain the final nonwoven product. The variation in the spaces between the moving belts of the device controls the density and thickness of the material and consequently modifies its sound absorption profile [73].

In the freeze-drying process a dispersion containing the animal fibres and the polymeric matrix is poured into moulds and then frozen at low temperatures (around $-28\,^{\circ}$C) for a certain period. Next, the sample is freeze-dried and a porous and more homogeneous structure is obtained [53]. In wool biocomposites, an improvement in the sound absorption over the whole frequency range has been reported using this method. This is provided by the reduction in fibre diameter and better filling of free spaces within and between the fibres [53].

Of the manufacturing methods described above, bonding is the most practical and straightforward method, while hot pressing is seen as an easy method to scale up to commercial-scale production [93].

It is worth mentioning that the methods and processes for preparing biocomposite samples, whether for acoustic purposes or not, have evolved considerably since alternative acoustic materials first appeared. There is currently a trend towards using natural polymeric matrices such as chitosan and gum arabic, with a view to further reducing the ecological footprint of these composites [37].

One of these innovative manufacturing methods was applied by Halashi et al. [25]. The authors used the response surface method, based on central composite design (RSM-CCD), to find the best combination of input variables, such as thickness, density and binder content, with the aim of maximising efficiency and minimising composite manufacturing costs. Other innovative and less conventional methods of producing acoustic construction materials of animal origin, especially sound absorbers, include electrospinning [89], 3D printing [94], the partial degradation of animal proteins [62,64] and the use of fungal enzymes in acoustic panels composed of mycelium [93].

3.2.3. Limitations and challenges

Acoustic building materials based on animal waste can replace man-made synthetic materials and be scaled up industrially. To achieve this, these materials need to have good acoustic performance but also be able to meet other construction requirements, such as durability, safety, mechanical resistance, aesthetics, and environmental sustainability. The steps of designing, prototyping, and testing the solution in an accredited laboratory are thus the starting point for certification and the product's success on the market. It is therefore necessary to analyse and thoroughly understand their vulnerabilities, drawbacks, and potentialities.

The first consideration is that animal-base acoustic materials have natural components with great variability and heterogeneity in their physical and resistance characteristics [34,36]. This means that some of these characteristics can overshadow the many positive aspects associated with the use of these materials, making them more difficult to apply to buildings. Therefore, it is often necessary to modify their initial properties through chemical, biological, or physical-mechanical treatment.

Although animal fibres, such as sheep's wool, are less susceptible to decomposition in damp and dark environments, unlike vegetable fibres, they are vulnerable to attack by pests, insects, and microorganisms, which reduces their durability. Treatment with antimicrobial and antiparasitic agents like boric acid are an effective option to overcome this type of limitation and prevent early degradation of these materials [15,34,37]. In addition, animal fibres can also contain impurities, dirt, and grease which, like microorganisms and pests, also need to be removed to stabilise and sanitise the fibres before they undergo the manufacturing process.

Another issue of concern is their high sensitivity to moisture and moderate thermal stability [4], which can be controlled by suitable chemical treatments. The low microbial resistance and the high sensitivity to moisture, if not properly resolved at an early stage of the material design, increase the possibility of the acoustic material rotting and releasing unpleasant odours. The unpredictable durability of animal fibres affects their processing and use as building acoustic materials, which is considered a major obstacle to their compliance and use in construction applications [43]. Another aspect is the fact that these materials do not exhibit thermoplastic behaviour, which makes it difficult (but not impossible) to form them into complex shapes with extrusion manufacturing methods. The irregularities in the microscopic internal structure of animal waste can hinder and weaken the surface adhesion of the fibres to the matrix in composites. In solid composite panels, for example, if the densities vary too much, it will be difficult to predict the acoustic behaviour of the material using theoretical-empirical models, and the uneven distribution of density will generate soundproofing failure in some parts of the material's structure.

A topic that has received increasing attention in the technical literature is the fire resistance properties of animal-based waste acoustic materials. Fire rating is essential for materials and composites intended for indoor applications. The fire resistance of animal-based waste sound absorbers is influenced by the density, thickness and amount of voids and air pockets in the sample. There are several studies in the technical literature addressing the issue of animal waste-based materials and composites for acoustic purposes, which have also been investigated with regard to the material's fire resistance.

Ma et al. [2] used needling and milling methods to develop a sound absorbing material made of Hu sheep wool mixed with oxidised polyacrylonitrile fibre (PANOF), in different blending ratios, to give the material the feature of a flame-retardant composite. The grooved structure and large specific surface area of the PANOF fibres contributed to the loss of sound energy in the fibre mesh, thus improving the sound absorption of the material. Impedance tube tests have shown that sound absorption improves with increased PANOF content in the material, due to greater interweaving between the wool and PANOF fibres and increased surface density. PANOF fibres have a good limiting oxygen index and excellent flame-retardant function. For the 80/20 mixture ratio of sheep's wool and PANOF, the sound absorption coefficient at medium and high frequencies was greater than 50 % and the horizontal and vertical combustion performance of the fabric met the standard flammability requirements.

In the same line of research as Ma [2], Lyu et al. [63] developed a nonwoven from waste wool and low melting point polyamide fibres, using a hot-pressing method, and examined the sound absorption and flame-retardant properties of the material. The effects of fibre length, hot pressing temperature, wool fibre mass fraction, bulk density, thickness, and back air layer on the sound absorption properties of the nonwoven were analysed. They concluded that under optimum process conditions it is possible to obtain a wider sound absorption band with a maximum value of up to 0.91 and meet the fire resistance requirements of the construction, using an 8 % concentration of potassium fluorotitanate, a treatment time of 40 min, and a treatment temperature of 80 °C.

Guna et al. [67] proposed a mixture of wool and coconut fibres to reinforce gypsum tiles in order to improve their performance in terms of structural integrity, moisture resistance, sound absorption and flammability. The coir and wool fibres were first washed and left to dry. After this, the coconut fibres were carded to untangle the fibres and then both fibres were ground and homogenised. The wool and coconut fibres were mixed with water and gypsum and the mixture was cast into open moulds until it was dry. No chemicals were used on the fibres. Gypsum boards prepared with different proportions of wool and coir showed different fire resistance because the protein structure of the wool, compared with the lignocellulosic structure of the coir fibre, has better resistance to flammability. The sound absorption in the frequency range from 0 to 1500 Hz was up to 0.25, while between 1500 Hz and 3000 Hz it showed absorption peaks of up to 0.32. A major sound absorption peak of 0.35 was found at 5500 Hz for gypsum ceiling tiles containing 30/00/70 coir fibre/sheep wool/plaster composite. The samples with 30 % coconut fibre achieved the lowest rating of all the samples evaluated (V2 rating), while for the samples with 30 % wool and a mixture of the two fibres the rating obtained was V1 [108].

In the work by Ilangovan et al. [35], described in section 3.2.1, in which wool, CFF and polypropylene (PP) were combined to create a composite, the authors made some important findings regarding the flammability of the materials investigated. Because of wool's excellent flame resistance, wool-reinforced composites resulted in less combustion than feather-reinforced ones. Furthermore, pure and hybrid composites had a flame resistance rating of V1 and V2, while the polypropylene composites reinforced with wool fibre and a polypropylene content of 20–30 % had a flame resistance rating of V0 [108].

Using cold pressing and bonding manufacturing methods, Beheshti et al. [99], in a second study on alternative construction materials, made different composite sound absorbers based on sheep wool, goat fibre, and camel wool, as well as pith and fibre bundles of sugarcane bagasse. The authors carried out thermal conductivity, thermal resistance, acoustic and moisture absorption, and fire resistance tests to evaluate the properties of the five composite panels. Composite materials made from wool, especially camel wool, performed better than materials based on sugarcane bagasse. The noise reduction coefficient of the composites incorporated with camel wool had the highest value (0.74), while the goat fibre composites had the lowest value (0.52). The maximum sound absorption coefficient was found for camel wool (0.95) above 1000 Hz. In the flammability tests, the fire performance of the five composite panels was compared with each other and better performance was found for the wool-based composites than for those made with bagasse. The melting characteristics for the wool composites was rated as Shrink and Melt, while for the sugarcane bagasse-based composites it was rated as Burs and Ash. The wool-based composites had an average smoke production of 7.6 s, an average ignition time of 37 s and an average continuous combustion time of 79 s. Meanwhile, the sugarcane bagasse-based composites had an average smoke production of 8.5 s, an average ignition time of 19 s and an average continuous combustion time of 108 s. This means that wool-based composites, when exposed to fire, take longer to start burning, burn for less time and give off less smoke than sugarcane bagasse-based composites. These results demonstrate the good behaviour of wool under the action of fire, and confirm data from other studies [35].

With the growing emphasis on circular economy principles, an important issue regarding animal-based waste acoustic materials is their reuse and repurposing after their end-of-life. Academic research on recycling commercial applications on sound absorbers and sound insulators containing animal waste content does not exist yet [103]. The European Union's 2008/98/EC directive [102] has established a four-tiered hierarchy for waste management, as shown in Fig. 4.

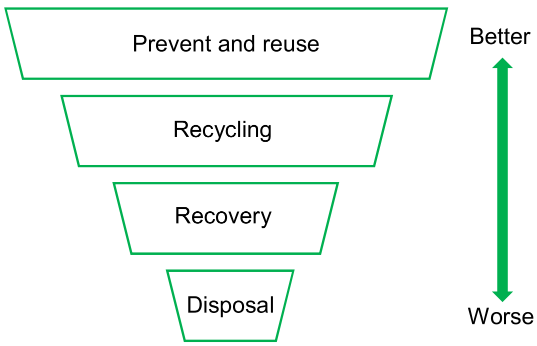

Fig. 4. Waste management hierarchy according to EU 2008/98/EC directive. Adapted from Ref. [101].

According to Fig. 4, the order of preference for managing waste is minimisation or prevention, followed by recycling, recovery, and disposal. The focus should be on minimising and preventing waste, since landfill space is precious.

Reducing the waste associated with animal-based acoustic materials is the most environmentally friendly route and requires attention to the early stages of the material's life cycle.

So, for example, improving manufacturing techniques by using standardised automatic methods results in less waste than is created by manual methods. Through this route, there is an important opportunity to consider how best to separate and recycle the parts and components of the material after its end of life, taking into account the potential variations in its strength and structure with effects on its acoustic properties. For example, the wool used in a dumping material to reduce impact noise in a floating floor system could be reused in the production of a new dumping material, provided that the mechanical properties of the reused underlayer (dynamic stiffness, compressibility and compression creep) [55] remained completely or at least partially functional.

Reusing and repurposing the fibres contained in composites, as in the case of sound absorbers made from animal waste, is a challenge since the properties of decommissioned composite parts can change after the parts are separated. In addition, it is necessary to consider to what extent the process of separating and reusing the fibres is attractive from a practical point of view and the associated costs, since the fibres have a low economic value and are available in large quantities as waste.

Compared to recovery and disposal methods, recycling is the most environmentally desirable method, consisting of three main pathways: mechanical, thermal, and chemical recycling.

Mechanical recycling involves grinding, milling and shredding the material into small parts and powder. It produces highly degraded, low-value recyclates and does not reclaim individual fibre content in composites. The mechanical method could be useful, for example, in wool-based knitted acoustic absorbers, to undo the interwoven structure of the threads and recover the fibres for new applications. It can also be applied in multi-layer wall systems with a fibrous and a non-porous part, such as plasterboard panels with woollen or chicken feather nonwovens in the cavity between the boards, or in concrete mixtures using animal fibres. On an industrial scale, mechanical recycling is the most economically viable recycling method.

Thermal and chemical recycling methods are quite appropriate in composites reinforced with fibres of certain commercial value, such as carbon and kevlar (para-aramid) fibres. Under controlled conditions designed to preserve the structure of the fibres as much as possible, these methods use heat and chemical agents to weaken the junction interface between the reinforcement and the matrix. Here it is also necessary to evaluate the environmental load of the chemical agent to be chosen in the process of separating the fibres from the matrix.

For the reasons already explained above, that is, low cost and ready availability of animal fibres, thermal and chemical methods would not be attractive in the case of recycling fibres from these materials. However, the environmental impact of binders in animal waste compounds for acoustic purposes could be reduced by studying biopolymers (with the same properties as synthetic polymers) in order to improve the biodegradability of the material and reduce dependence on the use of synthetic materials. This is still a little explored gap.

Incineration is still a common practice in which the organic content of the material (e.g. in composites) is burned. Germany is one European country where incineration has already been banned. In other countries where incineration is still practised, European guidelines say that thermal energy must be recovered in a practical way to generate, for example, steam and power [101]. Currently, incineration with energy recovery is regarded as a less profitable and environmentally dubious disposal method, since 50 % of burned waste remains as ash and ends up in landfills. In addition, this method increases atmospheric pollution caused by combustion [105].

Landfilling is the method with the greatest environmental impact and therefore the one most subject to government legislation and regulation. European Union Directive 2018/850 [104] on landfilling of waste set the target for only 10 % of urban waste to be landfilled by 2035. Landfill is the last alternative and should be avoided as much as possible compared to other methods, given the numerous adverse consequences this practice can have, such as methane and the contamination of groundwater with leachate

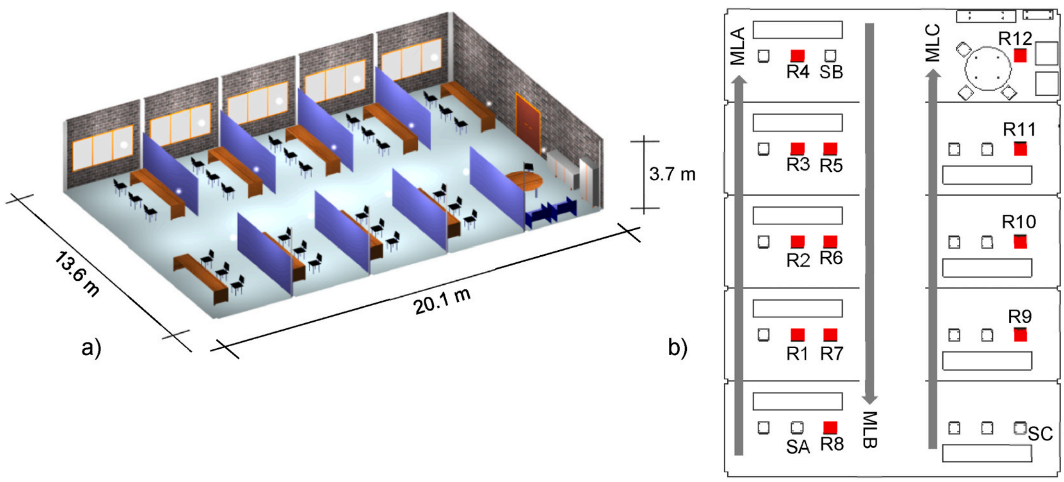

Fig. 5. Open plan office: a. perspective; b. plan view.

infiltration. In principle, all sound absorbers and sound insulation materials can be disposed of by incineration and landfill. However, with the potential limits on landfilling and incineration and the circular economy agenda, it is recommended that after their useful life sound absorbers and sound insulation materials based on animal waste be revalorised through reuse, recycling and waste recovery strategies.

4. Software simulations

The aim of this section is to compare the acoustic performance of the different absorbers described in the literature review when they are applied in the same room configuration. Besides the acoustic characteristics of the sound absorbers, the room layout and geometry can influence the acoustic parameters of the room. Some considerations about this are mentioned in the discussion section. The acoustic simulations are performed with EASE®4.4 software [97], using AURA module (v3), assuming the following parameters: 64,000 particles, 1130 ms, default value for surfaces without scattering data equal to 20 (slightly structured surfaces) and number of calculation threads equal to 8. Fig. 5 a shows the open plan office created for the simulations. The dummy-room with dimensions 13.6 m × 20.1 m and 3.7 m has thirty occupants spread across ten workstations separated by partitions. The plan view of the room in Fig. 5 b shows the omnidirectional sound sources SA, SB, SC, the listener seats R1 to R12 and the measurement lines MLA (arrow SA-R1-R2-R3-R4), MLB (arrow SB-R5-R6-R7-R8), and MLC (arrow SC-R9-R10-R11-R12) of the 3D acoustic-geometric model. The sound spectrum of the sound sources was that of a man using normal speech, with the listeners' seats positioned at 1.20 m from floor level, and the in situ noise level ($L_{NA,Bau}$) set at 40 dB(A). Each measurement line was simulated individually in the model, considering the location of the listeners and the sound source associated with the respective measurement line. The settings for the room simulations were: local decay at each listener seat in 1/3 frequency band (100 Hz–10.000 Hz); patch size resolution of 0.10 m; background noise level of 40 dB(A); sound spectrum of the sound sources of a man using normal speech; sound sources and listener seats at 1.20 m from floor level.

Table 3 summarises the surface areas (m^2) and sound absorption coefficients of the materials used in the simulations.

Seven cases were simulated, with the absorption coefficients assigned to the ceiling while all other boundary conditions remained unchanged. The hatched part in Table 3 refers to the materials placed in the ceiling. In Case 1, the room was calculated without acoustic treatment, i.e. in its most unfavourable condition, with highly sound-reflecting materials (ceiling is smooth concrete). In Case 2, the smooth concrete of the ceiling (273.20 m^2) was replaced with a PU foam (50 mm and 28 kg/m^3) and the room was recalculated. The foam was then replaced with glass wool tiles with plenum (25 mm and 100 kg/m^3) in Case 3. The placement of sheep wool [54] (75 mm and 12 kg/m^3) in the ceiling corresponds to Case 4, while Cases 5, 6 and 7 correspond to the placement of Camel wool, CFF nonwoven, and Leather scraps, respectively. Table 4 and Fig. 6 show the results of the simulations in terms of sound propagation and reverberation time.

The Level in the last column of Table 4 refers to the propagation of sound along a measurement line, and is classified into three categories L_1, L_2 and L_3 [13]. Level L_1 is for D2,s ≥ 8 dB(A) and Lp,A,S,4 m ≤ 47 dB(A), Level L_2 is for D2,s ≥ 6 dB(A) and Lp,A,S,4 m ≤ 49 dB(A), and Level L_3 is for D2,s ≥ 4 dB(A) and Lp,A,S,4 m ≤ 51 dB(A). D2,s is the spatial attenuation rate of the sound pressure level in dB(A) when doubling the distance between the receiver and the source, while Lp,A,S,4 m is the sound pressure level in dB(A) of a receiver positioned 4 m from the source. The shaded area in Fig. 6 indicates the reverberation time limits associated with room acoustic class (RAC) A, B or C of VDI 2569:2019 [13]. An open plan office is grouped in a particular RAC if it fulfils the conditions set out in

Table 3
Surface areas and sound absorption coefficients of the materials used in the simulations.

Material	Area (m^2)	Frequency (Hz) 125	250	500	1000	2000	4000	SAA
Floor – tile glazed	273.20	0.01	0.01	0.01	0.01	0.02	0.02	0.01
Ceiling smooth concrete	273.20	0.01	0.01	0.02	0.02	0.02	0.05	0.02
Walls – masonry	177.52	0.01	0.05	0.06	0.07	0.09	0.08	0.07
Chairs - Upholstered	30 units	0.08	0.16	0.22	0.23	0.24	0.24	0.21
Sofa – Upholstered	2 units	0.08	0.16	0.22	0.23	0.24	0.24	0.21
Large door – wood	5.04	0.15	0.11	0.10	0.07	0.06	0.07	0.09
Small doors - wood	5.52	0.15	0.11	0.10	0.07	0.06	0.07	0.09
Rectangular table	33.84	0.12	0.12	0.13	0.13	0.11	0.11	0.12
Circular table	2.70	0.12	0.12	0.13	0.13	0.11	0.11	0.12
Ressonant panel	142.49	0.60	0.42	0.35	0.12	0.08	0.08	0.25
Windows – double glass	22.05	0.35	0.25	0.18	0.12	0.07	0.04	0.16
Metal stud - stell	3.10	0.05	0.10	0.10	0.10	0.07	0.02	0.09
Office cupboards - steel	7.24	0.05	0.10	0.10	0.10	0.07	0.02	0.09
PU foam 50 mm [95]	273.20	0.15	0.58	1.00	0.98	0.94	0.91	0.87
Glass wool tile 25 mm [96]	273.20	0.17	0.53	0.84	0.99	0.99	0.97	0.84
Wool 75 mm [54]	273.20	0.42	0.68	0.85	0.89	0.83	0.86	0.81
Camel wool 50 mm [66]	273.20	0.10	0.36	0.79	0.99	0.99	0.89	0.78
CFF nonwoven 50 mm [74]	273.20	0.13	0.41	0.84	0.88	0.83	0.80	0.68
Leather scraps 50 mm [90]	273.20	0.05	0.15	0.49	0.83	0.98	0.95	0.63

Table 4
Sound propagation results.

Ceiling Treatment	ML	Lp,Source,1 m dB(A)	Lp,A,S,4 m dB(A)	Lp,8 m dB(A)	D2,s dB(A)	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 [95] (Case 2)	A	59.2	48.0	39.0	9.0	L_2
	B	60.9	46.0	42.0	4.0	L_3
	C	59.7	45.0	41.0	4.0	L_3
Glass wool tile 25 mm with plenum [96] (Case 3)	A	61.0	48.0	39.0	9.0	L_2
	B	61.0	47.0	42.0	5.0	L_3
	C	61.2	46.0	41.0	5.0	L_3
Wool 75 mm [54] (Case 4)	A	61.0	48.0	38.0	10.0	L_2
	B	60.9	46.0	40.0	6.0	L_2
	C	61.2	46.0	41.0	5.0	L_3
Camel wool 50 mm [66] (Case 5)	A	61.2	49.0	41.0	8.0	L_2
	B	61.2	49.0	44.0	5.0	L_3
	C	61.4	48.0	43.0	5.0	L_3
CFF nonwoven 50 mm [74] (Case 6)	A	61.1	49.0	41.0	8.0	L_2
	B	61.2	48.0	43.0	5.0	L_3
	C	61.3	47.0	42.0	5.0	L_3
Leather scraps 50 mm [90] (Case 7)	A	61.5	51.0	45.0	6.0	L_3
	B	61.6	51.0	47.0	4.0	L_3
	C	61.7	50.0	46.0	4.0	L_3

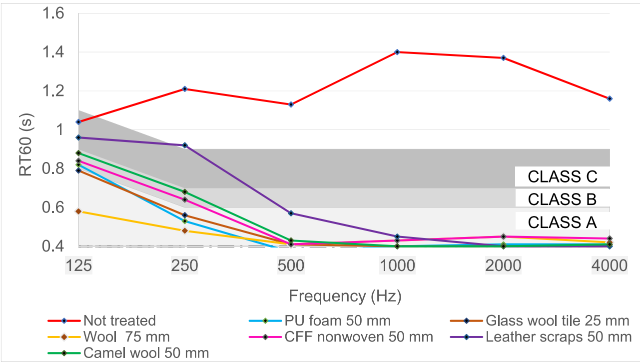

Fig. 6. Reverberation time results.

Table 5
Conditions to classify open plan offices into room acoustic class [13].

RAC	Classification of ML in levels	Reverberation time (s)		LNA,Bau dB(A)
		125 Hz	250 Hz to 4000 Hz	
A	2/3 of ML in L_1 and rest in L_2	≤0.8	≤0.6	≤35
B	2/3 of ML in L_2 and rest in L_3	≤0.9	≤0.7	≤40
C	1/3 of ML in L_2 and rest in L_3	≤1.1	≤0.9	≤40

Table 6
RAC of the open plan office in the acoustic simulations [13].

Open plan office treatment	ML level	Reverberation time (s)		LNA,Bau dB(A)	RAC
		125 Hz	250 Hz - 4000 Hz		
Not treated	–	1.04	1.21–1.16	40.0	–
PU foam 50 mm [95]	1/3 L_2, 2/3 L_3	0.82	0.53–0.41	40.0	C
Glass wool tile 25 mm [96]	1/3 L_2, 2/3 L_3	0.79	0.56–0.40	40.0	C
Wool 75 mm [54]	2/3 L_2, 1/3 L_3	0.58	0.48–0.42	40.0	B
Camel wool 50 mm [66]	1/3 L_2, 2/3 L_3	0.88	0.68–0.41	40.0	C
CFF nonwoven 50 mm [74]	1/3 L_2, 2/3 L_3	0.84	0.64–0.44	40.0	C
Leather scraps 50 mm [90]	all in L_3	0.96	0.92–0.40	40.0	–

Table 5 [13].

Table 6 shows the different classifications obtained for the simulated room according to the various materials assigned to the ceiling. This allows comparing the acoustic performance of the room, under VDI 2569:2019 [13], based on the use of synthetic and animal-based sound absorbers.

5. Discussion

The temporal distribution of the selected records in the Systematic Literature Review in Fig. 2 indicates that the research topic has attracted increasing attention over the last seven years. In the distribution pattern of the records by typology, in Fig. 1 b, research articles are in the majority over conference papers, book chapters and review articles, totalling 74 %. It is also interesting to note that articles focus mainly on sound absorption applications, rather than airborne sound insulation or impact sound insulation, as shown in Table 2. A possible explanation for this could be the fibrillar nature, low density, and abundance of certain animal waste in the environment, such as the by-products of wool and chicken meat production, all of which ultimately facilitate their transformation into porous and lightweight sound absorbers, with less expenditure on raw materials. Of the material components listed in Table 2, wool fibres are the main raw material used for acoustic purposes, accounting for 50.0 % of the total, while avian fibres and non-fibrous animal waste account for 31.0 % and 19.0 % of the total, respectively. By grouping the sound absorbers in Table 2 into thickness ranges and raw material categories, it is possible to obtain and analyse the average and maximum SAA for each range, as shown in Table 7.

As the range thickness increased, the average SAA also increased, for all raw material categories. For example, from the first thickness range (1 mm–25 mm) to the second (26 mm–50 mm), the average SAA more than doubled for the hair fibre category and almost doubled for the other two categories. The same trend is observed in relation to the maximum SAA, thereby corroborating the finding reported in previous studies that sound absorption increases with the thickness of the material, especially for frequencies between 100 Hz and 2.0 kHz [33]. Sound absorbers based on animal hair fibres showed the best maximum sound absorption values, in all thickness ranges. In the first interval of Table 7, the type of raw material was not relevant to the average SAA, while in the second and third intervals, hair fibre sound absorbers had an average SAA 21 % higher than sound absorbers with avian fibres and non-fibrous components.

Regarding the data obtained in the simulations (Table 4 and Fig. 6), the results for the room with synthetic absorbers and with sound absorbers of animal origin are very close. The room corrected with synthetic sound absorbers complied with VDI 2569:2019 [13] in acoustic class C, while among the alternative sound absorbers, the rooms with wool, camel wool, and CFF nonwoven complied with acoustic classes B, C, and C, respectively. The room with scrap leather in the ceiling (Case 7) did not meet the standard [13] in the example created. A possible reason for this is the material's lack of sound absorption from 125 Hz to 500 Hz. Simulation results displayed in Table 4 show that animal-based waste sound absorbers are as or more efficient at improving room acoustic quality than synthetic materials, making them an alternative for replacing traditional and less sustainable materials. Table 4 shows that for the room with synthetic absorbers the sound pressure level of the receivers positioned 4 m from the sound source ($L_{p,A,S,4m}$) ranged from 45 dB(A) to 48 dB(A), while for the room with alternative absorbers it was 46 dB(A) to 51 dB(A). This means that synthetic materials were slightly more effective at reducing noise than the alternative ones, with an average difference of 2 dB(A). When the distance to the sound source is doubled, the average value of $D_{2,s}$ for the untreated room is 4 dB(A), and for the room with the synthetic and alternative absorbers it is 6 dB(A). In this latter case it is as if the listener perceives the sounds in a free field, where the high sound absorption area has caused a significant dissipation of acoustic energy and therefore very low RT60s. Fig. 6 confirms that synthetic and animal sound absorbers, 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. For the rooms with PU foam (Case 2), glass wool tiles (Case 3), camel wool (Case 5) and CFF nonwoven (Case 6), there is a certain closeness between the RT60 values below 500 Hz, while for the rooms with wool (Case 4) and leather scraps (Case 7), the RT60 is slightly more dispersed above and below, respectively. In this frequency range, the reverberation time of the room with PU foam is slightly lower than that of the rooms with CFF nonwoven and camel wool. This is probably because the foam has a more porous internal microstructure than the other two, which ends up reducing the resistance to airflow and benefits the dissipation of sound energy. In addition, it is possible to use sound absorbers of animal origin and achieve RAC indices higher than C, as demonstrated by the wool absorber, for which the room obtained the best RAC index (B) of the simulated cases in the example.

Acoustic descriptors of offices, whether using traditional or alternative sound absorbers, are influenced by the layout and configuration of the room. Delle Macchie et al. [100] carried out experimental tests and sound simulations to explore the variations in the acoustic parameters of six different types of open-plan offices with different areas and heights that represented the most widespread office types. The results showed that offices with spatial typologies with reduced height and equal floor plan dimensions performed better than offices with large height and poorly proportioned floor plan dimensions.

Non-traditional approaches to creating alternative building acoustic materials have been inspired by living organisms, where the living being itself is the main component of the new material. This is the case with the cultivation of *Pleurotus ostreatus*, a fungal species, on cardboard, office paper and newsprint substrates to produce biodegradable acoustic panels [93]. In other situations, it is the biological structure that living beings have developed to adapt to nature that serves as inspiration for man-made materials. An example is the membrane-type acoustic metamaterial (MAM) proposed by Huang et al. [94], based on a spider's web and designed for broadband low-frequency sound insulation. Huang's bio-inspired model is a lightweight structure consisting of a polymer membrane and a set of resonators in which multi-state anti-resonance modes lead to the suppression of discontinuities at low frequencies, thus widening the attenuation bandwidth of the material.

Table 7
Average and maximum SAA of animal-based waste sound absorbers.

Thickness range (mm)	Hair fibre (46.34 %)		Avian fibre (34.14 %)		Non-fibrous (19.52 %)	
	Avg.	Max.	Avg.	Max.	Avg.	Max.
1–25	0.30	0.60 (24 mm)	0.30	0.41 (25 mm)	0.31	0.31 (10 mm)
26–50	0.67	0.78 (50 mm)	0.56	0.68 (50 mm)	0.55	0.63 (50 mm)
51–100	0.70	0.81 (75 mm)	0.66	0.66 (80 mm)	–	–

Acoustic building materials based on animal waste are potentially scalable for widespread adoption in buildings. Currently, there seems to be growing public interest and enthusiasm for ecological materials and solutions. In addition, many local authorities are already specifying the mandatory use of sustainable building materials in their public tenders, as a strategy to decarbonize the sector and reduce global warming. However, the incorporation of these materials into mainstream construction practices is still incipient relative to traditional acoustic materials, for cultural or economic reasons.

Some of the barriers for the wider use of alternative construction materials, such as the acoustic materials analysed in this work, is the time and economic effort spent in the pre-manufacturing stage of the material, when various preliminary processes are needed to clean and prepare the animal fibres.

A search carried out by the authors on the websites of some manufacturers identified a good number of materials based on wool waste, designed to improve room acoustic parameters associated with reverberation, airborne noise, and impact noise [109,115]. To the best of the authors' knowledge, no commercial acoustic building material with CFF and/or leather waste were found during the search. One possible explanation for the more intensive use of wool waste rather than other animal waste in building acoustics could be that the structure of wool favours the manufacture of nonwovens and knitted structures, due to the inherent ease with which wool fibres interconnect. In addition, CFF is usually coarser and shorter than wool fibres and its processing into textile structures is technically more difficult. The choice or development of new and different manufacturing methods such as electrospinning and 3D printing is an encouraging aspect that could support the large-scale production of these materials and can help overcome some of their disadvantages.

Table 8 shows a comparison between the prices of recycled and non-recycled acoustic materials of the same thickness, used to reduce floor impact noise. Recycled materials are of animal origin (pure sheep wool) and synthetic origin (recycled tar crumb and reconstituted bonded rubber). Materials of purely synthetic origin are polyolefin foam and polyethylene foam.

In the examples shown in Table 8, purely synthetic, non-recycled acoustic materials are less expensive than recycled materials of animal and synthetic origin. Of the recycled materials, the acoustic material made from wool waste had an attractive price, costing less than 50 % of the price of materials recycled from synthetic components. Polyethylene-based material was the cheapest (6.0 euros/m^2) while recycled bonded rubber material was the most expensive (31.0 euros/m^2). Although the data presented in Table 8 do not represent a large sample, and therefore cannot be generalised to any situation, they do show that animal waste-based acoustic materials have a competitive market price and therefore (in this respect) have the potential to expand their applications in construction.

6. Conclusion and research opportunities

In this review, the latest advances in animal-based waste for building acoustic applications have been analysed. An in-depth search of the literature revealed that the topic has been attracting increasing attention in recent years, with most of the scientific output consisting of articles dealing with the physical and acoustic properties of fibrous and non-fibrous materials to see if they can improve the quality of acoustics in buildings. Most of the materials described in the articles analysed here are still at the prototype stage and will need further development to overcome some drawbacks, including fire safety and moisture resistance, and meet certification requirements before their use as normal building materials. The main application of animal waste in construction is related to sound absorption rather than airborne and impact sound insulation purposes. Among sound absorbers of animal waste origin, those based on hair fibres are found most often, and have the best average and maximum sound absorption performances, followed by those based on avian fibres and non-fibrous components. In addition, from the point of view of availability and the economic potential for converting or reusing hair fibres as sound absorbers, it should be noted that the price of sheep wool has fallen a lot, and in some countries, producers are burning it. However, comparing the price of some products in the market reveals that non-recycled acoustic materials tend to be less expensive than recycled materials of animal and synthetic origin. Some of the obstacles to the broader use of alternative acoustic materials analysed in this work are the time and economic effort expended in the pre-manufacturing stage of the material. In the acoustic simulations, when comparing the results for a hypothetical room with animal-based sound absorbers and synthetic sound

Table 8
Recycled and non-recycled underlayers for floor systems.

Material type	Thickness (mm)	Dimensions (m)	Euros/m^2
Pure sheep wool [109]	10	1.00 × 10.0	12.0
Polyolefin foam [111]	10	1.20 × 50.0	11.0
Recycled tar crumb [112]	10	1.25 × 10.0	27.0
Polyethylene foam [113]	10	1.20 × 48.0	6.0
Recycled bonded rubber [114]	10	1.25 × 6.00	31.0

absorbers, it was found that the former were as effective or more effective than the latter in terms of meeting regulatory requirements for noise reduction and reverberation time. However, their fibrillar nature means they perform well at medium and high frequencies but poorly at low frequencies, so future research could focus on this aspect to broaden their scope of use, perhaps in acoustic panels and noise barriers. Other topics that deserve more research include the use of new biopolymer matrices in composites, the combination of different types of animal fibres, and combinations of animal fibres with vegetable and synthetic fibres, to form sound absorbers and sound insulation materials. It is hoped that this work can make a useful contribution towards creating sustainable and high-quality buildings.

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CRediT authorship contribution statement

Marco A. Oliveira: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Julieta Antonio:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

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