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Recycling of wasted wool fibers from sheep shearing for green building components: A review

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ABSTRACT

It is nowadays recognized that the building sector causes the greatest environmental impact in terms of both waste production and carbon emissions. Within the context of ecologically sustainable development (ESD), the construction sector is looking for more eco-friendly materials, such as natural fibres. Natural fibers are worldwide recognized as ideal replacement for traditional construction materials, providing excellent thermal and acoustic insulation for building but also for adoption as reinforcement fibers in cement mortars, composite materials, solid boards/panels, raw biomasses, multi-layers, filled loosen/foaming types, particles, slurry types, coils, bricks, etc. The aim of this work is to provide a clear overview on the natural fibers currently employed in the green production of building components, with the main focus on wool fibers deriving from the livestock sector, where wool waste disposal is a crucial problem. This article is a review conducted using the Systematic Literature Review (SLR) approach, a globally recognized method that is not inherently innovative. The innovation of this article lies in the addressed topic, which is relatively new and has only recently gained significant attention, resulting in a limited number of highly relevant articles in the literature.

A systematic literature review of the use of wool fibers for green building components is conducted herein to highlight the characteristics that make such material a usable resource in the construction sector and the limits of its use. Given the findings from the reviewed papers, the authors could document that most of the reviewed articles aimed at analyzing the mechanical, thermal, and acoustic properties of building components containing wool fibres. The review highlights that the strength of the wool fiber relies on its thermal properties which can be exploited for building thermal insulation. The wool fiber is also featured to provide good resistance to flexural loads; conversely, all the studies highlighted a negative effect of wool fibers on the compressive behavior of the investigated building components. The analysis of the acoustic properties showed that given the strong capacity of the wool fiber to absorb sound, wool is a great alternative to the conventional materials derived from non-renewable resources.

Nevertheless, despite the eligibility of such fiber to be employed soon in the building sector, the analysis about the economic viability of the manufacturing process suggests that the high costs for the raw material, labor, electricity, and above all the high volume of water have to be drastically reduced by prompting the development of sheep wool fiber waterless processing. The achieved results could represent a first step in planning the sustainable re-use of wool waste as natural, renewable, and biodegradable fiber in the construction sector, providing the possibility of creating a new supply chain and solving the problem of its disposal.

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1. Introduction

Nowadays, sustainable environmental management and the preservation of natural ecosystems are paramount goals driving scientific research, policymaking, and societal efforts worldwide. This heightened focus arises from the urgent imperative to mitigate environmental degradation, combat global warming, and address climate change, underscored by pivotal international agreements such as the "2030 Agenda" in 2015 [1], the "Paris agreement" in 2016 [2] and the "European green deal" in 2019 [3] are an example of such commitment. One of the sectors which mostly threatens the ecosystem is the constructions sector [4]. Among all sectors, the construction industry stands out as a significant contributor, accounting for approximately 50 % of CO_2 emissions, solid waste production, and energy consumption [4]. Ecologically Sustainable Development (ESD) has emerged as a critical framework aimed at enhancing sustainability and energy efficiency within this sector [5]. Key strategies include promoting the adoption of eco-friendly materials, particularly natural fibers used for thermal insulation in green building applications [2]. Unlike traditional materials such as plastics and synthetic fibers—commonly employed in thermal insulation but derived from non-renewable resources with associated environmental and health concerns—natural fibers sourced from agricultural waste or by-products offer promising alternatives [6].

Hence, the main target is to reduce and replace all the materials coming from non-renewable sources. It has been demonstrated that many natural materials, that can be employed in the "green" building, come from agricultural waste or by-products, and can be reused in different applications as natural fibers in the building sector [7]. These natural fibers not only provide excellent thermal and acoustic insulation properties for buildings but also serve as reinforcement materials across a range of construction products (e.g., composite materials, solid boards/panels, raw biomasses, multi-layers, filled loosen/foaming types, particles, slurry types, coil, bricks) [8]. This trend is corroborated by the rising demand, production, and utilization of "green" products within the construction sector. For instance, Duan et al. [9] analyzed the potential of recycling plastic fiber for use in sustainable cementitious composites. Similarly, Liu et al. [10] explored the impact of partially replacing Portland cement with rice husk ash. The selection of "green" products is primarily driven by the optimal tradeoff between material properties, characteristics, recyclability, cost, and environmental impact [11]. Certification systems like Green Mark, LEED, BREEAM or DGNB validate the sustainability of construction projects based on criteria such as material recyclability, reduced energy consumption, and waste production [6]. Despite the availability of certifications ensuring sustainability for certain materials, the market still lacks a wide array of sustainable options, with many materials under ongoing investigation [12].

Their use would contemporarily exploit renewable sources by reducing agriculture wastes. Agriculture waste accounts for about 10 % of the overall material waste, with approximately 998 million tons produced worldwide annually out of 7–10 billion tons [6]. The agriculture waste consists of liquids, slurries or solids and is generated by cultivations, livestock productions and aquaculture [13]. The agriculture activities, in general, do not foresee a proper waste management system and therefore a large part of scrap material is not valorized. This high volume of wastes contributes to air pollution and water/soil contamination [14]. The conversion of the agriculture waste into raw materials for the building sector and their valorization could lead to the production of new resources deployable as much as the currently used conventional materials [15]. The use of natural fibres, either vegetal or animal ones, would reduce the environmental issues linked to their disposal (less waste from agriproducts) and would create and advantage for the building sector in terms of usable ecofriendly products which would guarantee the achievement of the sustainability goals. Furthermore, beside a greener approach towards the environment, several economic benefits can derive from the reuse of such waste like the reduction of production costs and job creation in line with the status of the circular economy [16]. This article is a review conducted using the Systematic Literature Review (SLR) approach, a globally recognized method that is not inherently innovative. The innovation of this article lies in the addressed topic, which is relatively new and has only recently gained significant attention, resulting in a limited number of highly relevant articles in the literature. Therefore, the aim of this work is to provide a clear overview of the natural fibers currently employed in the green production of building components, with the main focus on wool fibers deriving from the livestock sector, where wool waste disposal is a crucial problem. In the next paragraph, a general classification of natural fibers adopted for green building components, their most investigated properties and characteristics that made them attractive for the building sector have been shown. Since, the waste wool is becoming a topic that is attracting the attention of both the scientific and non-scientific world, the authors performed a Systematic Literature Review (SRL) on the use of wool fiber. It was demonstrated that the wool properties and characteristics are suitable for the green building sector, and moreover, its recycling and valorizing would contribute to improve the overall waste handling and contribute to a more sustainable building sector.

2. Natural fibers for green building components

The use of natural fibers in the construction sector was first explored in 1974, and their actual use was developed after 2003 [7]. In the field of thermal insulation, natural fibers, especially vegetal ones, contrast with mainstream plastics such as expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PU), polyisocyanurate (PIR), phenolic foam or phenolic insulation board (PIB), and inorganic materials including rock wool (e.g., mineral wool or stone wool), fiberglass (i.e., glass wool), expanded perlite and aerogel, *etc*. [7]. The common plastics adopted in the building sector do not derive from renewable sources and their deployment generates a huge impact on the environment and the human health. On the other hand, the natural fibers provide a complete green solution. They are recyclable, renewable, eco-friendly, bio-degradable, with low environmental impact and low energy consumption. Moreover, vegetable fibers can even reduce the CO_2 content in the atmosphere.

In general, natural fibers can be divided into organic fibers of vegetable or animal origin and inorganic fibers of mineral origin, as reported in Fig. 1. Among the fibers of mineral origin there are asbestos [7,17], carbon and glass [17], instead, among the fibers of animal origin, classified as hair and threads with a predominantly protein structure, there are sheep wool, cashmere, silk, and alpaca [7]. Since fibers of vegetable origin, with a lignocellulosic structure, can be extracted from both monocotyledons and dicotyledons plants and from different regions of the plant itself, some crops produce more than one type of fiber.

In the case of monocotyledons, as fibers of vegetable origin there are leaf fibers, fruit fibers, and spear fibers. In detail, abacà, henequen, cantala, yucca, photo sum, para [7], sisal [7,18], pineapple and agave [17,18] belong to the leaf fibers group. Among the fruit fibers, there are coir [17,18] and oil palm [17], instead of, bamboo [7,17], rice, corn stem, wheat [17,18], and bagasse [17] are considered spear fibers. Otherwise, in the case of dicotyledons, the fibers are divided into seed fibers, stem fibers, and fruit hair. Cotton [7,17,18] and kapok [17,18] belong to the seed fibers, while flax, hemp, nettle, sunn, poplar, Norway spruce [7], jute, kenaf, and ramie [7,18] are included into stem fibers group. Among the fruit hair, there are kapok [7,17] and paina [7], as reported in Fig. 1.

Natural fibers are globally recognized as ideal replacements for traditional building materials, offering significant thermal and acoustic insulation properties. Recently, they have also been adopted as reinforcement fibers for cement mortars, composite materials, solid boards/panels, raw biomasses, multi-layers, loose-fill/foaming types, particles, slurry types, coils, and bricks [8]. Beyond their environmental compatibility, characterized by high availability, low cost, renewability, and biodegradability, natural fibers must meet various requirements—including thermal, mechanical, acoustic, hydraulic, and economic considerations—to be effectively used in the construction sector.

However, a fundamental issue in the use of natural fibers in building components is their durability. Natural fibers are highly sensitive to environmental degradation caused by factors such as temperature, UV light, and humidity, which significantly reduces their service life [19]. This vulnerability is more pronounced in animal fibers based on keratin compared to plant fibers based on cellulose [20].

Some authors reported a list of the natural fibers properties most investigated in literature, based on the order of declining paper numbers [7]. Considering a descending order, the most investigated properties include thermal attributes (such as thermal conductivity, heat capacity and thermal diffusivity), density, compressive strength, water absorption (including water permeability), microstructure, moisture content, flexural strength, thickness, sound insulation, fire performance, durability, and volatile dust *etc.* [7].

The outcome of several research studies is a very good tensile strength of the natural fibers but still lower than synthetic fibers. Nevertheless, the natural fibers are featured by high rigidity (comparable to glass fibers) [18], competitive Young's Module, high resistance to bending stress and above all low density [21]. In addition, it has been proven that fibers' physical, chemical, and morphological properties can influence mechanical properties, e.g., a greater cellulose content increases tensile strength and positively increases the Specific Young's Module [7]. Although some of the fibers-based building components are already available in the market, others are currently under feasibility studies, since, the use of these products is not widespread, and, in some cases, it is limited to an experimental laboratory stage. This occurs because, despite the several important advantages (i.e., renewability, availability, biodegradability, high thermal-acoustic insulation, good hygroscopic behavior, high capacity of air regulator, low density, production process with low CO_2 emissions, and low energy demand [22], there are also disadvantages that can limit the large-scale use of these sustainable alternatives. Among the disadvantages, it is possible to find the high cost, sometimes not adequate mechanical properties, the need to use not biodegradable binders, a huge humidity absorption due to the significant hygroscopic skills, flammability and above all the susceptibility to insect attack which allows the growth of mold and mildew [7].

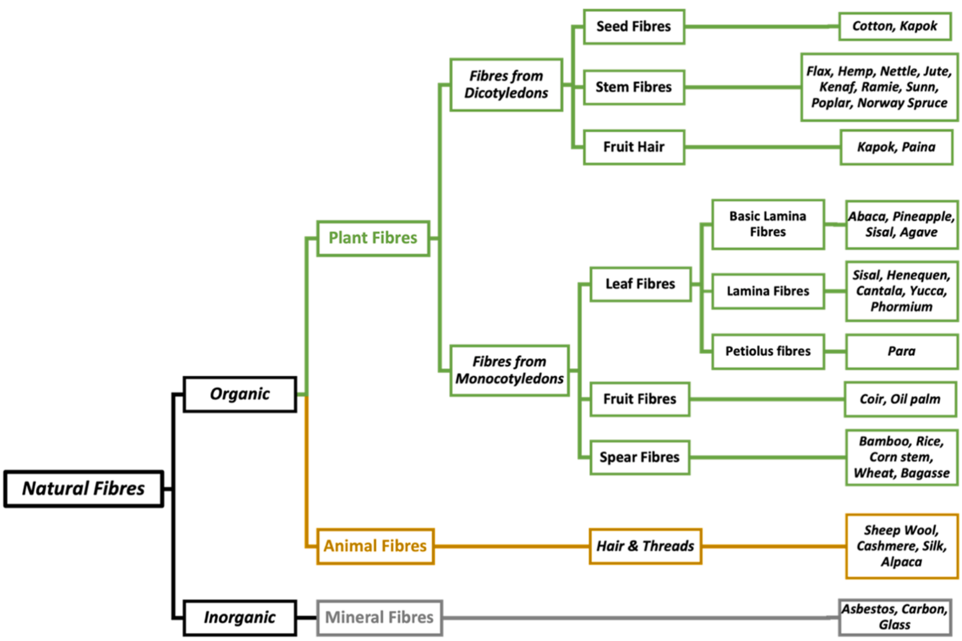

Fig. 1. Classification of natural fibers [7,17,18].

Following the aim of this study, among all the natural fibers adopted in literature, it was decided to deepen the use of wool fiber since, as stated above, the management of this important resource is nowadays an important environmental issue that is attracting the worldwide attention of scientists, researchers, technicians, and industries. Due to its characteristics, several studies found in literature, highlight the suitability of wool fiber for the green building sector [7]. Wool fiber is a natural fiber derived from the fleece of a sheep. The main components of the wool fiber are the keratin (60 %), fat (10 %), wool sweat (10 %), moisture (15 %) and impurities (about 5 %) [4]. Particularly, the physical characteristics of the wool make it an appetible raw material for the thermal insulation thanks to its high resistance, hydrophily and hydrophobic attributes, high thermal performance, and its natural ability to regulate temperatures and fire resistance [23].

Several studies have investigated the mechanical properties of wool fiber [21,24–26]. Parlato et al. [21] analyzed fibers from the fleece of Sicilian domestic sheep, evaluating tensile strength, breaking strength, and elasticity, following ASTM D 2256–10 standards. Their results showed an average strength of 137.31 MPa, an initial secant modulus of 1.74 GPa, and an elongation at break of between 45 % and 50 %. These data are consistent with other research studies, such as that one carried out by Murillo et al. [24], who reported an average mechanical strength of 147 MPa, a tensile modulus of 2.9 MPa, and an elongation at break between 25 % and 45 % for sheep wool fiber. Furthermore, the results obtained by Mahir et al. [25] and Fuqua et al. [26] offer further comparable results. Mahir et al. [25] indicated an average tensile strength of 147 MPa and a tensile modulus of 2.7 GPa, with an elongation between 25 % and 35 %, while Fuqua et al. [26] reported a lowest tensile strength of 150 MPa, an average tensile modulus of 5.7 GPa, and an elongation of 25–40 %. The recyclable, renewable, and ecological properties of wool make it a natural sustainable resource to be used in the building sector [27]. Therefore, the use of waste wool fiber to generate components would allow at the same time the reuse of high amount of industrial waste and the sustainable future. Moreover, wool is processed by new methods that would make it a potential marketing tool beside a simple and reliable resource, and its different uses allow considering this resource as a new entry in the market of industrial insulating materials.

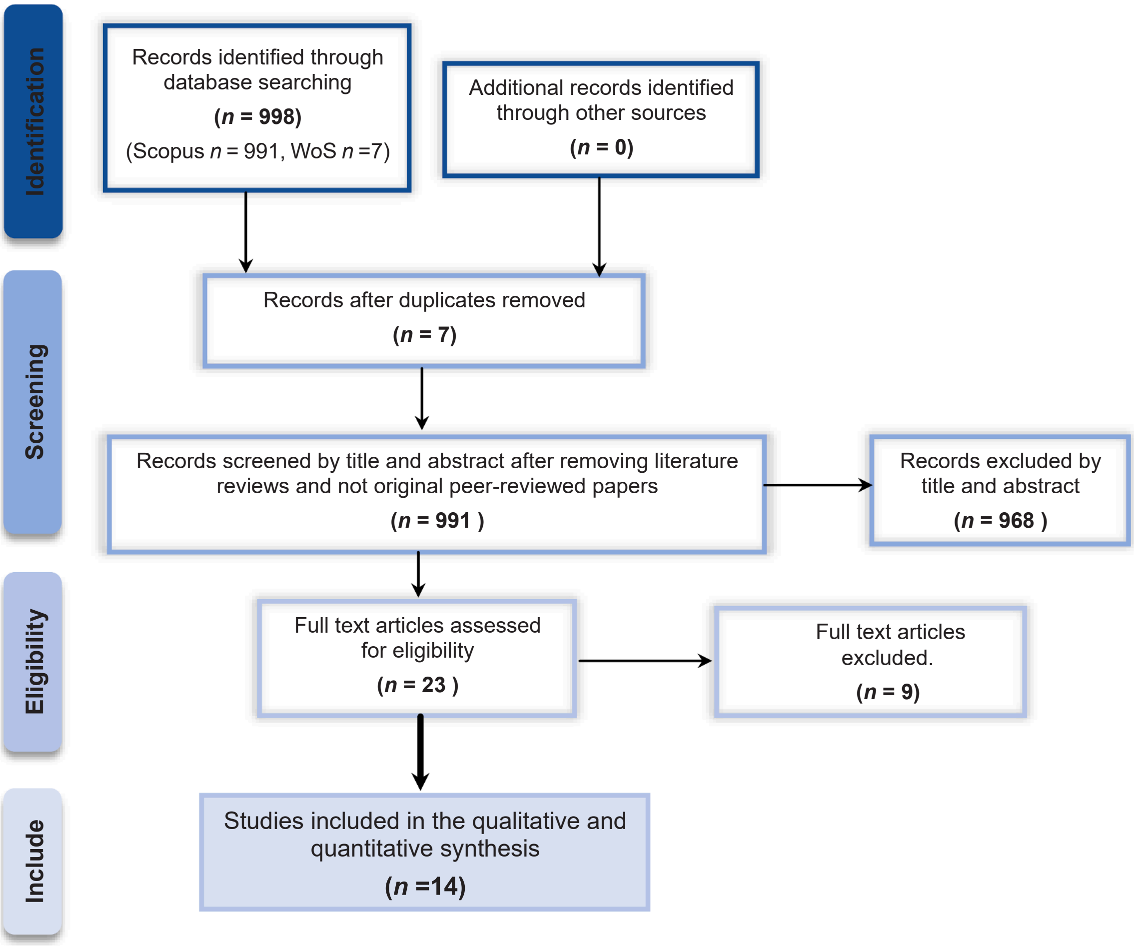

Fig. 2. Flowchart of the SLR performed in this paper.

3. Review of use of wool fibers for green building component

In this section, the findings from a Systematic Literature Review (SLR) conducted on the use of wool fibers for green building components are reported. As a first step the authors selected “wool”, “fiber”, and “green building component” as the most research-representative keywords. The selected keywords were queried on both Scopus and Web of Science (WoS) database, to achieve a high scientific impact for this review, and as those are widely acknowledged to be the most comprehensive databases of peer-reviewed journals. Later, the authors merged the two databases to increase the probability of detecting all the relevant contributions in the selected field, ensuring a high level of rigor in the selection of the research papers to be included in this review.

In detail, the following criteria were adopted as a guide for developing review:

1. Only peer-reviewed articles written in English were considered.
2. Only review articles and research articles were considered; papers published in book chapters and conference proceedings were not included.
3. Overlapping between the two databases was taken into account to avoid double-counting papers covered by both databases. A representative, congruous review-sample, consisting of articles indexed in Scopus and/or WoS, was create.
4. Firstly, a preliminary screening of the papers was carried out at abstract level to best recognize the addressed topic and its consistency with this review’s objectives, based on the assessment methodologies adopted in those research papers. Therefore, the authors excluded all the papers focused on mineral wool, on fibers for construction in general, and of the use of wool for sectors other than the building.
5. Only research papers meeting the criteria at points reported above were selected, and the related full texts were acquired and thoroughly reviewed for their relevance within the aims of this review.
6. All references in the papers of the sample formed at point 5) were scanned to check whether other papers could have been added to the sample, but none were found.

Fig. 2 presents the paper-flow diagram. It is organized into several boxes with the number of the included or excluded papers at each step of the review process. Indeed, as the result of the material collection, screening, and evaluation process, by following the methodology reported above (i.e., points 1) to 6), fourteen studies, published within the period 2013–2023 (Fig. 3), were selected by the authors, developing a review sample that could:

- be consistent with the aim of this review paper;
- be representative of the literature currently available on the selected topic;

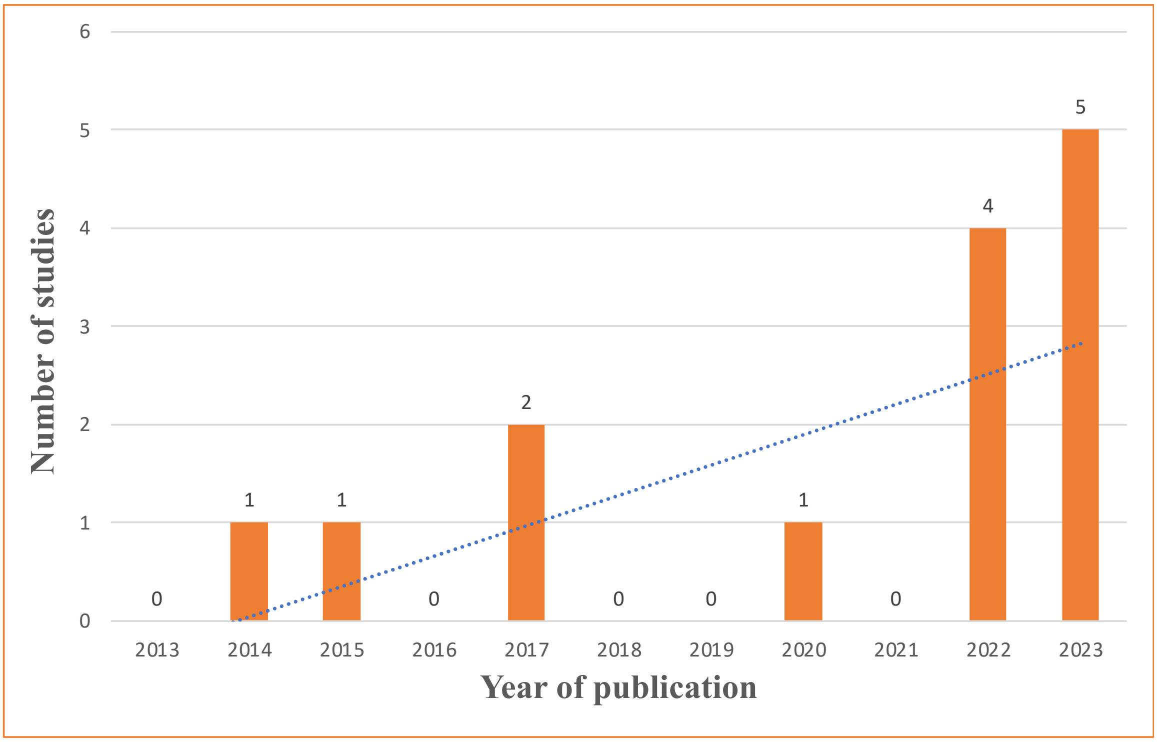

Fig. 3. Research articles published within 2013–2023-time interval, selected for literature review.

- allow developing an overall exhaustive overview in the field of green building with wool fibers resource.

By doing so, this review can primarily contribute to understanding the main characteristics that have been mostly investigated and that could make this kind of waste or by-product suitable to replace the conventional materials deriving from non -renewable sources. Furthermore, the review explores the type of wool-based building components that can be obtained, along with an examination of the advantages, disadvantages, and possible future directions for exploiting this waste exploitation within the green building sector. In detail, among the reviewed studies, it was possible to note that most of them deepened, both separately but also at the same time, the study of mechanical, thermal, and acoustic properties of the building components based on wool. Other studies took into consideration the wool production and transformation process, the problems relating to its disposal but also analyses for localizing and quantifying wool waste to sustainable identify territorial areas suitable for hosting new collection centers and develop close supply chains that allow using this resource within the circular economy context.

The collected journals cover a wide variety of scientific areas as reported in Fig. 4, including the construction engineering sector and the environmental sector for the conservation, use and recycling of materials. All the journals chosen for publishing the selected research articles follow the sustainability approach.

Moreover, looking at the scientific studies published in the last 10 years, the number of articles of interest for this review has increased by five times in 2022 compared to 2020 and remained stable in 2023 (Fig. 3).

According to this so far, the following sections have been organized to collect and best analyze the topics and results reported by the reviewed articles. Therefore, in sections 2.1, 2.2 and 2.3, as stated before, fourteen articles, divided in three groups, were revised considering their key objectives, as shown in Table 1. In detail, in section 2.1 all the results relating to the study carried out on mechanical, thermal, and acoustic properties (Group 1) are reported. Subsequently section 2.2 deals with the problems concerning to the transformation process and the related disposal practices (Group 2). Finally, in the 2.3 section all the studies (Group 3) focused on quantifying the wool waste with the aim of locating new collection centers that can create a new supply chain were described (Table 1).

3.1. Reviewed studies on thermal, mechanical, and acoustic properties of building components containing wool fibres

This section aimed at reviewing the research papers which investigated the wool mechanical, thermal, and acoustic properties. The largest number of selected articles were included in this section, because the study of these properties is essential to evaluate their possible use as building component [7].

In detail, the above-mentioned properties were analyzed in different ways and for different new building components suitable for green buildings as shown in Table 2. In some articles the analysis was carried out on a group of properties of the same nature, e.g., mechanical, thermal etc., while other articles were focused on the combination of these properties, e.g., thermo-mechanical, thermo-acoustic etc. The authors decided to further organize this section into subsections to separately report and discuss the results achieved by the selected studies.

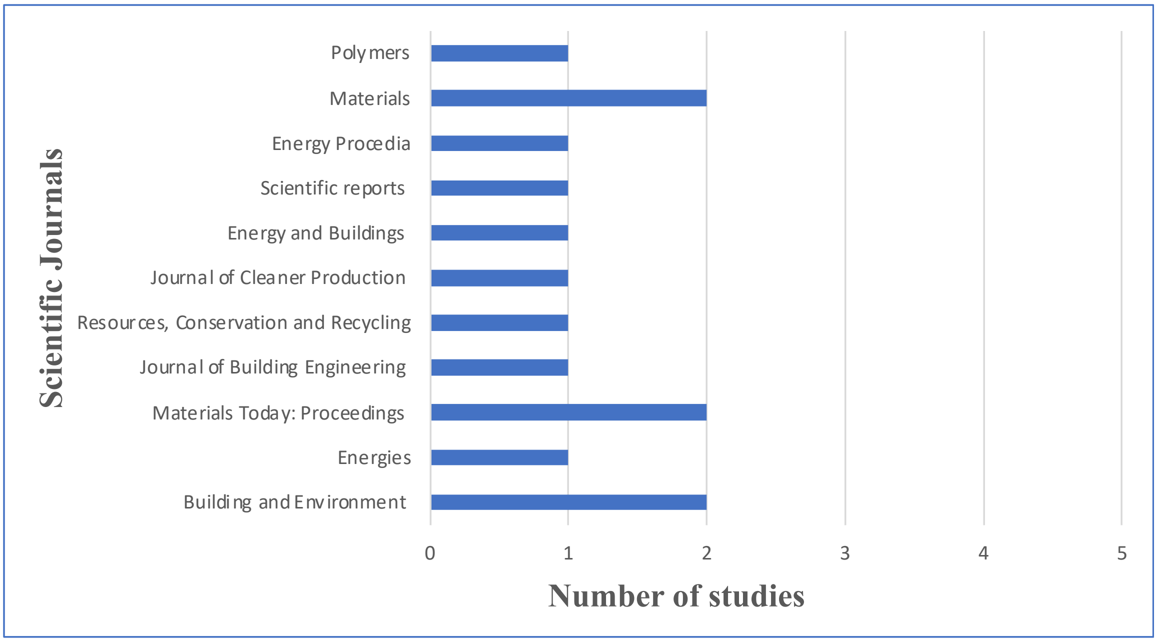

Fig. 4. Scientific journals analyzed in this review.

Table 1
Classification of the fourteen reviewed articles per topic.

Reference	Year	Country	Topic		
			Mechanical, thermal, and acoustic properties (Group 1)	Transformation process (Group 2)	Quantification and localization (Group 3)
Corscadden et al. [23]	2014	Canada	X	X	
Patnaik et al. [29]	2015	South Africa	X		
Cardinale et al. [27]	2017	Italy	X		
Allafi et al. [30]	2020	Malaysia		X	
Atbir et al. [31]	2022	Morocco	X		
Alyousef [28]	2022	Saudi Arabia	X		
Parlato et al. [4]	2022	Italy			X
Parlato et al. [6]	2022	Italy			X
Atbir et al. [32]	2023	Morocco	X		
Atbir et al. [33]	2023	Morocco	X		
Sharma et al. [34]	2023	India	X		
Kicińska-Jakubowska et al. [39]	2023	Poland	X		
Ulutaş et al. [22]	2023	Turkey	X		
Del Rey et al. [40]	2017	Spain	X		

Table 2
Selected research articles focused on wool mechanical, thermal, and acoustic properties.

Reference	Year	Country	Properties			Building component
			Mechanical	Thermal	Acoustic	
Corscadden et al. [23]	2014	Canada		X		Panels
Patnaik et al. [29]	2015	South Africa		X	X	Nonwoven mats
Cardinale et al. [27]	2017	Italy	X	X		Panel made by cement mortar and sheep's wool fibers
Atbir et al. [31]	2022	Morocco	X	X		Bricks with wool and clay
Alyousef [28]	2022	Saudi Arabia			X	Concrete reinforced with wool
Atbir et al. [32]	2023	Morocco	X	X		Bricks with wool and clay
Atbir et al. [33]	2023	Morocco	X	X		Porous plaster reinforced with a network of wool
Sharma et al. [34]	2023	India	X	X		Wool fiber filled epoxy composites
Kicińska-Jakubowska et al. [39]	2023	Poland		X	X	Mats
Ulutaş et al. [22]	2023	Turkey		X	X	Identifying the most efficient natural fibres with an integrated model
Del Rey et al. [40]	2017	Spain			X	Mats

3.1.1. Mechanical properties

In this first section, all the main results related to the analysis of the mechanical properties of wool-based building components have been reported and discussed. In all fourteen studies reviewed, both for this section and for the following ones (thermal and acoustic properties), the wool used was categorized as waste wool, coming from different breeds of sheep (i.e., Timahdite, Coring, Dorper, Merino, Suffolk, Valle del Belice), raised in different parts of the world, including Italy, Morocco, India, Turkey, South Africa, Canada and other countries (Table 1). Wool fiber has been used as a reinforcing fiber in several contexts, including clay brick, plaster, concrete and in the form of panels (Table 2). The main mechanical properties examined include bending and compressive behavior, as well as tensile strength. The information presented in this section is summarized in Table 3.

Atbir et al. [31,32] conducted two research studies in 2022 and 2023, respectively, to valorize and exploit the use of Moroccan sheep wool for obtaining bricks reinforced with wool filaments. Still in 2023, another research was carried out by Atbir et al. [33] with the aim of reusing wool filaments for producing reinforced porous plaster. In all the three studies, both the mechanical properties, below reported, and thermal properties of the building components, discussed in next section, have been investigated.

In their first research article Atbir et al. [31], discussed the development of a new technique based on multi-layer reinforcement of solid brick with sheep's wool yarns. The multilayer reinforcement technique involved the use of yarn in the form of a "wool grid layer method". The wool yarn had a length of 160 mm, crossed with wool threads at a width of 40 mm and was used to produce two different types of bricks, the first one with red clay and water, instead the other one with white clay and water. For each type of brick (white and red), five samples were prepared, each incorporating varying percentages of wool (0 %, 1 %, 2 %, 4 %, and 6 %), with the aim of examining the corresponding mechanical performance in relation to the amount of wool. The samples were subjected to mechanical tests in accordance with EN 196–1, with a specific focus on investigating flexural strength. Each sample had a volume of 256 cm^3, a load rate of 50 N/S, and was tested after a curing period of 70 days. It was found that the sample without wool broke with a single

Table 3
Mechanical properties of wool-based building components.

Reference	Type of sample	Dimensions of the sample	Type of tests	Mechanical properties upgrade*
Atbir et al., 2022 [31]	Solid bricks with different percentage of multi-layer sheep's wool yarn reinforcement.	Mold of 256 cm^3 filled with clay (red or white), water, and layers of sheep's wool yarns, 160 mm long, crossed at a width of 40 mm.	**Flexural test** (Pilot Compact-Line Controls- EN 196–1 standard). Load speed: 50 N/s Curing period: 70 days	Best result in bricks with 6 % of wool and white clay: +119 % flexural strength
Atbir et al., 2023 [32]	Same sample investigated by Atbir et al., 2022 [31] modifying the sequence of wool layers in the opposite direction.	**Flexure strength:** Same dimension as reported by Atbir et al., 2022. **Compressive strength:** Mold of 64 cm^3.	**Flexural and compressive test** (Pilot Compact-Line Controls- EN 196–1 standard). Load speed: 50 N/s (flexural) 500 N/s (compressive) Curing period: 90 days	[a] Best tradeoff in the bricks with 15 % of wool yarn and clay: + 43 % flexural strength (white) – 11 % compressive strength (red).
Atbir et al., 2023 [33]	Porous plaster reinforced with different amounts of twisted wires of sheep wool.	**Flexural strength:** mold of 256 cm^3 filled with plaster, liquid soap, and twisted wires of wool. **Compressive strength:** mold of 64 cm^3 filled with plaster, liquid soap, and twisted wires of wool.	**Flexural and compressive test** (Pilot Compact-Line Controls- EN 196–1 standard). Load speed: 50 N/s (flexural) 500 N/s (compressive) Curing period: 28 days	[a] Best tradeoff in the sample with 4 % of wool: + 67 % flexural strength – 58 % compressive strength
Cardinale et al., 2017 [27]	Concrete with different amount of recycling wool.	**Flexural and compressive strength test:** Molds of 256 cm^3 filled with cement Portland, water and wool fiber cut to a length of 10 mm.	**Flexural and compressive test** (Dual Column Instron 3369 frame - EN 1015–11 standards). Load speed: 50 N/s Curing period: 28 days	[b] Best result for sample with 2 % of wool: – 9,1 % flexural strength – 14,7 % compressive strength
Sharma et al., 2023 [34]	Panel of sheep wool fiber-filled epoxy composites.	Four panels with a composition of 75 % resin and 25 %wool.	**Tensile test** (Universal Testing Machine - ASTM D3039 standards) Cross head speed: 1 mm/min	The sample reference without wool was not tested
Alyousef, 2022 [28]	Concrete composites reinforced with wool fiber.	Cylindrical Mold measuring 100 mm in diameter and 200 mm in length, filled with varying quantities and types ('natural' and 'modified') of sheep's wool fibers (60–70 mm in length and 95–130 μm in diameter), combined with Portland cement, sand, gravel, and water."	**Compressive test** (ASTM C39–19 standards). **Modulus of Elasticity- MOE** (ASTM C496–14 standards) Curing period: 90 days	[c] Best mechanical properties in concrete with 0,5 % of "modified wool": – 4,5 % compressive strength – 1,97 % MOE

* The table was designed to express, through percentage data, the influence of the wool fiber on the parameters investigated compared to the control samples without wool fiber.
[a] The increase in wool quantity results in a high flexural strength and a low compressive strength.
[b] The increase in wool content is accompanied by a decrease in both flexural and compressive strength.
[c] "Natural" fiber (subjected only to a cleaning pre-treatment); "modified" fiber (subjected to a cleaning pre-treatment and a chemical pre-treatment to improve the fiber-cement interaction.

vertical crack, while all the wool-reinforced samples, containing varying percentages of wool, showed greater resistance. This increased resistance is attributed to the mechanical behavior of the wool fibers under load. Specifically, the presence of wool fibers distributed within the material matrix improves the material's ability to resist crack propagation and distribute stress more evenly, thus enhancing its overall structural integrity.

The samples with a 6 % wool content demonstrated the highest flexural strength performance for both types of clay. Specifically, the flexural strength was 4.38 MPa in the white clay bricks and 2.27 MPa in the red clay bricks, an increase of 34 % and 119 % respectively compared to the sample without wool. The results show that an increase in the percentage of wool correlates with better mechanical bending behavior. This is particularly evident in bricks filled with white clay.

Following the results obtained in their first study [31], in 2023, Atbir et al. started new research with the aim of optimizing the thermomechanical behavior of bricks reinforced with wool yarns [32]. Unlike the previous study, a new method for placing the yarn inside the brick was explored, intending to assess whether there would be an increase in mechanical properties and achieve a lighter weight for the reinforced raw bricks. The examined brick showed a pattern of alternating layers, featuring layers of clay and yarn. The yarn was initially placed in a vertical orientation and later shifted to a horizontal position, with lengths of 40 mm and 160 mm, respectively. In this second study as well, two different types of bricks were created, one with white clay and one with red clay, reinforced with varying amounts of wool yarn (0 g, 6 g, 15 g, 18 g, 27 g), aiming to test not only flexural behavior [31] but also compressive one. In this regard, two samples were prepared with different volumes, one with a volume of 256 cm^3 for flexural strength tests and another with a volume of 64 cm^3 for compression tests. Mechanical properties were studied following the EN 196–1 standard; the used bricks had an age of 90 days, and the loading speeds of 50 N/s for flexural tests and 500 N/s for compression tests were applied. The results of the mechanical performance tests indicated that all samples, with varying percentages of wool and different types of clay (white and red), had better flexural strength, in line with their first article [31], but lower compressive strength. The authors attributed the high flexural strength of the bricks to the different orientation of the yarn, which increased the hardness and reduced the formation of cracks, thus avoiding the "shrinkage phenomenon" typical of clay-based components. On the contrary, the introduction of the yarn, due to the porous nature of the wool fibres, resulted in a decrease in the density of the brick, making it less resistant to compression. Their best tradeoff was achieved by the final samples with maximum 15 g wool added in both bricks with red and white clay, leading to a maximum increment of 43 % in flexural strength for the white-clay bricks and a minimum decrease of 11 % in compressive strength for the red-clay bricks [32].

In their third research study, carried out later in the 2023, Atbir et al. [33], developed a porous plaster with added sheep wool yarns skeleton as a new multilayer insulator. The authors aimed at finding the best combination of thermal-mechanical properties to obtain a wool-based composite which is lighter, stiffer, and less sensible to humidity than those ones already present in literature. In this research, the adopted sample is featured by twisted yarns in mesh nets, characterized by a more complex structure than the previous research. In this study also, two types of samples were prepared for flexural and compressive tests; the preparation involved twisted yarns, plaster, and a mixture of water and liquid soap with a neutral pH. For the flexural samples (dimensions 256 cm^3), the loading speed was 50 N/s, while for the compressive samples (dimensions 64 cm^3), the loading speed was 500 N/s. Both types of samples were allowed to cure for 28 days. In total, four samples were prepared and tested, each characterized by a different percentage of wool (0 %, 4 %, 9 %), and a reference sample consisting solely of plaster (0 % wool, 0 % soap). Also for the porous plaster, the results confirm that the addition of wool leads to an increase in flexural strength but at the same time results in a decrease in compressive strength. In particular, the sample with the highest percentage of wool, i.e., 4 %, showed a significant improvement in flexural strength, reaching approximately 2.24 MPa with a gain of 67 %. Although, the wool porosity is a positive factor for the flexural behavior since the air is kept inside the porous surface and support to absorb the flexural axial load, at the same time the porosity results in an overall lower density of the composite and, consequently, a lower compressive strength. The sample with 4 % wool-fraction was identified by the authors as the optimal thermo-mechanical point [33]. Indeed, the sample with the highest percentage of wool (i.e., 4 %) exhibited a decrease in compressive strength, reaching approximately 4.13 MPa with a loss of 58 %.

Cardinale et al. [27] have assessed the possibility of using sheep wool fibers, derived from recycling waste containing raw unspun wool, as a raw material for mortar, particularly for wall coatings. The wool, used as a reinforcing fiber along with Portland cement, sand, lime, and water, was cut to a length of 10 mm and added in varying quantities. In total, four different mixtures were prepared, including three with wool percentages of 2 %, 5 %, and 7 %, and a reference mixture without wool (i.e., 0 %). For both flexural and compressive strength tests, the samples, in accordance with EN 1015–11 standards, had dimensions of 256 cm^3 and were subjected to a load speed of 50 N/s. The results showed a decrease in both flexural and compressive strength. The reductions in mechanical performance compared to the reference sample were less pronounced in the samples with 2 % wool. However, as the wool content increased, there was a deterioration in both flexural and compressive behavior, resulting in an 80 % reduction in both cases. The authors attribute this mechanical performance decrease to the need to add a greater amount of water for enhancing the workability of the mortar in the presence of wool fiber.

Sharma et al. [34] investigated the mechanical properties of bisphenol-aliphatic amine-based epoxy composites reinforced with waste wool fibers. The primary objective was to assess the enhancement of mechanical performance in composites made of epoxy resin and wool fiber, known for their excellent thermal properties.Four panels with a resin-to-wool ratio of 75–25 % were analysed. The first panel utilized felt wool, the second used rolled compressed felt wool, the third was embedded with needle-punched non-woven wool, and the fourth employed bi-directional woven wool. The tensile strength and tensile modulus of the four panels were examined following ASTM D3039 standards. The results revealed an effective interaction between the resin and the wool fiber in the panels reinforced with wool fiber. However, different fiber orientations (due to different wool processing) led to different outcomes. The polymer composite filled with needle-punched non-woven wool fibers recorded a maximum tensile strength of 46.4184 MPa, while that one containing bi-directional woven wool fibers exhibited the lowest tensile strength at 35.41 MPa. Meanwhile, the maximum tensile modulus of 1.4844 GPa was observed for the compressed wool panel. It is important to note that the results reported by Sharma et al. [34] are not consistent with those reported in other studies regarding the use of wool combined with resins. Most studies highlight that fiber-matrix adhesion is a recurring issue, contrary to Sharma’s findings of an efficient wool-resin interaction. Many studies mention the use of chemical treatments on wool fibers to improve fiber-matrix adhesion, which is typically weak, with evident voids around the fiber, as analyzed by Scanning Electron Microscopy (SEM). These voids cause the fiber to detach from the matrix, as it is not properly incorporated, leading to a deterioration in the composite’s mechanical properties [35–38].

The research carried out by Alyousef [28], aimed at evaluating the effects of waste sheep wool fiber on the mechanical properties of concrete. The authors chose to evaluate both the effect of the addition of "natural" wool fibers (subjected only to a cleaning pre-treatment) and "modified" wool fibers (subjected to a cleaning pre-treatment and a chemical treatment on the fiber surface to increase fiber/cement interaction) cut to a length of 60–70 mm on the mechanical properties of the concrete mix. For each type of fiber (i.e., natural and modified), five concrete mixes with an amount of wool ranging from 0.5 % to 2.5 % were created, together with Portland cement, sand and gravel and a reference sample without wool for a total of 11 concrete mixes. All mixtures were tested for compressive strength and elasticity (MOE) in accordance with ASTM C39–19 and ASTM C496–14 standards after 90 days of age. These standards involve the preparation of cylindrical samples with a diameter of 100 mm and a height of 200 mm. The results showed that the addition of both "natural" and "modified" wool fibers negatively influenced the compression behavior compared to the reference blend without wool. However, although below the value of 40 MPa recorded for the reference sample without wool, the modified wool fiber blends showed a more limited reduction in the compression coefficient compared to the natural ones up to a maximum of 30.1 MPa with a 25 % reduction. The authors attribute the drop in compressive strength to the hydrophilic properties of the wool fiber. The absorption of water by the fiber makes the concrete less compact and, consequently, less resistant. Also, for the modulus of elasticity (MOE) the obtained results showed a decrease compared to the reference mixture without wool which reported a modulus of elasticity equal to 27.4 GPa. However, even in this case the modified wool fiber containing blends recorded a smaller drop in performance up to a maximum of 25 GPa with a reduction of 5 %. Finally, the authors also wanted to evaluate the quality of concrete mixtures using non-destructive ultrasonic pulse velocity (UPV) testing in accordance with ASTM C597–09 standards. The results indicate a decrease in UPV values as the percentage of wool added to the mixture increases. However, all the mixtures showed qualitatively satisfactory values, ranging between 3900 and 4400 m/s. These values do not differ significantly from those obtained for the reference sample without wool, which had a value of 4110 m/s.

As detailed in Table 3, for bricks reinforced with wool and clay, increasing the percentage of wool yarn improved flexural strength but significantly compromised compressive strength. This outcome is attributed to the porosity of wool fiber. While the porosity of wool is beneficial for flexural behavior—trapping air within the porous surface helps absorb axial flexural load and reduces the formation of cracks, thereby mitigating the typical "clay shrinkage phenomenon"—it also results in a lower overall composite density and, consequently, reduced compressive strength. Despite this, the best elastic behavior and the smallest reduction in compressive strength were observed when using red clay, making it preferable for producing bricks with superior mechanical properties [31,32]. Similar conclusions and explanations regarding the increase in flexural strength and the decrease in compressive strength were found when using wool yarn to reinforce porous plaster [33].

In contrast, the use of wool fibers as reinforcement for cementitious mortars resulted in a decrease in both flexural and compressive strength, especially as the wool content increased. According to the authors, the decline in mechanical properties is linked to the porosity of the wool fiber, which, being hygroscopic, retains moisture from the environment in its micropores and internal spaces. Consequently, higher amounts of water were needed to improve the workability and compactness of the mortar [27]. The issue of

Table 4
thermal properties of wool-based building components.

Reference	Type of sample	Dimensions of the sample	Type of tests	Thermal properties upgrade*
Atbir et al., 2022 [31]	Solid bricks with different percentage of multi-layer sheep's wool yarn reinforcement	Molds of 300 cm^3 filled with clay (red or white), water, and layers of sheep's wool yarns, 160 mm long, crossed at a width of 40 mm.	**Thermal conductivity** (Asymmetric Hot Plate method).	[a] Best result in bricks with 6 % of wool and white clay: – 40 % conductivity
Atbir et al., 2023 [32]	Same sample investigated by Atbir et al., 2022 [31] modifying the sequence of wool layers in the opposite direction.	Molds of 300 cm^3	**Thermal conductivity, effusivity and diffusivity**: (Asymmetric Hot Plate method).	[a] Best tradeoff for bricks with 15 % of wool and white clay: – 27 % in conductivity – 15 % in effusivity – 26 % in diffusivity
Atbir et al., 2023 [33]	Porous plaster reinforced with different amounts of twisted wires of sheep wool.	Molds of 300 cm^3 filled with plaster, liquid soap, and twisted wires of wool.	**Thermal conductivity, effusivity and diffusivity**: (Asymmetric Hot Plate method).	Best tradeoff in the sample with 4 % of wool: – 47 % in conductivity – 31 % in effusivity – 53 % in diffusivity.
Cardinale et al., 2017 [27]	Concrete with different amount of recycling wool.	Molds of 1800 cm^3 filled with cement Portland, water and wool fiber cut to a length of 10 mm.	**Thermal conductivity:** (Heat Flow Meter - EN 12664)	Best result for sample with 7 % of wool: – 71,9 % in conductivity
Sharma et al., 2023 [34]	Panel of sheep wool fiber-filled epoxy composites.	Four panels with a composition of 75 %- 25 % resin and wool.	**Thermal conductivity:** (Hot Disk TPS 500)	The sample reference without wool was not tested.
Kicinska -Jakubowska et al., 2023 [39]	Mats with different quantities of vegetable fiber, wool, and jute net as reinforcement.	Five mats with a total of 18 layers and a total weight of 40 kg.	Thermal resistance (Rct): (heat-insulated SGHP−8.2 -PN-EN ISO 11092 standard) Thermal conductivity coefficient (λ): (Laser Comp FOX314 - PN-EN 12667 standard)	The sample reference without wool was not tested.
Patnaik et al., 2015 [29]	Nonwoven mats with varying quantities and types of wool along with different percentages of recycled plastic.	Nonwoven of 300 mm × 300 mm × thickness (ranging from 15 to 17 mm).	**Thermal conductivity: (**Laser Comp Fox 314 heat flow meter -ASTM C518–10 standard).	The sample reference without wool was not tested.
Corscadden et al., 2014 [23]	Two types of wool layers, "carded" and "felted," from five different sheep breeds.	Six insulation panels, each weighing 0.4 kg and with dimensions of 0.61 m x 1.22 m x 0.09 m.	**Thermal resistance RSI:** (hotbox method- ASTM C1363)	The sample reference without wool was not tested.

* The table was designed to express, through percentage data, the influence of the wool fiber on the parameters investigated compared to the control samples without wool fiber.

[a] The best results are achieved for white clay bricks, for all the different percentages of wool.

increased water demand due to the hydrophilic properties of wool was also demonstrated when incorporating wool fibers with cement. The study's authors addressed this issue by testing both natural wool fibers and chemically modified wool fibers to enhance fiber-matrix adhesion, which is compromised by wool's hydrophilic nature. The results indicated that although mechanical performance was compromised for both natural and modified fibers, the modified fibers showed a smaller reduction in performance when mixed with cement [28].

Finally, the only study concerning the mixing of wool fibers with epoxy composites highlighted good fiber-matrix adhesion, achieving acceptable mechanical performance [34]. However, other studies in the literature [35–38] frequently report issues with fiber-matrix adhesion, often requiring chemical treatments on the fiber surface to optimize the mechanical performance of wool and resin-based composites.

3.1.2. Thermal properties

In this second section, all the main results relating to the analysis of the thermal properties of wool-based building components have been reported and discussed. The main thermal properties examined concerned the analysis of the thermal coefficients of conductivity, effusivity and diffusivity. These coefficients provide important information about a material's capacity to conduct, transfer, and diffuse heat with its environment. The information presented in this section is summarized in Table 4.

As reported above, Atbir et al. [31,32], in 2022 and 2023, carried out two research studies related to the valorization and exploitation of the Moroccan sheep wool for obtaining bricks reinforced with wool filament [31,32], and, with the aim of reusing wool filaments for producing porous plaster reinforced [33].

In addition to the results on mechanical behavior shown in the previous section, the first research conducted by Atbir et al. [31] investigated the thermal properties of five bricks reinforced by the wool grid layer method (according to the methodology described in the mechanical section). Thermal conductivity tests were carried out on samples with a volume of 300 cm^3, following the Asymmetric Hot Plate method. The results highlight that the inclusion of yarn, any percentage, for both white clay and red clay, determines a delivery of thermal conductivity, giving this animal fiber reinforcement the qualities suitable for the thermal insulation of buildings. For the sample with the highest wool content equal to 6 %, a thermal conductivity of 0.33 W/(mK) and 0.36 W/(mK) was recorded respectively for the white clay bricks and for the red clay bricks. Furthermore, when comparing the average thermal conductivity of the bricks, estimated to be 0.346 W/(mK), it was found that all brick samples containing white clay and wool fibre had above average thermal insulation properties. This highlights a positive synergy between white clay and wool fibre in improving the thermal insulation capacity of bricks.

In their subsequent study [32], the authors focused on the effect of layers of sheep's wool yarn arranged according to a new method compared to that one previously adopted (according to the methodology described in the mechanical section) on the thermal behavior of the composites. Thermal conductivity, effusivity, and diffusivity were evaluated on the two different bricks with white and red clay reinforced with different quantities of wool from 6 to 27 g. The samples had a volume of 300 cm^3 and a thermal thickness of 30 mm. All three tests were performed according to the asymmetric hot plate method. In general, the results showed that the conductivity, effusivity, and diffusivity decrease when the porosity of the composite increases, i.e., when more wool threads are added. The addition of wool reinforcements reduced the composite's ability to conduct heat, resulting in improved thermal insulation properties. As regards thermal conductivity, a gain ranging from 4 % to 41 % for white and from 6 % to 39 % for red was observed in the wool fractions from 6 to 27 g. Similarly, thermal effusivity shows an increase between 2 % and 24 % for white and between 2 % and 22 % for red in the same wool fractions. Finally, thermal diffusivity records an increase ranging from 4 % to 39 % for white and from 7 % to 37 % for red in the wool fractions considered. Since the optimal amount of wool content is a compromise between compressive strength and thermal properties, the best result was obtained considering 15 g of wool content. The thermo-mechanically best performing sample showed significant improvements in the white clay bricks, with an overall increase of 27 % in thermal conductivity, 15 % in effusivity, and 26 % in diffusivity. For bricks with red clay, an overall increase of 17 % in thermal conductivity, 9 % in effusivity, and 17 % in diffusivity was observed. As already observed in the results of the previous study [31], also in the present study [32], the best results in terms of thermal properties were recorded in bricks filled with wool and white clay.

In their latest research Atbir et al. [33], evaluated the thermal conductivity, effusivity, and diffusivity of porous plaster with a sheep's wool yarn skeleton as a multilayer insulation material (according to the methodology described in the mechanical section). As in the previous study, samples having a volume of 300 cm^3 were tested using the same method as the asymmetric Hot Plate Method. The results confirm what was previously found for bricks. Even in the case of porous plaster, the addition of wool fiber resulted in an overall increase in thermal conductivity, effusivity, and diffusivity with an increase in thermal insulating properties. The incorporation of sheep's wool fibers together with plaster and soap significantly increased the porosity of the composite, generating an increase in conductivity that expanded from 40 % to 52 % (with a minimum and a maximum value of 0.288 Wm^{-1} K^{-1} and 0.605 Wm^{-1} K^{-1} respectively) as the amount of wool increased. As a result, thermal effusivity and diffusivity have increased from 26 % to 39 % and from 42 % to 60 % respectively. This promotes greater energy absorption and slows down heat transmission. Since the optimal amount of wool content is a compromise between compressive strength and thermal properties, the best result was obtained considering 4 % of wool content. The thermo-mechanically best performing sample showed significant improvements, with an overall increase of 47 % in thermal conductivity, 31 % in effusivity, and 53 % in diffusivity.

In the research conducted by Cardinale et al. [27] it was demonstrated that the use of wool fiber in the mortar (according to the methodology described in the mechanical section) for the application of wall coverings contributed to significantly reducing the thermal conductivity values. Thermal conductivity was measured using a heat flow meter on samples having a volume equal to 1.8 cm^3 and according to the EN 12664:2002 standard. Samples containing different percentages of wool equal to 2 %, 5 % and 7 % recorded a conductivity demand of 24.4 %, 63.8 %, and 71.9 % respectively. These results confirm the excellent thermal insulating properties of wool even inside mortars. Furthermore, the authors compared wool fiber-reinforced mortar panels to a common one, widely used and sold gypsum plasterboard, which could become a competitor for natural fiber-based panels, such as wool-based ones, in the future of the future market. The results indicated that the gypsum plasterboard had higher thermal conductivity and therefore lower thermal performance compared to samples with 5 % and 7 % wool fibre. However, the thermal conductivity of the plasterboard panel was better than that reported for the panel with only 2 % of wool, highlighting once again how a greater percentage of wool introduced into the mortar significantly improved the thermal behavior.

The four panels with a 75 % resin and 25 % wool blend, described by Sharma et al. [34], were subjected to thermal tests to evaluate the impact of introducing wool fibers in different forms on the thermal properties (according to the methodology described in the mechanical section). Using the Hot Disk TPS thermal analyzer and following the ASTM D3418 standard, the results showed significant variations in thermal conductivity due to different ways of processing the wool. The compressed and rolled felt panel showed the highest thermal conductivity (i.e., 0.23478 W/mK), indicating a lower insulating capacity. On the contrary, the panel with bidirectional woven wool recorded the lowest thermal conductivity (i.e., 0.22249 W/mK), demonstrating a greater insulating capacity. The thermal superiority of the two-way wool panel over the rolled one is attributable to its ability to trap more air, thus contributing to greater porosity and, consequently, better thermal efficiency.

The research carried out by Kicinska -Jakubowska et al. [39] aimed at evaluating the acoustic and thermal properties of mats produced by means of the needle-punching technique with different wasted natural fiber. Overall, five mattresses were produced and tested using a combination of hemp and flax fibers, along with sheep wool and a jute net. Specifically, the first sample did not contain wool fibers, three contained hemp, flax, and wool fibers in different compositions (25 %, 50 %, 75 %), and the last one consisted of 100 % wool. Hemp and flax fibers had an average length of 69 mm, while wool fibers had an average length of 108 mm and a diameter ranging from 41 to 77 μm. The use of jute net for each produced mattress had a thickness of 1.1 mm and was necessary to provide additional reinforcement to the non-woven mattresses. Each mattress weighed 40 kg and was composed of eighteen layers with an overall density of 50 cm2. The values of thermal resistance and thermal conductivity coefficient were examined in accordance with the PN-EN ISO 11092 and PN-EN 12667 standards, respectively. The results revealed a positive correlation between the percentage of wool and the increase in thermal resistance, with a 75 % increase compared to the mattress composed of 100 % hemp and flax, reaching a maximum value of 0.2443 m^2 K/W. In addition, the thermal conductivity coefficient shows a significant improvement with the presence of wool. This recorded a reduction of approximately 40 % compared to the value found for the mattress composed of 100 % other natural fibres, reaching a minimum of 0.034 W/mK. Among the five produced mattresses, those composed of 75 % wool and 100 % wool recorded the best results, confirming the high insulating power of animal fiber.

Patnaik et al. [29] carried out a study using the needle punched technique to create and test five mattresses with different combinations of wool and recycled polyester (RPET). The wool used in the study came from two distinct sheep breeds, Coring and Dorper. The size of the fibers from the two breeds differed, with lengths of 22 mm and 38 mm and diameters of 20.7 μm and 28.6 μm for Coring and Dorper, respectively. The authors motivated the adoption of wool fibers in combination with RPET due to the limited availability of wool in the study area, South Africa. Three mattresses were made, each composed of 100 % Coring wool, 100 % Dorper wool, and 100 % RPET. The two remaining mattresses had a balanced composition of 50 % Coring wool and 50 % RPET, and 50 % Dorper wool and 50 % RPET, respectively. The manufacturing process was consistent for all five mattresses, with the only variation being the thickness, which ranged from 15 to 17 mm. All mattresses were treated with a 5 % solution of diammonium phosphate and sodium tetraborate to improve flame retardancy in line with industry standards and reduce susceptibility to microorganisms such as fungus and moths. Mattresses containing wool were also treated with 1 % silicon to increase their resistance to moisture. The main objective of the silicon-based treatment was to determine whether the high hydrophilicity of wool fibers and the consequent high moisture absorption could interfere with the thermal performance of mattresses. However, the moisture absorption observed following the treatment ranged between 4 % and 6 %, slightly higher than the specific minimum requirement of 2 %. Despite this, no reductions in thermal performance were observed, as the silicon treatment effectively acted as a barrier against moisture penetration. For the five different selected mattresses, thermal properties were evaluated in accordance with the ASTM C518–10 standard. The main result is that there were no significant variations in the thermal conductivity values among the various samples. The authors were able to demonstrate that the thermal conductivity of the mattress with 50 % wool and 50 % RPET was comparable to that of the mattress composed of 100 % wool, with an average value of 0.032 W/mK. This result emphasizes that optimal thermal performance can be achieved even by using a lower percentage of wool along with other waste materials, following a circular economy approach.

Corscadden et al. [23] developed a pilot project on the production of wool insulation. Two types of padding were produced: 'carded' and 'felted', both with the same dimensions of 0.6096 m × 1.2192 m × 0.0889 m ($2' \times 4' \times 3.5''$) and a weight of 0.4 kg per unit. The study used wool from five different sources: Romanov, Suffolk, North Country Cheviot, and two commercial breeds referred to as 'Commercial A′ and 'Commercial B′. Thermal resistance (RSI) values were measured for all five mattresses in accordance with the ASTM C1363 standard. The thermal resistance results were comparable. On average, the mattresses had a thermal resistance of approximately 0.6015 m^2 K/W. The mattress with North Country Cheviot wool demonstrated the best performance with an RSI of 0.6101 m^2 K/W. The achieved results confirmed the wool insulation properties values comparable to those ones found in literature related to other materials like fiberglass, polystyrene, and cellulose. Therefore, also in this case, the analyses revealed the good insulation properties provided by the presence of wool.

As reported in Table 4, the increase in the percentage of wool used as reinforcement fiber, both in bricks [31,32] and in plaster [33], significantly improved thermal performance. In bricks, in particular, performance was further optimized when combined with white clay. The same conclusion applies to the use of sheep wool as reinforcement in mortar for wall coatings, which showed superior thermal performance compared to traditional gypsum panels [27]. For the production of panels and mattresses, it has been demonstrated that different processing techniques and the orientation of wool within the panels studied can enhance thermal performance

[34]. Additionally, comparisons between various panels and mattresses with different percentages and combinations of wool and other natural fibers [39], and panels with wool and recycled synthetic fibers [29], have highlighted that the best performance is achieved by increasing the percentage of incorporated wool, with the maximum result obtained when the panel is composed of 100 % wool. This result was also confirmed by Corscadden et al. [23], who reported that wool-based insulating panels have thermal performance comparable to materials such as glass, polystyrene, and cellulose.

3.1.3. Acoustic properties

In this last section, all the main results relating to the analysis of the acoustic properties of wool-based building components have been reported and discussed. The main examined acoustic properties include the sound absorption coefficient and the noise reduction coefficient (NRC). In detail, the NRC is the index which quantifies the sound absorption capability by measuring the average of the sound absorption coefficients which depend on the frequency, moreover it is also adopted to characterize the acoustic barrier of the product [41]. The information presented in this section is summarized in Table 5.

Alyousef [28] conducted a study to test the effect of two types of wool fiber on concrete. As mentioned previously, "natural" wool fibres, subjected exclusively to a cleaning pre-treatment, and "modified" wool fibres, subjected to a cleaning pre-treatment and a chemical surface treatment to enhance the fibre/cement interaction, were used. The research investigated the acoustic properties initially on wool-free concrete and subsequently on reinforced concrete containing a percentage varying from 0.5 % to 2.5 % of wool, both natural and modified. The analysis aimed to evaluate the acoustic properties in terms of sound absorption and noise reduction (NRC). Furthermore, two other indices, commonly considered in the literature, were evaluated to quantify sound absorption: the Sound Transmission Loss Coefficient (TLC) and the Sound Transmission Class (STC) [41]. Alyousef's research [28] demonstrates a significant improvement in the sound absorption coefficients of concrete enriched with 1 % wool, both natural and modified. Specifically, at the frequency of 2000 Hz there is a marked increase, with values of 0.66 and 0.75 respectively. These results contrast with the sound absorption coefficient of wool-free concrete, which had a significantly lower value of 0.25. The noise reduction coefficient (NRC) is also significantly improved with the addition of 1 % wool for both natural and modified fibers with a percentage of 38.9 % and 42.6 % respectively, far higher than 9.5 % recorded for wool-free concrete mix. By increasing the noise reduction, there was also a decrease in the TLC and STC coefficients for all concretes with natural and modified wool. The inclusion of waste wool fiber within the concrete significantly improved its overall acoustic properties. As evidenced by the values reported for the sound absorption coefficient and the NRC, the concrete containing the modified fibers has superior acoustic performance. This result confirms the sagacity of the authors in applying a chemical treatment to the fiber, concretely obtaining an improved fiber-cement interaction, with consequent enhancements in the acoustic properties. In all cases, the hollow structure of the fibers acts as an effective sound trap, hindering sound

Table 5
acoustic properties of wool-based building components.

Reference	Type of sample	Dimensions of the sample	Type of tests	Acoustic properties upgrade*
Alyousef, 2022 [28]	Concrete composites reinforced with wool fiber.	Two cylindrical molds measuring 99 mm×100 mm and 28 mm×100 mm. The wool fiber inside it had lengths ranging from 60 to 70 mm and diameters varying between 95 and 130 μm.	**Sound absorption coefficient and Noise Reduction Coefficient- NRC** (ASTM E1050–19 and ASTM E413–16 standards for frequencies of 50–1500 and 1500–4000 Hz).	[a] Best acoustic property in concrete with "modified wool": + 212,5 % sound absorption coefficient; + 9,5 % NRC
Kicinska -Jakubowska et al., 2023 [39]	Mats with different quantities of vegetable fiber, wool, and jute net as reinforcement	Five mats with a total of 18 layers and a total weight of 40 kg.	**Sound absorption coefficient and Noise Reduction Coefficient-NRC** (PN-EN ISO 10534 standard)	The sample reference without wool was not tested.
Patnaik et al., 2015 [29]	Nonwoven mats with varying quantities and types of wool along with different percentages of recycled plastic.	Nonwoven of 300 mm × 300 mm × thickness (ranging from 15 to 17 mm).	**Sound absorption coefficient** (ASTM E1050–10 standard test method.	The sample reference without wool was not tested.
Ulutas et al., [22]	Twenty insulating panels, each composed of different materials, were subjected to comparison.	Different panels from literature.	Assessment of the following criteria.: VDRF, SAC, EC, EE, C, RF, SHC, TC, and D.	Sheep wool panels were ranked as the top alternative in the selection process.
Del Rey et al., 2017 [40]	Seven non-woven fabric made from 80 % wool from two different breeds (Merino, Churro) and 20 % recycled PET flakes.	**Merino wool:** 60–80 mm in length and 18–20 μm in diameter. **Churro wool:** 80–120 mm in length and 35–40 μm in diameter	**Sound absorption coefficient for normal incidence** (following the ISO 10534–2 standard) **Sound absorption coefficient in reverberation chamber** (following ISO 354 standard).	The sample reference without wool was not tested.

* The table was designed to express, through percentage data, the influence of the wool fiber on the parameters investigated compared to the control samples without wool fiber.

[a] "Natural" fiber (subjected only to a cleaning pre-treatment); "modified" fiber (subjected to a cleaning pre-treatment and a chemical pre-treatment to improve the fiber-cement interaction.

transmission. This result underlines the considerable potential of this waste in the role of insulating material.

In addition to analysing the thermal properties of wool and bast fibre mats, in their study Kicinska-Jakubowska et al. [39], also investigated their ability to act as effective acoustic insulators. The evaluation focused on the sound absorption coefficient and the noise reduction coefficient (NRC). The results obtained for the mats with varying percentages of wool and vegetable fibres, as described in the thermal section, showed that those with a higher percentage of vegetable fibres (a mixture of hemp and linen) had better acoustic properties. The optimal performance for both the sound absorption coefficient and the noise reduction coefficient (NRC) is evident in the mat containing 75 % vegetable fibers and 25 % wool. This mat exhibits higher sound absorption values, ranging between 0.09 and 0.90, and a notable NRC of 0.34. Mattresses with a wool percentage greater than 25 % experienced a decrease in NRC of up to 6 %, with a minimum value of 0.28 found in the mattress containing 100 % wool. However, the acoustic performance of all the examined mattresses, although reduced in the presence of a greater quantity of wool, demonstrated a good ability to absorb sounds at medium and high frequencies, with a decrease in this ability at low frequencies.

Patnaik et al. [29], in their research study, also assessed the sound absorption coefficient of the previously introduced five mats (according to the methodology described in the thermal section), confirming its dependency on the frequency range. This dependence was observed to be lower at low frequencies and higher at medium and high frequencies, as previously identified by Kicinska-Jakubowska et al. [39]. Through the comparison between the five mats, it was observed that the recycled polyester (RPET) had the lowest sound absorption coefficient of 0.6. In contrast, the mattress with 50 % Dorper wool and 50 % recycled polyester had the highest value of 0.75, indicating that this combination provides the best sound insulation which resulted above 70 % overall along the full frequency spectrum. Moreover, in this study, the authors analyzed the effect of the thickness and the tortuosity of the mats. Greater thickness promotes greater thermal dispersion of sound waves, limiting their propagation. Tortuosity, measured as the ratio between the length of open pores and material thickness, indicates the degree to which sound waves follow a tortuous path. A greater thickness causes sound waves to pass through more tortuous paths, resulting in greater friction losses and an increase in the sound absorption coefficient. Conversely, a lower thickness does not generate significant losses. In conclusion the authors confirmed the sheep-wool very good sound insulation properties as compared to polystyrene or rock wool for wall insulation application.

In the research carried out by Ulutas et al. [22] the authors aimed to build an integrated method Multi-Criteria Decision Making (MCDM) to find the best insulating material to be further used in the building sector for optimizing the energy efficiency. A total of 20 insulating panels made from various materials were compared, including Cotton stalk fibers, Cotton waste, Hemp, Kenaf, Rice husk, Sheep wool, Wood fiber, Cellulose, Cork, and Flax. The assessment was based on a set of parameters used as criteria to fulfill selecting the most efficient material. The criteria ranged from the resistance to vapor passage (VDRF) to the capability to absorb sound (SAC), including the production of pollutants such as CO_2 (EC), the required energy to be spent from the extraction to the disposal (EE), environmental and social sustainability of the process (C), fire resistance (RF), the required heat to raise the material temperature (SHC), the amount of heat flow per unit time (TC) and the material density (D). Starting from initial 20 different materials, the outcome provided by the adopted algorithm puts the sheep wool at the first position in the ranking of the considered materials, by strongly confirming the potential of the waste sheep wool as suitable insulating material.

Del Rey et al. [40] developed a study on the acoustic characteristics of sheep's wool combined with PET flakes, obtained through a thermofusion process. Seven distinct nonwovens were manufactured using a composition of 80 % wool and 20 % recycled PET fibre. The nonwovens varied in density (ranging from 25 to 40 Kg/m^3), weight (ranging from 1200 to 2000 g/m^2), and thickness (ranging from 40 to 60 mm). Two types of wool were used in this study. The first type was Merino wool, which is considered top quality and produces fine fibers that are 60–80 mm long and 18–20 μm in diameter. The second type was Churro wool, which is considered second quality and has fibers that are 80–120 mm in length and 35–40 μm in diameter. An analysis was carried out to measure sound absorption coefficients at normal and diffuse incidence in accordance with ISO 10534–2 and ISO 354 standards. In both cases, high values of the sound absorption coefficient were recorded, particularly at medium and high frequencies, especially when the component had a greater thickness. The study concludes that the use of two different qualities of wool, first and second quality, did not affect sound absorption. The sample containing 40 % first quality wool and 40 % second quality wool recorded a sound absorption between 0.8 and 0.9, which is even higher than that reported for mineral wool or recycled polyurethane foams. This implies that even inferior quality wool, which is unsuitable for the textile industry, can be utilised in the manufacturing of building components for sound insulation owing to its exceptional sound-absorbing characteristics.

As outlined in Table 5, incorporating wool into concrete, whether in its natural state or chemically modified to enhance matrix adhesion, resulted in a significant increase in acoustic absorption coefficients and noise reduction, particularly at mid and high frequencies. Notably, the chemically modified fibers exhibited even better results, underscoring the importance of chemical treatment for achieving superior performance [28]. Carpets made from a blend of wool and plant fibers such as hemp and flax also demonstrated enhanced performance at mid and high frequencies. The optimal performance was observed in carpets composed of 75 % natural fibers and 25 % wool. Interestingly, increasing the wool percentage led to a decrease in acoustic performance, highlighting the superior efficacy of plant fibers. Nonetheless, carpets with a higher wool content still maintained commendable performance [39].

In a study examining five mattresses with varying proportions of wool fibers and recycled polyester (RPET), the optimal acoustic performance was found to be frequency-dependent. The mattress with a 50 % wool and 50 % RPET composition exhibited the best acoustic insulation, showcasing wool's versatility when combined with other materials. Additionally, mattresses with higher wool content outperformed those documented in the literature for polystyrene and rock wool. Moreover, it was confirmed that thicker mattresses enhance the thermal dispersion of sound waves and increase the tortuosity of the sound path through the material, thereby improving the acoustic absorption coefficient [29].

The combination of wool and polyester (PET) was also utilized in the production of seven non-woven fabrics via a thermo-fusion process. This study reaffirmed the superior performance of thicker fabrics at mid and high frequencies, surpassing the capabilities of rock wool and recycled polyester foams [40]. Finally, through an integrated method using Multi-Criteria Decision Making (MCDM) to identify the best insulating material in the construction sector, 20 different panels made from materials such as hemp, flax, kenaf, and sheep wool were compared. Sheep wool emerged as the top choice, highlighting its remarkable potential as an effective and sustainable insulating material, particularly valued for its exceptional acoustic absorption properties [22].

3.2. Wool transformation process and its problems

Although significant literature exists on the mechanical, thermal, and acoustic properties of wool, the economics and manufacturing aspects related to the wool treatment and processes are less explored. In this new section, the reported reviewed articles highlighted the main aspects, advantages, and disadvantages of the manufacturing process of insulating panels, and the critical issues related to the use of high volumes of water.

Corscadden et al. [23] in their research study, introduced a pilot project considering, beside the others, also the economic aspects, and the production-scale of sheep wool insulation. The analyzed process began from the examined raw wool (from North America area) through five different steps: tumbling (bris falls removal); scouring (purging); picking (wool fibres separation); carding (fibers combing); and wet felting (wool fibres compacting). For each of the considered steps the authors assessed the yield, waste, processing time and throughput, energy consumption, manpower cost and water requirements and overall process costs. The highest costs which came out from the analysis resulted the raw material (wool), labor, electricity, and water. Indeed, the raw material cost is relatively high due to the material loss which comes from the scouring phase of the process, up to 40 % material loss. The third highest cost comes from labor, followed by the amount of water spent during the scouring phase. Since the raw wool contains high impurities, these must be washed out. Considering an insulation batt or unit with a weight of 0.4 kg/unit (i.e., 0.6096 m x 1.2192 m x 0.0889 m) the evaluation of the production cost per unit reported by the authors was $1 deriving from the material, $3.38 deriving from the labor, $0.99 deriving from electricity and $0.03 due to water consumption, with a total estimated cost, without considering the capital costs, shipping, distribution, marketing, and margin for resellers, of about $5.4 per unit. As stated by the authors, the evaluated high costs might be justified if the production chain was capable to produce yearly higher volumes of material to make the process more sustainable, for example, involving more automation. Indeed, from the study, it has been pointed out that the main constrain of the manufacturing phase derives from the deployment of picker and carder machines, which can produce a maximum of 10.88 kg every 8 hours and therefore around 2829 kg in a year. Therefore, defining the optimal manufacturing process by varying production scales represents the key factor to provide a less impactful process from an economic point of view.

As reported by Corscadden et al. [23] and confirmed by Allafi et al. [30], one of the main issues in the manufacturing process of the waste wool is the water consumption. The high dependence on water-based treatment is one of the major environmental concerns because of the associated generation of significant amounts of wastewater with pollutants. As stated by Allafi et al. [30], the washing phase is necessary due to the presence of impurities such as wax, grease, suint, mineral soil, dead skin, dust, and vegetable matter. Indeed, the raw dirty wool undergoes water-based treatments, like scouring, bleaching, fulfilling and carbonization, that imply high volume consumptions of both water and chemicals, generating huge volumes of toxic effluents from wet-chemical treatment processes. In this regard, wastewater processing to remove impurities prior to the discharge or recycling of water, was confirmed critical and crucial due to the impact on the environment and economic.

For these reasons, the yearly wool production in the textile industry has dropped by the 75 % and the scientist community is currently assessing alternative water-based treatment methodologies to be applied to the sheep wool processing. Through the conventional water-based treatments the sheep wool undergoes adverse conditions like mechanic compression, pH, temperature, and chemical compounds, which lead to a loss of fiber strength and in general to mechanical damages of the fiber. Therefore, in their study [30], the authors recommended using the supercritical carbon dioxide technology ($scCO_2$) as a valid alternative to solve the aspects related to the water consumption, microbes' contamination, and fiber deterioration. Indeed, the $scCO_2$ technology is based on gases and permits the extraction, sterilization, cleaning and drying. In detail, it was demonstrated that the low viscosity, high diffusivity, and low surface tension of the $scCO_2$ facilitated the extraction of wax material. The achieved results of the extraction of Lanolin showed that approximately the 98 % of wool wax acids have been dissolved in $scCO_2$, without any impact on the color and the status of the fiber. Furthermore, it was shown that, beside the Lanolin, the $scCO_2$ could completely also extract the lipids and the other impurities within 45 minutes. The sterilization is allowed bringing the $scCO_2$ to a supercritical working point in terms of high temperature and pressure, so to sterilize the materials which are more sensitive to the heat without causing any damage. In detail, the drying process through $scCO_2$ is a delicate process which can be executed at low temperature and relatively low pressure, without degrading the material and avoiding mechanical failures. Furthermore, the authors reported that the wool fibres treated by $scCO_2$ improved their thermal properties. Other main advantages such as the absence of toxic effluents, an overall shorter process in terms of time, lower processing cost and improved dyeability were highlighted by the authors thanks to the use of the $scCO_2$ technology. Nevertheless, this technology has also some limitations coming from the high cost associated to deploy high-pressure circuit and the low solubility of polar compounds that would require the addition of organic solvents (i.e., Ethanol) to increase the solubility. Finally, the authors stated that, this technology could represent a valid solution to replace the conventional water-based treatments of the wool once suitable polar solvents are determined to optimize the solubility of the CO_2.

3.3. Localization of wool waste for a new supply chain

Despite all criticalities related to the transformation and manufacturing of wool in the construction sector and the massive use of water, in some areas the reuse of such precious fiber increasingly attracts the scientific community attention. Many researchers carried out studies on which the disposal of wool is utmost of importance. The articles reported in this third and last section aimed to locate and quantify the waste wool to design a proper network of collection centers which can allow the development of new-closed supply chains. The first selected research, carried out by Parlato et al. [4] analyzed and discussed how the disposal of the wool is becoming nowadays a significant ecologic issue. Indeed, the authors reported that, yearly million tons of wool without any post application have been produced. This occurred because the wool is coarse and classified as “waste” therefore not suitable for textile industry. In their study the Geographic Information Systems (GIS) tool was used to evaluate the distribution of sheared sheep wool in Italy with the aim of developing an adaptive manufacturing process of sheep wool insulating products. In their article, for the first time, the authors introduced a hypothetical building insulator production based on wool waste, soft mats (100 % wool) and semi-rigid panels (80 % wool and 20 % polyester). According to the research, the reuse of the wool waste (e.g., more than 9.8 million kg/year) could contribute at generating more than 1.5 million of soft mats or more than 11.5 million of semi-rigid panels. Based on the achieved results related to the quantification of the insulating mats, still in 2022, Parlato et al. [6] carried out a research study focused on the waste wool localization. In this research, Sicily region was selected as study area, since it is the second Italian region for number of livestock and therefore with highest amount of wool without any reuse process. In their study one of the objectives was to identify those areas more suitable to host new centers in which the wool can be collected and turned into a green building material ready to be deployed. With the aim of minimizing the environmental impact derived from the logistic and supply phase suitable territorial areas were identified. The adopted methodology, using as input the sheep farms, the number of sheep and the amount of wool produced in a year, allowed the authors to select three areas, respectively belonging to three different Sicilian provinces located in the South, North-East, and South-East of the region. The proposed methodology could be further adopted worldwide since it provides a valid support to develop a whole sustainable chain which properly reuses the wool within the context of circular green economy. In this regard, starting a new structured wool chain, of which this work showed a first representation, and reducing the huge amount of livestock wastes would lead to benefits on the environment and the humans and animals’ wellness.

4. Discussions

Based on the findings from this review, it is evident that the thermal and acoustic performance of wool-based building components significantly surpasses their mechanical performance.

- Thermal Properties: All studies on the thermal properties of sheep wool in composites indicate that increasing wool content enhances thermal resistance. This improvement is due to the high porosity of wool, which traps air and boosts thermal efficiency to levels comparable to conventional materials like glass, polystyrene, and cellulose.
- Acoustic Properties: Wool fibers exhibit excellent acoustic performance because their hollow structure effectively traps sound, particularly at mid and high frequencies, although this ability decreases at low frequencies. Additionally, for mats, mattresses, and non-woven fabrics, increased thickness favors greater thermal dissipation of sound waves and increases the tortuosity of the path through the material, thereby improving the acoustic absorption coefficient.
- Mechanical Properties: heep wool generally shows inferior performance in mechanical properties for most building applications. In bricks and plaster reinforced with wool, an increase in wool percentage improved flexural strength but compromised compressive strength in all analyzed studies. Using wool as reinforcement for mortars and cement resulted in a general decline in mechanical properties, exacerbated by the increased wool fiber content. This decline is primarily due to the increased water needed to improve workability and compaction of the matrix. The reviewed articles attribute the decline in mechanical performance to wool’s porosity and hydrophilic properties.

A distinctive feature of wool fiber is its hygroscopic nature, enabling it to absorb water from 13 % to 18 % of its dry weight at 65 % relative humidity, and up to 40 % at 100 % relative humidity [42]. This characteristic is particularly valued for building thermal and acoustic insulation, contributing to both sound absorption and thermal insulation, thereby enhancing building comfort and reducing energy consumption for heating and cooling. The literature confirms that wool-based building components offer thermal and acoustic performance comparable to materials like fiberglass, polystyrene, and rock wool, with the added benefits of being eco-friendly and derived from a renewable resource [23,29]. However, the hydrophilic nature of wool can be a disadvantage in some construction applications [43,44].

As discussed, the mechanical properties of wool-based building components are compromised by the fiber’s moisture retention, especially when used as reinforcement in mortars [27] and cement [28]. Authors report that this decline is linked to the need for larger water amounts to achieve proper compaction and workability. Other studies stress the importance of carefully evaluating the use of natural fibers like wool in humid environments [45,46]. A potential solution could be preliminary chemical treatments to reduce wool’s hydrophilicity and improve matrix adhesion [47].Moreover, issues related to wool’s high hydrophilicity, which lead to poor fiber-matrix adhesion and mechanical performance decline, also affect the durability of wool-based composites. This is closely linked to matrix adhesion [48]. The literature indicates that the durability of natural fiber composites, such as wool, is significantly influenced by environmental degradation [19]. In composites where wool is mixed with lime and cement, the fiber is exposed to aggressive conditions due to the high alkalinity of the matrix, leading to fiber deterioration and compromised durability due to corrosion, similar to other natural fibers used in such applications [49,50].

5. Conclusion and future trends

The authors of the research studies reviewed for this systematic literature review focused on the issues related to use of wool fibers in the green building sector. As demonstrated by the final number of few papers, the presence of the topic in the scientific literature is still limited but continuously increasing, proving the interest in reusing these fibres. The reviewed articles primarily analysed the mechanical, thermal, and acoustic properties of building components containing wool fibres. The findings from these studies indicate a growing recognition of the potential benefits of using wool fibers in sustainable construction. Despite the relatively limited number of studies, the increasing interest is evident, highlighting the unique properties and advantages of wool fibers in building applications. The research reviewed spans various aspects, focusing primarily on the mechanical, thermal, and acoustic properties of wool-fiber-based building components. These properties position wool fibers as a promising alternative to traditional building materials. Considering the achieved results:

- Thermal Insulation: Wool fibres are highly effective for thermal insulation, significantly enhancing the thermal performance of building components.
- Mechanical Properties: While wool fibres improve the resistance of building components to flexural loads, they negatively impact the compressive behaviour of these components.
- Acoustic Properties: Wool fibres exhibit excellent sound absorption capacity, making them a viable alternative to conventional non-renewable materials for acoustic insulation.
- Economic Considerations: Economic analysis highlights the need to reduce the high costs associated with raw materials, labour, energy, and water consumption in the production process.
- Sustainable Manufacturing: Developing a sheep wool fibre manufacturing process that minimizes water consumption is crucial. Implementing new, sustainable technologies is essential to reduce the environmental and economic impacts associated with the wool cleaning process.

Several challenges and areas for improvement remain. To advance the application of wool fibres in green building components, the following steps are recommended:

- Enhance Mechanical Properties: Improve the mechanical properties of wool-based building components by enhancing fiber-matrix adhesion through chemical treatments designed to reduce wool hydrophilicity.
- Scale Production: Define a production scale suitable to market demand.
- Reduce Water Consumption: Implement new technologies for wool treatment to reduce water consumption.
- Prototype Testing: Investigate the potential use of sheep wool fibre in new green building components through mechanical and physical testing of prototypes.
- Life Cycle Assessment (LCA): Apply LCA methodology to assess the sustainability of the entire process and compare environmental impacts with alternative wool-based products.

These steps could represent a significant advancement in planning the sustainable reuse of wool waste as a natural, renewable, and biodegradable fibre within the construction sector, creating a new supply chain and addressing disposal issues.

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Giusi Midolo: Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Marta Del Zoppo:** Writing – review & editing, Visualization, Validation, Data curation, Conceptualization. **Simona M.C. Porto:** Visualization. **Francesca Valenti:** Writing – review & editing, Visualization, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

References

[1] United Nations Resolution 70/1. Transforming Our World, The 2030 Agenda for Sustainable Development, Adopted by the General Assembly on 25 September 2015, https://documents-dds-ny.un.org/doc/UNDOC/GEN/N15/291/89/PDF/N1529189.pdf?OpenElement.
[2] United Nations Framework Convention on Climate Change, UNFCCC. The Paris Agreement - Publication. Paris Climate Change Conference - November 2015. Publication date. 29 Nov 2018. Available at link: https://unfccc.int/documents/184656
[3] European Commission, The European green deal, European Commission 53 (2019) 24, https://doi.org/10.1017/CBO9781107415324.004.
[4] M.C.M. Parlato, S.M.C. Porto, F. Valenti, Assessment of sheep wool waste as new resource for green building elements, Build. Environ. 225 (2022) 109596, https://doi.org/10.1016/j.buildenv.2022.109596.
[5] T.M. Tiza, S.K. Singh, L. Kumar, M.P. Shettar, S.P. Singh, Assessing the potentials of Bamboo and sheep wool fiber as sustainable construction materials: a review, Mater. Today Proc. 47 (2021) 4484–4489, https://doi.org/10.1016/j.matpr.2021.05.322.
[6] M.C.M. Parlato, F. Valenti, G. Midolo, S.M.C. Porto, Livestock wastes sustainable use and management: assessment of raw sheep wool reuse and valorization, Energies 15 (2022) 3008, https://doi.org/10.3390/en15093008.
[7] J.R. Zhao, R. Zheng, J. Tang, H.J. Sun, J. Wang, A mini-review on building insulation materials from perspective of plastic pollution: current issues and natural fibres as a possible solution, J. Hazard. Mater. 438 (2022) 129449, https://doi.org/10.1016/j.jhazmat.2022.129449.
[8] S. Liuzzi, S. Sanarica, P. Stefanizzi, Use of agro-wastes in building materials in the mediterranean area: a review, Energy Procedia 126 (2017) 242–249, https://doi.org/10.1016/j.egypro.2017.08.147.
[9] Z. Duan, Q. Deng, C. Liang, Z. Ma, H. Wu, Upcycling of recycled plastic fiber for sustainable cementitious composites: A critical review and new perspective, Cem. Concr. Compos. 142 (2023) 105192, https://doi.org/10.1016/j.cemconcomp.2023.105192.
[10] W. Liu, H. Zhang, C. Liu, Y. Zhu, C. Wu, Z. He, Wang, Recycled aggregate concrete with the incorporation of rice husk ash: mechanical properties and microstructure, Constr. Build. Mater. 351 (2022), https://doi.org/10.1016/j.conbuildmat.2022.128934.
[11] Sangmesh B. Patil, N. Jaiswal, K.K. Gowrishankar, T.P. Selvakumar, K.K. Jyothi, M.S. Jyothilakshmi, R. Kumar, S. Development of sustainable alternative materials for the construction of green buildings using agricultural residues: a review, Constr. Build. Mater. 368 (2023) 130457, https://doi.org/10.1016/j.conbuildmat.2023.130457.
[12] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials (2015), Sustain, Mater. Technol. 4 (2015) 1–17, https://doi.org/10.1016/j.susmat.2015.05.002.
[13] R. Murano, N. Maisano, R. Selvaggi, G. Pappalardo, B. Pecorino, Critical issues and opportunities for producing biomethane in Italy, Energies 14 (9) (2021), https://doi.org/10.3390/en14092431.
[14] F. Valenti, M.C.M. Parlato, B. Pecorino, R. Selvaggi, Enhancement of sustainable bioenergy production by valorising tomato residues: a GIS-based model, Sci. Total Environ. 869 (art. no) (2023) 161766, https://doi.org/10.1016/j.scitotenv.2023.161766.
[15] M.C.M. Parlato, F. Valenti, S.M.C. Porto, Spatial analyses to assess the availability of sheep wool as potential eco-friendly material, 252 LNCE, Lect. Notes Civ. Eng. (2022) 155–164, https://doi.org/10.1007/978-3-030-98092-4_17.
[16] F. Valenti, R. Selvaggi, B. Pecorino, S.M. Porto, Bioeconomy for sustainable development of biomethane sector: potential and challenges for agro-industrial by-products, Renew. Energy 215 (art. no) (2023) 119014, https://doi.org/10.1016/j.renene.2023.119014.
[17] Barth M., Carus M. Carbon footprint and sustainability of different natural fibres for biocomposites and insulation material. nova-Institute publishes first results of the sustainability assessment within the project Multi Hemp, April 8, 2015, http://eiha. org/media/2019/03/19–03-13-Study-Natural-Fibre-Sustainability-Carbon-Footprint.pdf⟩.
[18] A. Karimah, M.R. Ridho, S.S. Munawar, D.S. Adi, Ismadi, R. Damayanti, B. Subiyanto, W. Fatriasari, A. Fudholi, A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations, J. Mater. Res Technol. 13 (2021) 2442–2458, https://doi.org/10.1016/j.jmrt.2021.06.014.
[19] O. Starkova, A. Sabalina, V. Voikiva, A. Osite, Environmental effects on strength and failure strain distributions of sheep wool fibers, Polymers *14* (2022) 2651, https://doi.org/10.3390/polym14132651.
[20] S.K. Ramamoorthy, M. Skrifvars, A. Persson, A review of natural fibers used in biocomposites: plant, animal and regenerated cellulose fibers, Polym. Rev. *55* (2015) 107–162, https://doi.org/10.1080/15583724.2014.971124.
[21] M.C.M. Parlato, M. Cuomo, S.M.C. Porto, Natural fibers reinforcement for earthen building components: Mechanical performances of a low quality sheep wool (Valle del Belice sheep), Constr. Build. Mater. 326 (2022) 126855, https://doi.org/10.1016/j.conbuildmat.2022.126855.
[22] A. Ulutas, F. Balo, A. Topal, Identifying the most efficient natural fibre for common commercial building insulation materials with an integrated PSI, MEREC, LOPCOW and MCRAT model, Polymers 15 (2023) 1500, https://doi.org/10.3390/polym15061500.
[23] K.W. Corscadden, J.N. Biggs, D.K. Stiles, Sheep's wool insulation: a sustainable alternative use for a renewable resource? Resour. Conserv. Recycl. 86 (2014) 9–15, https://doi.org/10.1016/j.resconrec.2014.01.004.
[24] M. Murillo, A. Sánchez, A. Gil, G. Araya-Letelier, C. Burbano, Y.F. Silva, Use of animal fiber-reinforcement in construction materials: a review, Case Stud. Constr. Mater. (2023) e02812, https://doi.org/10.1016/j.cscm.2023.e02812.
[25] F.I. Mahir, K.N. Keya, B. Sarker, K.M. Nahiun, R.A. Khan, A brief review on natural fiber used as a replacement of synthetic fiber in polymer composites, Mater. Eng. Res. *1* (2) (2019) 86–97, https://doi.org/10.25082/MER.2019.02.007.
[26] M.A. Fuqua, S. Huo, C.A. Ulven, Natural fiber reinforced composites, Polym. Rev. *52* (3) (2012) 259–320, https://doi.org/10.1080/15583724.2012.705409.
[27] T. Cardinale, G. Arleo, F. Bernardo, A. Feo, P. De Fazio, Thermal and mechanical characterization of panels made by cement mortar and sheep's wool fibres, Energy Procedia 140 (2017) 159–169, https://doi.org/10.1016/j.egypro.2017.11.132.
[28] R. Alyousef, Enhanced acoustic properties of concrete composites comprising modified waste sheep wool fibers (Elsevier), J. Build. Eng. 56 (2022) 104815, https://doi.org/10.1016/j.jobe.2022.104815.
[29] A. Patnaik, M. Mvubu, S. Muniyasamy, A. Botha, R.D. Anandjiwala, Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies, Energy Build. 92 (2015) 161–169, https://doi.org/10.1016/j.enbuild.2015.01.056.
[30] Allafi F.A.S., Hossain M.S., Ab Kadir M.O., Shaah M.A.H., Lalung J., Ahmad M.I. Waterless processing of sheep wool fiber in textile industry with supercritical CO2: Potential and challenges, *Journal of cleaner production, 285*, 124819, https://doi.org/10.1016/j.jclepro.2020.124819.
[31] Atbir A., Cherkaoui M., El Wardi F.Z., Khabbazi A. Improvement of thermomechanical characteristics of multilayer biomaterial of and clay, Mater. Today Proc. 58, 1331–1336, https://doi.org/10.1016/j.matpr.2022.02.224.
[32] A. Atbir, A. Khabbazi, M. Cherkaoui, K. Ibaaz, F.Z. El Wardi, S. Chebli, Improvement of thermomechanical properties of porous plaster reinforced with a network of Morocco sheep wool skeletons for Energy efficiency, Build. Environ. 234 (2023) 110171, https://doi.org/10.1016/j.buildenv.2023.110171.
[33] A. Atbir, A. Khabbazi, M. Cherkaoui, K. Ibaaz, F.Z. El Wardi, S. Chebli, Improvement of thermomechanical properties of porous plaster reinforced with a network of Morocco sheep wool skeletons for Energy efficiency, Build. Environ. 234 (2023) 110171, https://doi.org/10.1016/j.buildenv.2023.110171.
[34] Sharma Y.K., Meena A., Sahu M., Dalai A. Experimental investigation on mechanical and thermal characteristics of waste sheep wool fiber- filled epoxy composites, Materials Today: Proceedings*,* 2214-7853 2023 Elsevier, https://doi.org/10.1016/j.matpr.2023.01.157.
[35] L. Conzatti, F. Giunco, P. Stagnaro, M. Capobraco, Castellano, E. Marsano, Polyester-based biocomposites containing wool fibres, Compos. Part A Appl. Sci. -ence Manuf. *43* (2012) 1113–1119, https://doi.org/10.1016/j.compositesa.2012. 02.019.
[36] K.N. Bharath, M. Pasha, B.A. Nizamuddin, Characterization of natural fiber (sheep wool)-reinforced polymer-matrix composites at different operating conditions, J. Ind. Text. *45* (5) (2016) 730–751, https://doi.org/10.1177/1528083714540698.
[37] A.S. Blicblau, R.S.P. Coutts, A. Sims, Novel composites utilizing raw wool and polyester resin, J. Mater. Sci. Lett. *16* (1997) 1417–1419, https://doi.org/10.1023/A:1018517512425.
[38] S. Boria, C. Santulli, F. Sarasin, J. Tirillo, A.P. Caruso, M. Infantino, Potential of wool felts in combination with glass fibres: mechanical and low velocity im- pact assessment, Compos. Part B Eng. *118* (2017) 158–168, https://doi.org/10.1016/j.compositesb.2016.09.088.

[39] A. Kicińska-Jakubowska, J. Broda, M. Zimniewska, M. Bączek, J. Mańkowski, Effect of blend composition on barrier properties of insulating mats produced from local wool and waste bast fibres, Materials 16 (1) (2023) 459, https://doi.org/10.3390/ma16010459.
[40] R. del Rey, A. Uris, J. Alba, P. Candelas, Characterization of sheep wool as a sustainable material for acoustic applications (art. no), Materials 10 (11) (2017) 1277, https://doi.org/10.3390/ma10111277.
[41] A. Kesharwani, R. Bedi, A. Kumar Bagha, S. Bahl, Experimental study to measure the sound transmission loss of natural fibers at tonal excitations, Mater. Today.: Proc. 28 (2020) 1554–1559, https://doi.org/10.1016/j.matpr.2020.04.839.
[42] V. Moody, H.L. Needles, 3 - Major fibers and their properties, in: V. Moody, H.L.B.T.-T.C. Needles (Eds.), Plastics Design Library, William Andrew Publishing, Norwich, NY, 2004, p. 3559, https://doi.org/10.1016/B978-188420799-0.50004-X.
[43] M. Feughelmann, A model for the mechanical properties of the α–keratin cortex, Text. Res. J. *64* (4) (1994) 236–239, https://doi.org/10.1177/004051759406400408.
[44] J.W.S. Hearle, Physical properties of wool, in: W.S. Simpson, G.H. Crawshaw (Eds.), Wool, Woodhead Publishing, Cambridge, 2002, pp. 80–129, https://doi.org/10.1533/9781855737648.80.
[45] C. Giosuè, A. Mobili, Q.L. Yu, H.J.H. Brouwers, M.L. Ruello, F. Tittarelli, Properties of multifunctional lightweight mortars containing zeolite and natural fibres. J. Sustain. Cem. -Based Mater. *8* (2019) 214–227, https://doi.org/10.1080/21650373.2019.1615012.
[46] K. Zhao, S. Xue, P. Zhang, Y. Tian, P. Li, Application of natural plant fibres in cement-based composites and the influence on mechanical properties and mass transport, Materials *12* (3498) (2019) 16, https://doi.org/10.3390/ma12213498.
[47] D. Jóźwiak-Niedźwiedzka, A.P. Fantilli, Wool-reinforced cement based composites, Materials *13* (2020) 3590, https://doi.org/10.3390/ma13163590.
[48] B. Mobasher. Mechanics of Fibre and Textile Reinforced Cement Composites, 1st ed., CRC Press, Boca Raton, FL, USA, 2012, p. 473, https://doi.org/10.1201/b11181.
[49] Fantilli, A.P.; Jóźwiak-Niedźwiedzka, D.; Gibas, K.; Dulnik, J. The compatibility between wool fibres and cementitious mortars. In Proceedings of the 2nd International Conference on Bio-Based Building Materials, RILEM Proceedings PRO 119, Clermont-Ferrand, France, 21–23 June 2017; pp. 42–47, https://doi.org/10.26168/icbbm2017.4.
[50] J. Wei, C. Meyer, Degradation mechanisms of natural fibre in the matrix of cement composites. Cem. Concr. Res. *73* (2015) 1–16, https://doi.org/10.1016/j.cemconres.2015.02.019.