Eco-materials with Noise Reduction Properties

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Abstract

Eco-materials employed to reduce noise are used either independently or as components of complex composite materials, which are a growing area of research. These eco-materials have the potential to be used as high-performance sound-absorbing noise isolators in a number of applications in areas such as transportation, architectural, industrial, and construction. Public concern about the environmental impact of transportation is leading to reduced fuel consumption and the use of recycled materials. These are clearly related to the reduction of weight, extending durable years. Currently, the concept of "green" building

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materials is used in practice in several European countries. In addition, public awareness and concern about the negative effects of pollution have led consumers to favor environmentally friendly materials, less contaminating processes, and recycled products. This chapter discusses eco-materials produced for the specific purpose of reducing noise. After an introduction to the subject, a section is devoted to the assessment of sustainable materials. Then, the fundamentals of the sound absorption, airborne sound insulation, and impact sound insulation properties of acoustical eco-materials are presented. The following section reviews common acoustical eco-materials, including those using natural fibers instead of synthetic ones, recycled fibers and surplus materials, advanced mix and composite eco-materials designed to provide better performance and produce lightweight materials that help in reducing fuel consumption and greenhouse gas emissions to the atmosphere, and, finally, green walls and roofs used on top of some buildings. All these eco-materials provide an alternative to chemical building materials, polymers, and other artificial non-sustainable materials.

Keywords

Eco-materials · Natural · Fibers · Green walls · Green roofs · Noise insulation · Sound absorption · Noise · Recycled · Composite · Biodegradable · Multi-layer · Life-cycle assessment · Noise reduction coefficient

Introduction

Since about 1965, the use and variety of available building acoustical materials have greatly increased. This has been due mainly to both increased technology and public awareness and concern about noise in everyday life. In addition, recent issues related to global warming caused by the emission of greenhouse gases into the atmosphere by industrial manufacture of materials may become increasingly important in future world trade considerations. Moreover, the concept of "green" building materials is used in practice in several European countries. In Italy, for instance, many municipalities have introduced specific recommendations into building regulations to increase the use of ecological materials in new constructions, allowing a reduction of construction taxes. These regulations also contain a list of non-sustainable materials that should be avoided (e.g., mineral fibers). Therefore, public awareness and concern about the negative effects of pollution have led consumers to favor environmentally friendly materials, less contaminating processes, and recycled products. In turn, this has led many public bodies and commercial public service operations to realize the benefits of providing good acoustical conditions for their clients by incorporating ecologically friendly materials [1].

The production of synthetic materials contributes to the emission of carbon dioxide (mostly from power plants and transportation), methane, and nitrous oxide. Thus, the total set of greenhouse gas emissions caused directly and indirectly by material production affects its carbon footprint, which may become increasingly important in future world trade considerations.

Although noise control in buildings can be achieved by using heavy screens and vibration isolation, modifying service machinery design, and using floating slabs, the use of sound-absorbing materials is the most common alternative. Architects and engineers can now choose from a wide range of acoustical materials that not only provide the desired acoustical properties but also offer an extremely wide variety of other properties.

Sustainability Assessment and Ratings

Many available materials in the market are labeled as "green" just because they contain small percentages of natural or recycled materials or because they are not harmful to human health. This kind of approach is evidently too simplistic.

Life-cycle assessment (LCA) is recognized as the best approach to assess the real environmental impacts of a product. This procedure analyzes the potential impacts deriving from the entire life history of a product (from cradle to grave). Thus, material extraction, production, transport, construction, operation and management, deconstruction and disposal, recycling, and reuse are taken into account. For designers and decision-makers, LCA analysis results are available as "eco-profiles" like ecoinvent, BRE Eco-Profiles, and eco-indicators [2]. Standard eco-indicators are numbers that express the total environmental load of a product or process. Thus, with these eco-indicators, any designer or product manager may analyze the environmental loads of products over the lifecycle.

ecoinvent is a Swiss LCA database that takes into account various impact assessment results: cumulated energy demand, non renewable energy fraction, global warming potential, and acidification power. A comparison based on the ecoinvent database between the environmental impacts of some traditional and innovative, natural sound insulation materials from cradle to grave is shown in Table 1. It can be observed that cellulose, flax, and sheep wool have the lowest impacts on the considered categories.

BRE Eco-Profiles is used in the United Kingdom for assigning a score (in "eco-points") to a product or a process. The score is calculated by weighing normalized impacts on climate change, acid deposition, eutrophication, eco-toxicity, ozone depletion, mineral extraction, fossil fuel extraction, human toxicity, waste disposal, and transport pollution.

Eco-indicator 99 is also used as an indicator by weighing various forms of potential damage, including potential damages to human health, expressed as number of life-years lost and/or lived with disability; to ecosystem quality, expressed as the loss of species in a certain area in a certain time; and to resources, expressed as the energy surplus needed for future extractions of minerals and fossil fuels.

Other ratings concerning eco-materials have been developed as labels (e.g., natureplus and Ecolabel), and they provide guidance to consumers about those materials that have been produced in an environmentally friendly way, do not represent a health risk, and assure that a significant part of the product has been manufactured using renewable and/or mineral raw materials.

On the other hand, the available energy that was used in the work of making a product is called the embodied energy. This is an accounting methodology that aims

Table 1 ecoinvent. Comparison of environmental impacts of natural and traditional acoustical materials [2]

Material		Density (kg/m^3)	Non renewable energy (MJ/kg)	Global warming potential (kg CO_2 eq.)	Acidification potential (kg SO_2 eq.)
Natural	Natural rubber	6.4	40	2.4	0.0086
	Coconut fibers	50	42	0	0.0250
	Flax fibers	25	4.4	0	0
	Sheep wool	30	12.3	−0.3	0.0046
	Cellulose flocks	35–70	4.2	0.2	0.0025
Traditional	Expanded polystyrene	30	95	2.3	0.0201
	Foam glass	130	67	3.7	0.0229
	Fiberglass	34	43	2.1	0.0155
	Mineral wool	50–60	17	1.2	0.0052

to find the total sum of the energy necessary for an entire product lifecycle, including raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction, and/or decomposition [2]. Although there is a general consensus that embodied energy can be used to compare the amount of greenhouse gas released during the production of a product, scientists have not yet agreed on absolute universal values. This is due to the large number of variables to take into account. Some natural materials, such as cellulose flocks or cotton, show very low values of embodied energy, while expanded polyethylene and polyurethane exhibit the highest values. It should be noted that some natural materials (e.g., wood fibers) report values of embodied energy as high as those of synthesized materials.

Acoustical Characterization of Eco-Materials

It is well known that every material has acoustical properties. However, an acoustical material is defined as one specifically designed to have a high acoustical performance. The acoustical performance of a material is usually related to its sound absorption, airborne sound insulation, and impact sound insulation properties. The characterization of these properties is independent of the sustainability of the material.

Sound Absorption

The great majority of sound-absorbing materials, independent of the composition, are of the porous and/or fibrous type. There are many studies about the absorption mechanisms of the acoustic energy in the interior of porous materials, differentiating the distinctive mechanisms in function of the type of pore of which the material is composed [1]. Based on their microscopic configurations, porous materials can be classified as cellular, fibrous, or granular.

When a porous material is exposed to incident sound waves, the air molecules at the surface of the material and within the pores of the material are forced to vibrate and, in doing so, lose some of their original energy. This is because part of the energy is converted into heat due to thermal and viscous losses of air molecules at the walls of the interior pores and tunnels within the material. At low frequencies, these changes are isothermal, while at high frequencies, they are adiabatic [3].

Several studies have proposed empirical and theoretical models to interpret the acoustic behavior of porous sound-absorbing materials. Many of these models are based on determining the characteristic wave impedance and the propagation constant of a plane wave traveling inside the absorbing material, both in function of the frequency, given the physical properties of the materials, such as the porosity, tortuosity, or airflow resistivity.

Although the models can be phenomenological or microstructural, the empirical models have reported simple yet accurate prediction results in most of the practical cases [4]. In a seminal study on glass fibers and mineral wools developed by Delany and Bazley [5], simple power-law relations obtained by curve-fitting a large amount of experimental results were presented. The success of their model is explained because it only requires the knowledge of the airflow resistivity as the input parameter, which can be readily determined from sampling measurements. This empirical model was analyzed later by Miki [6, 7]. Other authors have recently used the same relations and calculated the corresponding regression constants for different natural materials [8].

Empirical models have been subsequently applied for characterizing polyurethane foams, plastic open-cell foams, textile fibers, different vegetal fibers, loose cellulose, and recycled polyester fibers [9–11]. In fact, the European standard on building acoustics [12] recommends the use of the Delany and Bazley [5] regression coefficients for the prediction of the sound absorption of materials made up of fibers and the Dunn and Davern [9] results for foam materials. Voronina [13] has characterized sound-absorbing materials from parameters such as tortuosity and structure factor associated with either the fibers or the pores layout. Oliva and Hongisto [14] have presented a comprehensive study on the accuracy of several empirical approaches for predicting the impedance of mineral wool configurations.

Allard and Champoux [15] presented a model derived from a more rigorous theoretical basis. Although this model is applicable to fibrous materials, its range of validity extends further than that of Delany and Bazley [5]. A generalized model for sound propagation over a wide frequency range is the so-called Johnson-Champoux-Allard model, which introduces the viscous and thermal characteristic lengths as parameters [15, 16]. These parameters are usually complex to measure, although some reliable inverse methods based on standing wave tube measurements have been presented [15, 16].

An important body of research has been presented on measuring techniques to obtain acoustic material properties such as porosity, airflow resistivity, tortuosity, and sound absorption coefficients. The experimental results are often used to provide information for validating and calibrating computational methods used to predict the performance of acoustical materials and multilayer systems.

Sagartzazu et al. [17] have presented an extensive review on the experimental techniques for characterizing sound-absorbing materials. Porosity has been measured through scanning electron microscope and ultrasound. However, a more direct way to measure this quantity is to employ a porosimeter such as the one devised by Champoux et al. [15]. In this technique, which is based on the ideal gas law, the isothermal pressure change in a closed volume containing the sample material is measured for a known change in volume.

Although alternative methods have been devised for measuring airflow resistivity [18], the standardized testing procedure is based on the passing of steady-state airflow through a sample according to the recommendations provided in the ISO standard [19]. Airflow can be created by a custom-made pump-controlled water column [17].

Measurement of sound absorption can be done using a reverberation room that meets the requirements of the standard ISO 354 [20]. The sound absorption is obtained from the change in reverberation time with and without a material sample. However, to apply this method, a large material sample is required, which can be expensive for testing material prototypes. On the other hand, normal incidence quantities can be determined using a standing wave tube. This technique guarantees a highly reproducible testing condition and a very convenient testing setup, especially when it is impractical to secure large samples for accurate random-incidence measurements in a reverberation room. In general, the method involves the measurement of the transfer function between the signals of two microphones mounted flush on the wall of a standing wave tube when a random stationary signal is produced inside the tube. This method has been standardized by ISO 10534-2 [21]. At low frequencies, large tubes may be required, and thus some alternative methods have been developed for measuring sound absorption [22].

Another parameter, which is often used to assess the performance of an acoustical absorber, is the single number known as the noise reduction coefficient (NRC). The NRC of a sound-absorbing material is given by the average of the measured random-incidence sound absorption coefficients for the 250-, 500-, 1000-, and 2000-Hz octave bands. This NRC value is often useful in the determination of the applicability of a material to a particular situation.

Airborne Sound Insulation

Sound absorbers are very often confused with sound insulator materials. Although sound absorption materials are used as components of multilayer composite panels, sound insulation requires the reduction of the sound transmitted through the structure, which is assessed by its transmission loss, TL in dB. In general, high bulk density panels provide high values of TL. However, there are practical limits to the use of increasing mass as a control measure.

Evidently, materials used for subdivisions in dwellings and tall buildings must have high values of sound insulation and reduced structural weight to be acceptable. In this sense, research on composite systems has received as much attention as acoustical materials (see section "Mixed and Composite Materials").

The transmission loss of a partition is usually measured in a laboratory by placing the partition in an opening between two adjacent reverberant rooms designed for such tests. The test procedure is described in relevant standard publications [23]. The ISO method of determining a single number (the weighted sound reduction index, R_w) to describe the sound transmission loss characteristic of a construction is outlined in Part 1 of ISO 717 [24]. Parts 2 and 3 of ISO 15186 [25] describe field and laboratory methods to measure TL, using sound intensity. A different method for testing transmission loss of material prototypes is based in the work by Song and Bolton [26]. This method provides the determination of the normal incidence sound transmission loss and related acoustical properties of a small sample using a four-microphone standing wave tube, where parameters are calculated from the transfer matrix representation. This method has been currently standardized by ASTM [26], but no ISO equivalent standard has been issued. Although this method does not represent the real transmission loss in a diffuse sound field, it is quite useful for testing small material prototypes in a fast and inexpensive way.

Impact Sound Insulation

On the other hand, the ability of a construction such as a floor or ceiling to prevent transmission of impact noise such as footsteps is quantified in terms of its impact isolation. This is measured using a standard tapping machine that should conform to the specifications of ISO 10140-3 [27] or ISO 16283-2 [28]. From this measurement, a single number for impact insulation can be determined [29]. Several studies have proven that the ability of a layer to reduce impact noise is closely related to the dynamic stiffness of the material, although practically no detailed information has been found in most acoustic material literature on their dynamic properties.

The dynamic stiffness as defined in the standard ISO 9052-1 [30] is equal to the apparent dynamic stiffness for closed-cell absorbing materials or when the airflow resistivity value is large. The method is based on the resonance frequency measurement of the fundamental vertical vibration of a mass-spring system formed by the sample material placed between a steel square load plate and an isolated base [30]. Typical values of dynamic stiffness per unit area of resilient materials range from 10 MN/m^3 (rock wool 30-mm thick and 60 kg/m^3) to 28 MN/m^3 (glass wool 13-mm thick and 36 kg/m^3). Pavoni Belli et al. [31] have presented a simple equation to estimate the impact sound reduction index, ΔL_w in dB, from measured values of dynamic stiffness.

Acoustical Eco-Materials

Most eco-materials used in noise control can be divided into four main categories: natural materials, recycled materials, mixed and composite materials, and green walls and roofs.

Natural Materials

The use of natural materials instead of nondegradable man-made ones produces environmental benefits that have been recently identified and contributes to achieving better sustainability of buildings. The more natural and less treated the materials are, the higher they generally perform in terms of energy saving. The use of native and/or vegetative materials should be preferred to reduce energy consumption during transport and to maximize the embedded carbon dioxide. In addition, during their growth, these materials help to limit our impact on climate change. Some of the disadvantages of natural materials that are known include limited fungus and parasite resistance and limited fire resistance in comparison with some traditional, synthetic materials. For this reason, in practical cases, natural materials may require chemical treatments that may reduce their sustainability rating.

In past years, many natural materials have been developed and tested for acoustical applications. In the technical literature, sound absorption and thermal conductivity have been the main properties that have been investigated, although airborne and impact sound insulation have been more recently determined for eco-materials. These properties are summarized in Table 2 for some natural materials, compared to some traditional materials. A comprehensive review about thermal properties of insulation materials for the building sector has been presented by Schiavoni et al.

Table 2 Acoustic and thermal properties of some natural and traditional insulating materials [2]

Material		Thermal conductivity (W/mK)	Sound absorption coefficient at 500 Hz	Index of reduction of impact noise ΔL_w (dB)
Natural	Hemp	0.04	0.6 (300 mm)	–
	Kenaf	0.044	0.74 (50 mm)	–
	Coconut fiber	0.043	0.42	23
	Sheep wool	0.044	0.38 (60 mm)	18
	Wood wool	0.065	0.32	21
	Cork	0.039	0.39	17
	Cellulose	0.037	1 (60 mm)	22
	Flax	0.040	–	–
Traditional	Glass wool	0.04	1 (50 mm)	–
	Rock wool	0.045	0.9 (50 mm)	–
	Expanded polystyrene	0.031	0.5	30

[32]. In the following, a description of and discussion on the advances made related to natural materials used in noise control are presented.

Natural fibers have been used for many years as a source of raw material to produce porous sound-absorbing and sound-isolating materials. Natural fibers are essentially completely biodegradable, and modern technical developments have made natural fiber processing more economical and environmentally friendly. These new methods may result in increased use of high-quality fiber at competitive prices for industrial purposes. The properties of natural fibers can be modified by pretreatments such as drying, carbonizing, impregnation, and mineralization. In addition, natural fibers are also safer for human health compared with most mineral synthetic fibers, since they do not need precautions in handling [1].

An important microscopic parameter of a fiber is its diameter. The fiber diameter is directly related to the sound-absorbing characteristics of the material. Table 3 shows a comparison of the average fiber diameters of several types of natural fibers commonly used to manufacture eco-materials. In general, the diameter of natural fibers tends to be larger than the diameter of synthetic fibers obtained by extrusion. Figure 1 shows the comparison between three natural fibers and a polyester fiber. Natural fibers have more irregular shapes and variable diameters compared to synthetic fibers. Thus, materials made of natural fibers are usually characterized by a large dimensional variability of their constituting fibers.

In general, natural fibers have been proven to contain many connected air cavities that are the major contributors to sound energy absorption and possess a multi-scale structure [33]. This fact was previously observed by [34] in a cell wall of a *sisal* subfiber, which was made up of millions of nanofibers. This fine morphology

Table 3 Typical average fiber diameter for several natural fibers

Fibrous material	Fiber diameter (μm)
Cotton	8–33
Coir	156–370
Kenaf	21–78
Hemp	5–94
Coconut	250
Wood	5–38
Wool	14–63
Flax	3–22
Bagasse	20
Ramie	24–37
Bamboo	90–425
Raw wool	37.1
Rice paddy	8–20
Sisal	213
Sugar cane	11–23
Jute	5–81
Quill (pulverized)	10–40

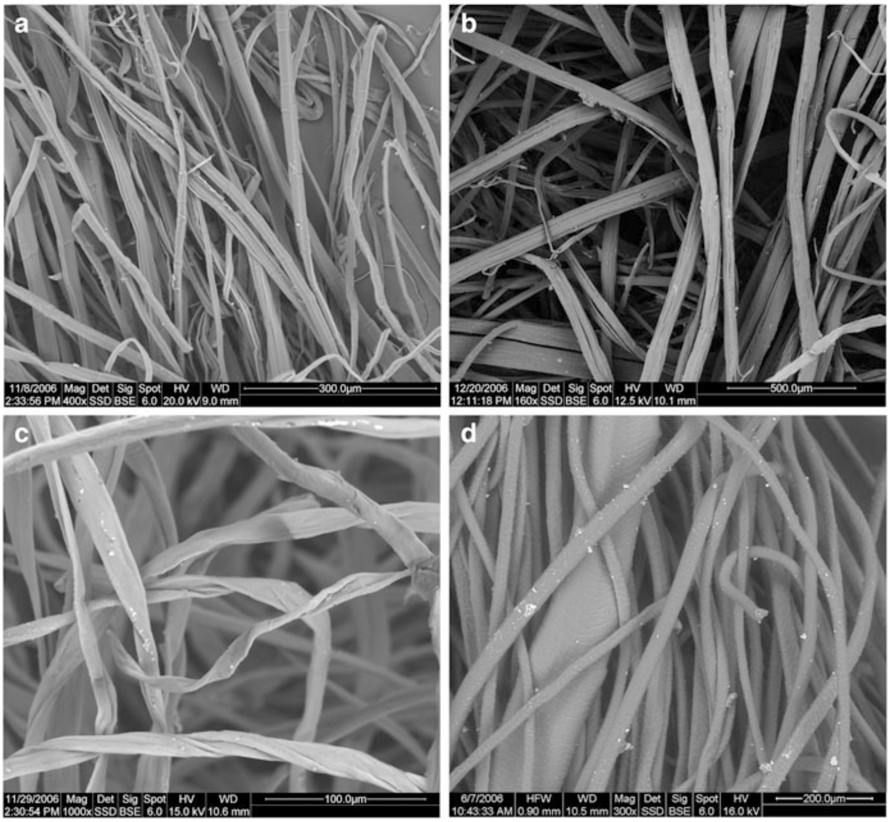

Fig. 1 Scanning electron microscope images of samples of (**a**) hemp, (**b**) kenaf, (**c**) cotton, and (**d**) wool. Images courtesy of J. Alba and R. del Rey (Universitat Politecnica de Valéncia, Spain)

increases the friction between sound waves and internal cell walls, leading to higher values of sound absorption. Figure 2 shows some scanning electron microscope images of samples of sisal and fiberglass [33].

Acoustical properties of *wool* were first reported by Ballagh [35]. He concluded that useful acoustical performance can be obtained for relatively thick layers of wool material. In addition, he presented measurements showing that woolen materials can increase the transmission loss of stud walls by 6 dB or more.

Acoustical properties of different types of *bamboo* fibers have been investigated. A sound-absorbing material made of Japanese bamboo fibers was discussed by Koizumi et al. [36]. They reported that fiber size was shown to be an important parameter that significantly changes the absorption. In addition, they showed that this material has a similar sound absorption coefficient to one of the same thickness made of glass wool. Acoustical properties of particleboards for building construction materials made from Indonesian betung bamboo were presented by Karlinasari et al. [37]. They found that increasing the board thickness produces an

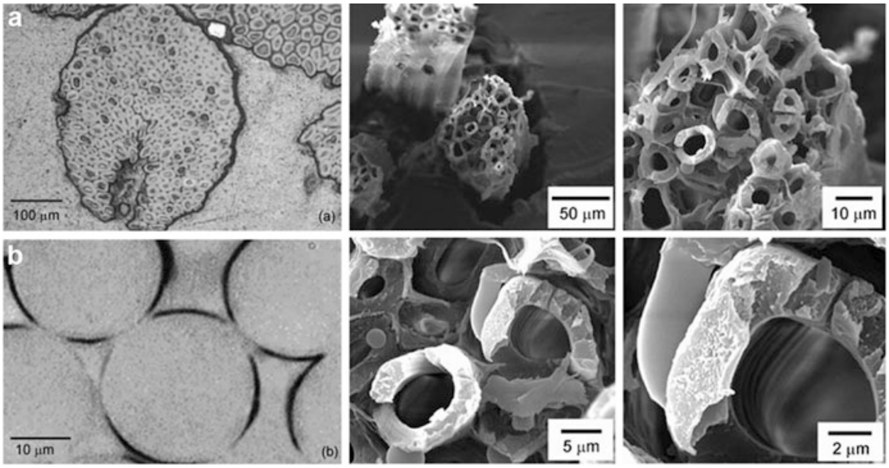

Fig. 2 Scanning electron microscope images of samples of sisal. Left: Cross-section morphology of (**a**) sisal fiber and (**b**) fiberglass. Right: Multi-scale and hollow lumen structure of sisal fibers at different magnification factors (Reused from [33] with permission from Springer)

increase in the transmission loss of the board and that the panel has good potential for the development of insulation boards in wood frame construction. Similar results were reported in 2008 for panels made from a *rice straw* composite (in the work by C.E. Mediastika, cited by Karlinasari et al. [37]).

Zulkifli et al. [38] compared the sound absorption characteristics of *coir* and *oil palm* fibers, reporting similar properties. Glé et al. [39] reported the acoustical properties of materials made from vegetable particles with different porosities, in particular high-porosity *hemp* concrete resulting from the mixture of hemp particles, a binder, and water. A number of sustainable sound absorbers from the biomass were tested by Oldham et al. [10], including *cotton*, *wool*, *jute*, *sisal*, *flax*, and *ramie* fibers.

Electrospinning is one of the most common techniques of extracting nanofibers from polymer solutions and gathering them to form nonwoven nanotextiles that can be used to form a highly porous mesh with potential sound absorption characteristics. A relatively new porous material created from nanofibrillated *cellulose* is called nanopaper. This material is made of very thin fibers (long nanowires of 10 to 40 nanometer in diameter). A homogeneous distribution of the fibers and high mesh porosity produces a very strong material. Sehaqui [40] produced a lightweight porous nanopaper that has mechanical properties similar to those of thermoplastics but with a much lower density. These properties make nanopaper an interesting choice as a sound absorber, although there is scarce information about its sound absorption properties. Nanopaper is hygroscopic since it is a cellulose-based material, which can negatively affect some of its mechanical properties at high humidity levels. However, Arenas et al. [11] reported that in general, no significant change in sound absorption is observed with respect to relative humidity (up to 69%) at room temperature for a loose, unbleached cellulose layer. These results are in agreement with those reported in previous studies, indicating that no significant change in sound absorption is generally observed with respect to relative humidity at room temperature for wood-based materials. It is noted that practical applications of nanopaper are still in development.

Zheng et al. [41] studied the sound absorption effects of yarn sizes, fiber diameters, and hybrid stacking of different fibers. They have shown that with thicker fabric yarn and bigger fiber diameter, better sound absorption properties can be obtained in natural fiber-reinforced sandwich structures.

Assemblies of *kapok* fibers (also called Java cotton) were analyzed by Xiang et al. [42]. They concluded that continuously increasing the bulk density decreases the sound absorption and that there is an optimal density for obtaining the best possible noise reduction. Faustino and his collaborators [43] studied a sustainable low-technology *corncob* particleboard. The acoustic insulation provided by this board was comparable to traditional materials used for building purposes, such as glass wool. The use of mechanical *wood* fibers for acoustical applications has been investigated by other authors [44].

Lightweight expanded *clay* aggregate (LECA) consists of small, lightweight, bloated particles of burnt clay. Thousands of small, air-filled cavities give LECA very good strength and thermal insulation properties. The material presents a relatively high open porosity (50–70%), which provides high values of acoustic absorption. In fact, a sound absorption coefficient close to or above 0.8 has been observed in a sample of LECA material of thickness 50 mm and grain smaller than 2 mm [45].

Hemp is one of the most important natural fibers. Hemp crops require virtually no chemicals during their production, since they are naturally resistant to most pests. On the other hand, cotton accounts for approximately 50% of all pesticides and herbicides used in US agriculture today. In addition, hemp produces significantly more fiber per square meter than cotton or flax and uses less water to grow. Hemp fiber is naturally antimicrobial and resistant to ultraviolet light, mold, mildew, and insects, which makes it of potential use in outdoor applications [1]. The sound absorption coefficient of material samples made from hemp reeds and batts has been evaluated in a reverberation room [10]. The researchers reported that a 50-mm layer of reed and a 70-mm layer of hemp are sufficient to obtain a sound absorption coefficient above 0.8 at frequencies higher than 160 Hz. The acoustical properties of mixes of hemp particles have been studied by Glé [46]. A study on the sound absorption of vegetal wools made of flax and hemp with a small proportion of polymer fibers for cohesion has been published recently [47].

Kenaf is a hibiscus plant related to cotton and okra. Its fibers have been used to strengthen concrete and other composite materials for construction applications and for materials used in the automotive industry. Measurements of sound absorption of kenaf samples have also been reported. One study showed that a 50-mm-thick sample of density 50 kg/m^3 exhibits average sound absorption coefficients equal to 0.65 in the 100 Hz to 500 Hz frequency range and 0.85 at frequencies between 500 and 5000 Hz. Good agreement has also been reported between experimental and predicted normal incidence sound absorption coefficient values of kenaf fiber samples.

Flax is a very important natural fiber widely used in the textile industry. This fiber is stronger than cotton fiber but less elastic. In the textile industry, long, high-quality fibers are obtained from about 20% of the plant mass. The rest is considered a low-cost surplus waste. Studies have shown that the shortest fibers (above 15% of the plant mass), also called flax tow, can be recovered and used as raw material to produce an eco-material for sound absorption and thermal insulation.

Sisal is a member of the agave family, and its fiber is extracted from the leaves of sisal plants which grow best in hot and dry areas. Sisal fiber is biodegradable, and almost no pesticides or fertilizers are used in its cultivation. Production of sisal fiber also causes a considerable amount of agricultural waste because sisal fibers shorter than 65 mm cannot be used in the textile industry. Results of sound absorption of an absorbing panel made of sisal fiber and a water-based binder were presented by Azevedo [48]. The panel had a thickness of 50 mm and a density of 140 kg/m^3. Sound absorption coefficients greater than 0.8 were measured for frequencies above 800 Hz.

Figure 3 shows the results of sound absorption as a function of frequency for some natural and synthetic fiber 40-mm-thick material samples measured in an impedance tube [33]

Recycled Materials

In the last few years, research on the use of eco-materials that come from residues, either from industrial plants or processes, has received much attention [2, 49]. It is well known that recovered materials and the use of environmentally friendly materials for noise control will be increased in the future. There are many examples of

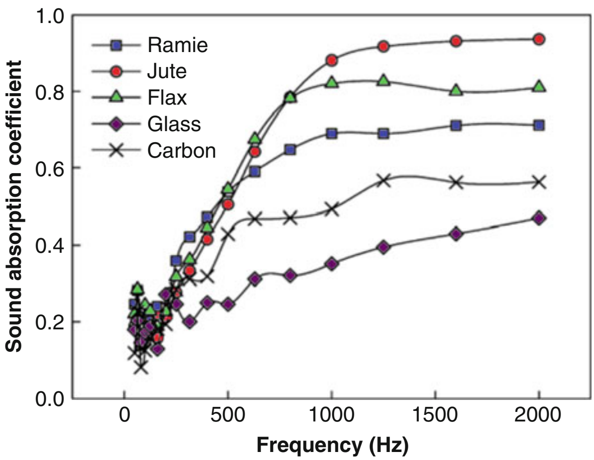

Fig. 3 Normal incidence sound absorption of some natural and synthetic fiber materials (thickness of 40 mm) (Reused from [33] with permission from Springer)

recycled eco-materials. A number of authors have presented studies on the sound absorption and sound insulation properties of this type of materials.

Alba et al. [50] have used a numerical inverse method to obtain fiber characteristics of materials. Sound absorption properties of different materials made from ground polyurethane foam waste were studied by del Rey et al. [51]. In their work, the sound absorption coefficient of six samples with different values of the bulk density (224 kg/m^3 for the denser, 61 kg/m^3 for the less dense) was measured. The results of the measurements evidenced that the sample with a lower bulk density had a higher value of the sound absorption coefficient, but more complex frequency dependence in the sound absorption coefficient was observed. In addition, the acoustical characterization of this recycled material was done by curve-fitting a large number of experimental results. The model developed, converged, and presented acceptable results for predicting the sound absorption coefficient of this recycled material.

More recently, sound absorption properties of inorganic polymeric foam with different thicknesses and densities were studied by Hung et al. [52]. Aluminum foams that could be recyclable and fabricated by an infiltration process were studied by Li et al. [53]. They measured the normal incidence sound absorption coefficient of this metal open-cell structure and showed that the sound absorption coefficient increases with an increase in the number of pore openings in the unit area or with a decrease in the diameter of the pore openings in the range of 0.3–0.4 mm.

Sun et al. [54] presented a study on the acoustical and thermal properties of glass fibers recovered from waste printed circuit boards. They showed that the sound absorption ability of this material can meet the requirement of national standards over a wide frequency range. Sedeqq et al. [55] investigated the sound absorption properties for recycled fibrous materials, including natural fibers, synthetic fibers, agricultural lignocelluloses' fibers, and biocomposites from *agricultural wastes*. Their results have indicated that recycled fibrous materials have good sound-absorbing properties and are inexpensive, lightweight, and biodegradable.

More recently, the acoustical characterization of unbleached *cellulose* obtained directly from pine through the kraft pulping process has been investigated. The corresponding regression coefficients for loose-fill cellulose were determined by means of an iterative method based on a minimization of a quadratic error function [11]. The results showed that this recyclable material could be a viable alternative to conventional materials for current and future applications in building construction, in particular when used as insulation in attic areas, under floors, and in wall cavities.

An insulating material made from *waste newspapers* and magazines with heat insulation and sound absorption properties was also developed by Yeon et al. [56]. Physical and mechanical properties of cardboard panels made from used beverage cartons with a veneer overlay were examined by Ayrilmis et al. [57]. More recently, Asdrubali et al. [58] investigated the thermal and acoustical properties of corrugated cardboard panels made from waste paper. These panels are commonly used in the packaging industry and are completely recyclable in their turn. Their results showed that cardboard panels reported good performance in terms of acoustic and thermal insulation, slightly lower than commonly used insulation panels. They noticed that the absence of any raw material in the panel manufacturing leads to promising performance in terms of life-cycle environmental impact (cradle to gate approach). In addition, the characteristic internal geometry of the panels guarantees a very low density with respect to packed cardboard panels and a reliable resistance to being compact and self-supporting.

A research study dealing with impact sound reduction of underlays made of recycled materials has been conducted by Rushforth et al. [59] concerning *carpet waste*. The material is composed of fibrous and granular parts.

Recycled tire granules have been recently proposed for manufacturing acoustic insulating and absorbing materials, to be used for noise control in buildings and road barriers. Materials made of rubber crumbs usually have high porosity, and they consequently show good sound absorption properties over a wide frequency range.

The development of novel acoustical materials made from end-of-life tires can possibly be a solution for the disposal of these materials, preventing them from going to landfills. The largest reuse market is tire-derived fuel, followed by civil engineering applications such as highway embankments; however, the production of rubber crumbs is growing, and the subsequent applications are gaining importance. Since the grains themselves show no mechanical strength, it is necessary to mix them with an adequate binder and to consolidate the compound in order to create a solid structure. The parameters that mainly influence the properties of this kind of material are grain size, binder type and concentration, compaction ratio, and final thickness. The damping loss factor is also an important parameter that describes the amount of the internal mechanical damping of an impact isolation layer.

Pfretzschener and Rodriguez [60] were among the first to demonstrate that recycled rubber products show excellent broadband acoustic absorption. Horoshenkov and Swift [61] provided a comprehensive description of the sound absorption properties of both loose and consolidated rubber crumbs. Sobral et al. [62] correlated the sound absorption properties of bound rubber crumbs with the mechanical ones. Hong et al. [63] studied improved acoustical performance by combining double-layer structures of rubber particles with porous materials and perforated panels, obtaining acceptable sound absorption properties. In addition, sound-absorbing materials made of recycled rubber crumbs have been used in traffic noise barriers, mainly due to their durability and broadband sound absorption [16]. A material made using various amounts of bio-binders with tire shred residue as the filler was presented by Khan et al. [64]. The Johnson-Champoux-Allard model was used to predict the sound wave propagation in this low-cost sustainable material that showed high acoustical performance.

A sound-absorbing material made from various types of industrial waste and *ball clay* was presented by Garcia-Valles et al. [65]. These types of waste included slag from the aluminum recycling process, dust from the marble industry, foundry sands, and recycled expanded polystyrene from recycling packaging. They showed that the material has good heat resistance and fireproofing due to its ceramic structure. The sound absorption of the material was measured using the impedance tube method, reporting a sound absorption coefficient higher than 0.9 in a narrow frequency range between 400 Hz and 600 Hz. It should be observed that for frequencies lower than

300 Hz and between 1200 and 1400 Hz, the sound absorption coefficient is less than 0.55, while no data are available for frequencies higher than 1400 Hz.

One of the most common types of litter in the world is cigarette butts. A recent study has reported the sound absorption characteristics of the cellulose acetate recovered from used cigarette filters [66]. The study showed that materials made of this waste fiber can be used as alternative to commercially available sound-absorbing materials made of synthetic fibers. However, further research is needed to treat the potentially harmful constituents of this recycled material.

Mixed and Composite Materials

These types of materials are made of both natural and conventional materials. In mixed materials, the sustainable material and the conventional one are simply mixed to create a new material. On the contrary, in composite materials, a natural fiber is, for example, chemically linked, thanks to a coupling agent, to a polymer, that made creating a composite possible. The percentage of natural fibers in mixed and composite materials is generally high, and for this reason, they can be considered eco-materials. In addition, these composite materials are usually designed to be lightweight, which is a very important requirement in the transportation industry for manufacturing airplanes, automobiles, etc. Reduction of weight can considerably reduce fuel consumption, a key issue for reducing greenhouse gas emissions to the atmosphere.

Lightweight and biodegradable composites made of activated *carbon fiber* exhibit high-performance and cost-effective properties. Other researchers have studied particulate-filled polymer composites to increase sound insulation characteristics by adding calcium carbonate [67].

A very common design of a sound-isolating panel is a barrier typically made up of a perforated cover plate enclosing a core of a porous absorbing material and air gaps [68]. Recycled materials can also be used as core elements of these barriers. Mechanically pulled waste clothing, known as shoddy, has been used to produce porous nonwoven fabrics. Nonwovens made of recycled fibers that are used in laminated components incorporate thermoplastic fibers to allow molding to conform irregular automotive shapes [69].

Some multilayer composites are developed in the form of sandwich structures and honeycomb panels. Natural material-based sandwich composites are suggested as environmentally friendly alternatives to common materials. Sargianis et al. [70] studied the acoustic response and damping properties of sandwich composite beams composed of natural materials (natural fiber composite face sheets of bamboo and cotton with vinyl ester resin) and compared them to commonly used traditional sandwich composites. They found that the natural fiber-based composite materials exhibited superior acoustical performance, with minimal sacrifices in stiffness-to-weight ratios. The same observation has been made by Rao et al. [71] for honeycomb cores used in sandwich panels. More recent work on the sound absorption properties of flax/epoxy composites compared with glass/epoxy composites has been presented by Lee et al. [72].

Hoodliner is very important for reducing engine noise and structure-borne vibration in automotive applications. In the past, hoodliners were made of a bulk fiberglass mat covered with a protective PVC film. Higher standards in noise reduction and fuel consumption have led to the development of composite multilayer structures for this purpose. These structures are made of a combination of both conventional or recycled fibers and micro textiles designed to conform irregular shapes of the engine compartment of a specific vehicle. These textiles can be treated to add water and oil repellent properties. A common multilayer alternative used for reducing engine noise is made of a fibrous felt sandwiched between two layers of heat-resistant resin-impregnated nonwoven [69]. A blended sisal-kenaf composite with an acrylonitrile butadiene styrene matrix has been recently suggested for potential use for automotive applications [73].

Studies on innovative materials made of honeycomb-like structures composed of many tiny tubes or channels have been reported. A prototype micro-channeled material [1] composed of metallic *nanotubes* has been developed to reduce noise in aircraft, although its sound absorption performance is still under study. More recently, nonwoven sandwich structures have been tested by Liu et al. [74]. They used a general regression neural network for predicting their acoustical properties from some easily measured structural parameters. They showed that the method is reliable and efficient. On the other hand, the improvement of the sound absorption properties of polyurethane foams by adding nanoparticles has recently been reported in the literature [75].

The sound absorption properties of *cork-gypsum* composites have been studied by Hernández-Olivares et al. [76]. They determined that this composite cannot be considered a good sound absorber for building applications unless perforations are made in the material. Zulkifli et al. [77] and later Fouladi et al. [78] developed a panel made from multilayer *coir* fibers. The resulting panel achieved an average transmission loss of 20 dB between 500 and 1000 Hz.

A study on the normal incidence sound absorption provided by three types of natural fibers (ramie, flax, and jute) and their composites was presented by Yang and Li [33]. They compared their results with those of synthetic fibers and their composites. It was found that both natural fibers and their composites achieve excellent performance for noise reduction applications when compared to synthetic fibers and their composites. They concluded that multi-scale and hollow lumen structures of natural fibers contributed to the high sound absorption performance. Sound absorption coefficients of these natural fibers were also calculated by two classical empirical models (Delany-Bazley and Garai-Pompoli). Although these models were originally developed for glass and polyester fibers, they showed good agreement with the experimental data.

Another recent development is the production of *wood-plastic composites* (WPC). This term refers to any material made by mixing plant fiber (cotton, jute, kenaf, etc.) with thermosets or thermoplastics. Thermosets are plastics that once cured cannot be melted by reheating. Examples of thermosets are the resins. Thermoplastics are plastics that can be repeatedly melted. Examples of thermoplastics are polypropylene, polyethylene, and polyvinyl chloride. Kenaf is one of the most acoustic performing fibers used in WPC for automotive nonwoven fabrics. Materials for thermal isolation and acoustic absorption made from a mixture of natural kenaf fibers, polyester fibers for strengthening, and a natural fireproof product are currently available commercially. Zhu et al. [79] have also presented a new technology for sound insulation using a plastic composite filled with natural fibers.

The sound absorption properties of industrial *tea-leaf* fiber waste material were studied by Ersoy and Kucuk [80]. Later, a study about the improvement of sound absorption properties of polyurethane foams by adding natural tea-leaf fibers was presented by Ekici et al. [81].

Feathers are a surplus residue from the poultry industry, and they pose an environmental challenge. Several studies have been aimed at using *feather fiber* to produce composite materials. Mechanical and sound absorption properties of composites made from chicken feather fiber (FF) and high-density polyethylene/polypropylene (HDPE/PP) fiber have been investigated and compared with pulverized chicken quill and jute composites [82]. The results have shown that the sound absorption provided by FF composites is similar to that of quill but 125% higher than that of jute, although the mechanical properties were inferior to the latter two. In ground form, FF and jute composite properties are similar.

Moreira da Silva et al. [83] have manufactured and tested multilayer panels made from *coconut and foam*. They reported sound absorption coefficients greater than 0.9 at around 1500 Hz. Other authors have made composite materials by mixing natural fibers (cotton, wool, jute, hemp, kenaf) and recycled polymers [84].

Sound and vibration damping properties of flax fiber-reinforced composites have been presented by Prabhakaran et al. [85]. They found that the sound absorption of the flax fiber-reinforced composites is 21%–25% higher than that of glass fiber-reinforced composites. On the other hand, flax fiber-reinforced composites exhibit 51% higher damping and 33% less weight than glass fiber-reinforced composites. The sound absorption of a nonwoven 10-mm-thick composite material that is based on a hot-pressed mix of flax and polymer fibers has recently been measured by Yakimovich et al. [86].

Table 4 shows some properties of eco-materials produced for impact noise control applications.

Green Walls and Roofs

Research on green walls and green roofs has received attention in recent years. A green roof is a system based in the covering of the upper surface of a building with a layer of living vegetation. Green roofs have been classified into three types: (1) intensive (substrate layer with a depth of more than 150 mm), (2) extensive (substrate layer with a maximum depth of about 150 mm), and (3) semi-intensive (a combination of the first two).

Green roof technology has mainly contributed to reduce the energy demand of a building. However, this technology also has other significant environmental benefits such as reducing air pollution, mitigating the heat island effect, reducing the storm

Table 4 Some eco-materials with impact noise reduction properties

Material	Density (kg/m^3)	Thickness (mm)	Dynamic stiffness (MN/m^3)	Impact sound reduction index ΔL_w (dB)[a]
Polyester (80% recycled PET)	100	8	15	34.8
Polyester (80% recycled PET)	50	30	1.8	48
90% Kenaf, 10% polyester	100	10	5.2	41
90% Kenaf, 10% polyester	200	4	18	33.6
25% Wool, 10% cotton, 20% polyester, 15% polypropylene, 30% other textile fibers	250	3	14	35
Recycled tires (1–2-mm-thick crumbs), 13% binder concentration	636	8	86	23.5
Recycled tires (3–5-mm-thick crumbs), 13% binder concentration	645	8	73	24.7
Recycled carpet shred (40/60 fiber/grain), 10% binder concentration	366	30	28	30.8
Recycled carpet shred (40/60 fiber/grain), 50% binder concentration	180	30	23.6	31.9

[a]Considering a floating floor with a surface mass of 200 kg/m^2 and using the equation given by Pavoni Belli et al. [31]

water runoff, and providing aesthetical views. From the acoustical point of view, green roofs used in buildings have two positive effects: (1) an improvement in the sound insulation and absorption properties of the roof, which reduces the sound pressure levels inside the building, and (2) a reduction of the diffracted noise component, since the greenery system has a sound-absorptive surface that reduces the strength of the diffraction component for the noise propagated from a busy road, which results in quiet areas behind the building façades. A scheme of a typical green roof is provided in Fig. 4.

The application of a green roof on top of a building improves the building's insulation properties due to its additional mass, low stiffness, and damping effect. The effect of this system (semi-extensive typology) was studied by Kang et al. [87]. In their study, they evaluated the acoustical performance of a green roof in a small test room that had highly insulating walls and floor. The relatively small dimensions of the specimen tested in the chamber can be justified since the materials used for the green roof are not resonant. The results of their study showed that the application of a dry growing medium caused an extra transmission loss from 10 dB to 40 dB depending on the frequency. The effect of the vegetation undergrowth and application of 3 l/m^2 of water to the soil substrate was found to be negligible.

Numerical studies of green roof systems have predicted slightly lower values of sound attenuation and have reported that the attenuation peak at 1000 Hz is due to the effect of the vegetation layer.

The results of a Swedish study conducted on a wooden shed demonstrate how the application of the green roof could improve the acoustic insulation of this structure. The sound pressure levels inside the shed were measured before and after the

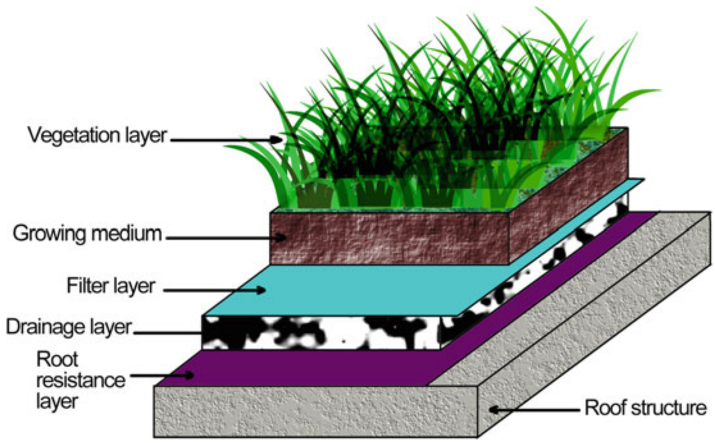

Fig. 4 Scheme of a typical green roof

installation of the roof system. The study reported a reduction of 6 dB inside the wooden shed after the installation of a green roof [88]. It should be noted that the roof of the shed was not made of concrete or of another heavyweight material; lower values of acoustic attenuation could be expected if this type of green roof were to be installed on a standard building with a heavy and thick roof. Further studies have reported improvements of the transmission loss from 5 dB to 13 dB in the frequency range between 50 Hz to 2000 Hz and 2 dB to 8 dB for higher frequencies. Measurements carried out on real buildings before and after the placement of a dry green roof have shown sound attenuations up to 10 dB. Obviously, thicker green roofs have always provided larger values of sound attenuation. Further studies have shown that the absorption properties of soil are negatively affected by the presence of water [89].

The surface of a green roof has significant acoustic absorption properties that affect the propagation of the sound at grazing incidence angles. A number of studies have evaluated, both experimentally and numerically, the effect of a green roof on the noise level generated by traffic on a busy road [90]. The results show that a green roof can play an active role in the attenuation of the diffracted component of traffic noise propagated from a busy road over the building roof to the quiet courtyard.

Wong et al. [91] have studied the acoustical properties of green walls and noise barriers with vegetation. It has been described that natural barriers are preferable, covered with native vegetation to make the structure more aesthetically appealing [92]. Figure 5 shows an example of a green roof and a green wall.

More recently, Horoshenkov [93] has applied the parameter inversion procedure to determine non-acoustical properties of living plants. He has used the Miki [7] empirical model to estimate the effective flow resistivity, tortuosity, and effective plant height from normal incidence sound absorption measurements.

It has been shown that the sound absorption coefficient of plants is controlled predominantly by the leaf area density and angle of leaf orientation. The effective

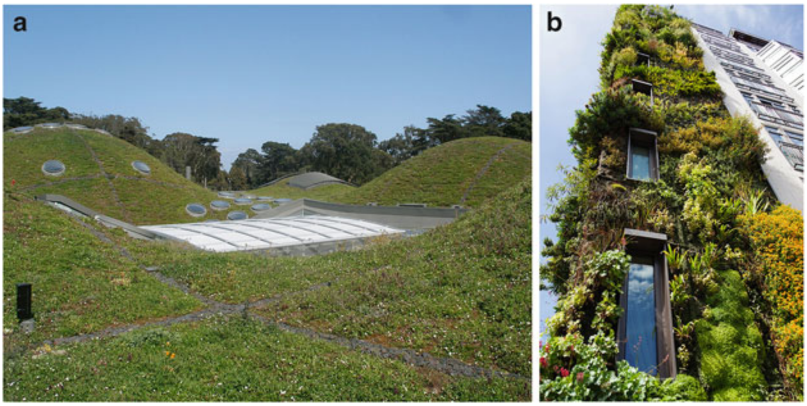

Fig. 5 Real examples of (**a**) a green roof and (**b**) a green wall

flow resistivity is directly linked to the plant leaf area density, whereas the tortuosity is linked to the dominant angle of leaf orientation. In addition, the equivalent fluid model for sound propagation in porous media predicts accurately the sound absorption coefficient of a plant in the frequency range of 50 Hz–1200 Hz [94]. Figure 5 shows two practical examples of a green roof and a green wall. Research on the acoustical properties of green roofs and green walls continues [95–97].

Conclusions and Further Outlook

Acoustical materials are commonly used for the control of noise in many situations where it is necessary to protect health and environmental quality. However, in recent years, issues related to global warming caused by the emission of greenhouse gases into the atmosphere by industrial manufacture of materials are having an important role in the marketing of acoustical materials. Public awareness and concern about the negative effects of pollution have led consumers to favor environmentally friendly materials, less contaminating processes, and recycled products. Thus, acoustical materials have evolved into more advanced materials over the years. Compared with the older materials produced in the 1960s, the new eco-materials have become safer, lighter, and more technologically optimized. Some of these materials are currently available on the market at competitive prices, but many others are still at design or prototype stage. Some of these eco-materials have shown to be viable alternatives to conventional materials for current and future noise control applications. Architects and acoustical engineers now have a wide choice of eco-materials that provide the desired acoustical properties with a low environmental impact.

Further work is still needed for a more systematic material characterization, both from the experimental and theoretical point of view. A new standard and robust procedure to evaluate the actual eco-material sustainability through the whole life-cycle analysis is essential. Existing life-cycle assessment studies on entire buildings have shown that the substitution of conventional thermal and sound insulating materials with sustainable ones has significant effects on the impact of all the various phases of the life of the building (construction, operation, and end of life). These new directions will hopefully encourage the development of new materials and/or the improvement of existing ones. Given the intensity of research and the development in manufacturing processes, it is expected that the range of new eco-materials with noise reduction properties will expand rapidly over the next few years.

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