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Review

Organized Framework of Main Possible Applications of Sheep Wool Fibers in Building Components

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Abstract: Greasy sheep wool is currently considered a special waste for its high bacterial load, with expensive disposal costs for sheep breeders. For this reason, wool is often burned or buried, with serious consequences for the environment. On the other hand, sheep wool is well regarded as one of the most performative insulating natural fibers due to its thermo-hygrometric and acoustic properties. In the building sector, sheep wool meets the requirements of green building components because it is an eco-friendly material, there is a surplus of it, it is annually renewable, and totally recyclable. If used instead of common insulation materials (e.g., fiberglass, rock wool, polyurethane foam, polystyrene), sheep wool offers significant benefits for sustainability such as a reduction in the production costs for new insulating materials and in environmental pollution. Mechanical and physical properties of sheep wool investigated in previous studies were assessed and discussed with the aim of providing an organized framework of possible applications of wool fibers in building components. This paper highlights in detail aspects that have not yet been investigated enough to detect new potential uses of sheep wool fibers in rural buildings and the reuse of traditional ones.

Keywords: agricultural waste management; natural fibers; environmental sustainability; thermal-acoustic insulation

1. Introduction

Based on an assessment of risks to the environment, the United Nation Environment Program stated that the construction industry is the sector with the highest environmental impact. The building sector is responsible for world global energy and water consumptions of 40% and 25% respectively, and for 40% of global resource utilization [1]. To reduce negative ecological effects and consequent climate change, the construction sector should carry out sustainable solutions in order to decrease environmental pollution and consumption of resources such as materials, fuels and energy. In buildings up to 30% of heat loss can be avoid by external wall insulation, for this reason the insulation of the external envelope is the most sustainable action to reduce energy consumption, economic losses, pollution, and CO_2 emissions.

Energy efficiency of buildings depends on their thermal insulation improvement, on energy savings, and on CO_2 emissions reductions. Therefore, a sustainable building process could be achieved by using natural insulation materials instead of those commonly used (e.g., polyurethane foam, polystyrene (EPS), fiberglass, mineral wool), in accordance with green building requirements [2].

Natural insulation materials (e.g., wood fiber and cellulose, sheep wool, hemp, cotton and flax) are usually water vapor permeable and they can regulate internal air humidity through their indoor moisture absorption capacity.

Picuno et al. [3] underlined the importance of using locally available materials for rural building renovation. The sustainability of rural environments is improved by using building materials locally available, recyclable, and characterized by lower energy consumption in their manufacturing. Moreover, if properly used, natural fibers provide thermal and acoustic insulation comparable to common insulation materials, but with a lower carbon footprint, that is the total amount of greenhouse gases produced, expressed in equivalent tons of carbon dioxide (CO_2).

Among natural fibers, sheep wool is considered the best performing, suitable for both thermal and acoustic building insulation and, if used as reinforced fibers for adobe clay or cement mix, also for its mechanical characteristics [4].

Sheep wool is an agricultural waste produced by sheep breeding. Wool is a renewable, recyclable and environmentally friendly material. Due to its natural properties and composition (e.g., 60% animal protein fibers, 15% moisture, 10% fat, 10% sheep sweat and 5% impurities) [5], sheep wool fiber is a material fitting different use in many fields and sectors, especially to improve building thermal efficiency.

At the same time, sheep wool is a special waste for its potential bacterial load, with high disposal costs for breeders because, for correct disposal, it should be landfilled. Therefore, wool is often wrongly disposed of (e.g., buried or burned), with a strong impact on soil and air.

In the context of a circular economy, the reuse of greasy wool could reduce both environmental pollution and energy consumption in the building sector. By turning sheep wool into a new raw material, it is possible to produce innovative building materials and/or components fully complying with eco-friendly construction criteria and environmental certifications (e.g., Building Research Establishment Environmental Assessment Method—BREEAM, Leadership in Energy and Environmental Design—LEED, German Sustainable Building Council "*Deutsche Gesellschaft für Nachhaltiges Bauen*"—DGNB, and Green Mark).

This paper aims at developing an organized framework of the main possible applications of sheep wool fibers in building materials and/or components to be used in the construction or renovation of rural buildings. Firstly, a literature review was carried out to assess strengths and weaknesses of sheep wool application as insulation or as a reinforcing material in comparison with other common commercial materials. Since sheep wool is a natural material, its possible applications should be precisely defined by using proper measurements and simulations to verify functionality and durability. Studies conducted until now provide important results for a correct application of sheep wool in different building components, such as external walls, internal partitions, and roofs. Based upon the literature review, papers published between 1996 and 2019, were analyzed in order to assess sheep wool fiber characteristics (i.e., physical and mechanical) and its use in building materials and/or components.

2. Literature Review

2.1. Physical Properties of Sheep Wool

In the last few years many studies have been conducted in order to evaluate the insulation properties of both natural fibers and recycled materials [6]. Among research studies carried out on natural insulating fibers, those related to the application of sheep wool fibers are becoming a new research topic. Sheep wool fiber has been used in the construction field as an insulating material [7], valued for its thermal and acoustic properties.

A recent paper review [8] was focused on the use of sheep wool fiber as a building material and provides a collection of measurements and tests concerning its main physical properties. Thermal insulation was evaluated by comparing wool with polystyrene. Results showed that wool is high performing. In fact, wool thermal conductivity—that is the ability for heat to pass from one side of a material through to the other—is between 0.038–0.054 (W/m K). Sheep wool is also suitable to control indoor air relative humidity. Due to their chemical composition, wool fibers could absorb more than 35% of their weight in water without the sensation of humidity and, since absorption is followed by desorption, wool contributes to the maintenance of a constant indoor air relative humidity.

Rajabinejad et al. [9] compared sheep wool, glass wool and polystyrene foam thermal conductivity, thermal resistance, thermal transmittance, water absorption and sound absorption coefficient. Collected values were similar for different materials (Table 1), with a consistent reduction of embodied energy for sheep wool which is the energy used for production and transportation of a construction material.

Table 1. Comparison of wool performances and common insulation materials [9].

Insulation material	λ value	R value (100 mm)	Thickness for U-value	Density	Embodied energy	Sound absorption coefficient	Water absorption
	[W/m K]	[m²K/W]		[kg/m³]	[GJ/m³]	[500–2000 Hz]	[% wt/wt]
Sheep wool	0.034–0.067	2.5–2.6	180–200	18–23	0.11	0.77 (60 mm)	up to 35%
Glass wool	0.032–0.04	2–3	170	10–30	0.83	0.65 (100 mm)	0.2%
Polystyrene foam	0.033–0.035	2.5–2.8	150	30–50	3.03	0.35 (50 mm)	0.03–0.10%

Volf et al. [10] compared the thermal, moisture and biological performances of some natural insulating materials such as sheep wool, hemp, flax, straw and wood fibers. In detail, thermal capacity, thermal conductivity, volume density and sorption isotherm were evaluated. With regard to sheep wool, they obtained the following thermal characteristics: Thermal conductivity 0.062 (W/m K), thermal diffusivity 1.03 (m^2s^{-1}), volume heat capacity 0.06 ($J\ m^{-3}K^{-1}$), specific heat capacity 2.02 ($J\ kg^{-1}\ K^{-1}$). These values were near to those found for the other tested materials (Table 2).

Table 2. Measured parameters for sheep wool and other natural fibers [10].

Natural fibers	Thermal conductivity	Thermal diffusivity	Dry density	Volume heat capacity	Specific heat capacity
	λ [$Wm^{-1}K^{-1}$]	a [m^2s^{-1}]	ρ [$kg\ m^{-3}$]	c_ρ [$Jm^{-3}K^{-1}$]	c_m [$J\ kg^{-1}\ K^{-1}$]
Straw bale	0.065	0.43	98.0	0.16	1.58
Flax fiber	0.052	0.54	27.0	0.10	3.60
Hemp fiber	0.052	0.52	36.2	0.10	2.75
Wood fiber	0.048	0.39	51.5	0.12	2.40
Treated sheep wool	0.063	1.23	11.3	0.05	4.55
Untreated sheep wool	0.062	1.03	29.7	0.06	2.02
Mineral wool	0.039	0.43	14.9	0.09	6.04

Other research works compared the thermal insulating capacity of sheep wool with rock wool [5,11]. These studies, based on experimental measurements, showed that sheep wool is an excellent thermal insulation material, very similar to mineral wool. Furthermore, by considering environmental aspects, sheep wool has many advantages, such as low transportation cost, because wool could be compressed allowing big reductions in volume, and highly energy efficient production. This is in accordance with results achieved in a study carried out in New Zealand and Northern Ireland that investigated the insulation performances of some sheep wool panels. Results showed that if wool density is more than 11 kg/m³ [12], thermal resistance is strictly correlated with panel thickness.

In their study, Jerman et al. [13] investigated thermal and hygric performances of five natural insulation materials, including sheep wool. The obtained experimental values for wool were low thermal conductivity, around 0.05 (W/m K), and high moisture diffusivity, achieved values ranged between 1.1×10^{-6} ($m^2\ s^{-1}$) and 1.2×10^{-5} ($m^2\ s^{-1}$). These results show that wool is suitable to insulate building elements, also without providing a vapor barrier system because the risk caused by water vapor condensation is contrasted by the hygroscopicity of wool. Moreover, wool hygroscopicity contributes to improved air quality and regulates relative humidity of indoor environment. This study also highlighted the importance of using natural materials for the renovation of traditional buildings because of the compatibility of sheep wool with the chemical composition of traditional construction materials.

Within an interdisciplinary project conducted between Vienna University of Technology and the Brno University of Technology, Zach et al. [14] performed a detailed investigation with the aim to compare sheep wool and mineral wool behaviors. Thermal performance, sound absorption, hygrothermal properties and life cycle assessments were evaluated. They stated that sheep wool is an excellent thermal and acoustic insulation material and that the high hygroscopicity of sheep wool fibers—which reaches up to 35%—prevents condensation, regulates humidity and creates a pleasant indoor atmosphere. Moreover, they found that air flows in the pore structure of the insulation, and bulk density of wool are inversely correlated, and that a better thermal insulation is achieved when bulk sheep wool density increases. Furthermore, they established that no additional acoustic benefit is achieved with a material thickness greater than 170 mm. In conclusion, this study underlined the advantages coming from the use of wool instead of commonly used insulating materials such as, environmental benefits, ease of use, no negative health impacts by handling the material, highly energy efficient production of the material, and higher fire resistance. Furthermore, they support the conclusions presented by Ballagh [15] regarding the sound index reduction of more than six decibels by using sheep wool fibers for acoustic insulation, because sheep wool insulates better from vibrations in respect to other analyzed materials, such as rock wool or fiberglass.

Acoustic and thermal insulation of sheep wool have been also investigated by Korjenic et al. [4]. They found that sheep wool has good acoustical performances suitable as noise barriers, sound acoustic absorbers inside a room, or vibration insulators. The acoustic absorption coefficient of sheep wool panels tested in the study was between 0.84 (Hz) and 2.00 (Hz), higher than acoustic absorption coefficient of glass wool, polystyrene, mineralized wood fibers, and it is slightly lower than the acoustic absorption coefficient of rock wool, polyester or kenaf fibers. Noise reduction under a concrete slab is not very high ($\Delta Lw = 18$ dB) for sheep wool when compared with glass wool ($\Delta Lw =$ 30dB) or expanded polystyrene ($\Delta Lw = 31$dB). However, it is similar to cellulose ($\Delta Lw = 22$ dB) or coco fiber ($\Delta Lw = 23$ dB) [16,17] noise reduction. Korjenic [4] also investigated a case of wall renovation by using an 8 cm thick layer of sheep wool insulating material. By using statistics and hygrothermal simulation programs a building-physics assessment was carried out to measure moisture content and dynamic thermal transmittance. In detail, a limited variation over the course of one year with minimal stress for building elements was observed for the thermal transmittance (U-value).

More recent studies [18,19] considered the sound reduction index of sheep wool panels measured in a standardized laboratory (Figure 1).

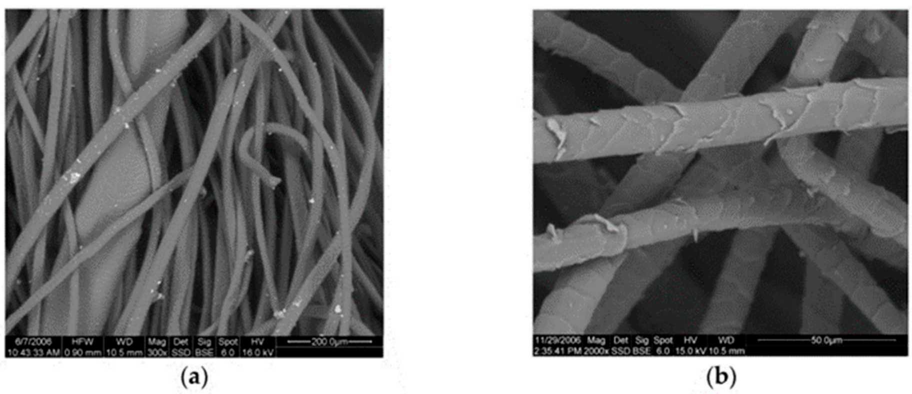


Figure 1. Electronic microscope details of sheep wool fibers (**a**) 200 μm rank; (**b**) 50 μm rank [19].

Another study, part of the European project of Eco-Innovation Wool4build named "Improved Isolation Material for Eco-Building—Based on Natural Wool", compared sheep wool fibers with other acoustic absorbent fibers such as polyester fibers (PET), recycled foam, and mineral wool. Some typical acoustic characterization parameters such as airflow resistivity, normal-incidence sound absorption coefficient and random incidence sound absorption coefficient were measured. Sheep wool samples with different composition were tested, and the results showed that sheep wool can be considered as a good acoustical insulation material.

Several studies also evaluated the sheep wool fire reaction. As reported by Dénes [8], in case of fire, sheep wool does not contribute to the flame propagation since it carbonizes and does not burn. Wool is a self-extinguishable material thanks to the high presence of nitrogen (Table 3). The fire reaction class of sheep wool is "E". This is in agreement with the findings of the research by Zach [14] and Saxena et al. [20]. By comparing wool with polystyrene, sheep wool presents the most advantages because wool fibers burn slowly, and in case of flame, there is a slight sputtering. Furthermore, polystyrene is characterized by a very high flammability with toxic fumes production.

Table 3. Chemical composition of raw sheep wool, chemical composition of wool's keratin is reported in detail.

Chemical Composition of Raw Sheep Wool			
Keratin	33%	Carbon	50%
		Hydrogen	12%
		Oxygen	10%
		Nitrogen	25%
		Sulphur	3%
Dirt	26%		
Suint	28%		
Fant	12%		
Mineral matter	1%		

Another potential use of sheep wool is as reinforced fiber for building components. In this context, some studies have been carried out [21–24] with the aim of investigating the possible use of sheep wool inside different composite matrixes, such as unfired clay adobe or cement mortar. In their review, Dénes et al. [8] evaluated mechanical performances by comparing wool with polypropylene fibers used as concrete reinforced fibers. Compressive strength, flexural strength and tensile strength have been measured. Results showed that wool fibers have a lower performance compared with the polypropylene fibers. Researchers concluded that experimental measurements are strictly related to wool fibers length and to wool dosage within the used samples.

2.2. Mechanical Properties of Sheep Wool

In the last decade, several studies were carried out in order to explore mechanical and thermal properties of natural fibers and their potential use as composite reinforcement for both engineering and bioengineering applications. Cheung et al. [25] reported the mechanical properties of different natural fibers as potential reinforcements for composite materials (Table 4).

Sheep wool is the natural fibers with the highest elongation at break, ranging between 25% to 35%, satisfactory tensile strength (120 Mpa–174 Mpa) and limited Young modulus (2.3 GPa–3.4 GPa).

The tensile stress-strain curve for a single wool fiber was also measured under different strain rates of 260, 340, 370, and 610/second (Figure 2). In the early region, the linear stress-strain behavior of wool is observed. Moreover, by analyzing the stress-strain curve, it is manifest that the flow stress of the wool fiber increases with the increase of strain rates [26].

Table 4. Mechanical properties of different types of natural fibers [25].

	Tensile strength (MPa)	Elongation at break (%)	Young modulus (GPa)
Flax	300–1500	1.3–10	24–80
Jute	200–800	1.16–8	10–55
Sisal	80–840	2–25	9–38
Kenaf	295–1191	3.5	2.86
Hemp	310–900	1.6–6	30–70
Cotton	264–800	3–8	5–12.6
Sheep Wool	120–174	25–35	2.3–3.4

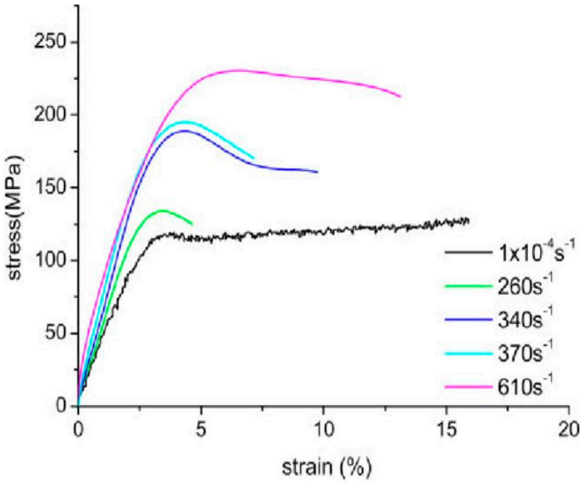


Figure 2. Tensile stress strain curve for a single wool fiber under different strain rates [26].

Fantilli et al. [27] examined the use of wool as mortar fiber-reinforcement. In detail, they tested cement small beams reinforced by untreated wool, or by wool previously treated with atmospheric plasma, an ionized gas was used for the modification of surfaces, in order to modify the nano-metric properties of the fiber surface. To compare the behavior of different vegetal fibers they also tested beams reinforced with hemp, largely investigated in the current literature. Three-point bending tests were performed. The obtained results showed that flexural strength and ductility increased when wool, untreated or not, was added to cementitious mortars. By adding 10 g of untreated wool, corresponding to 1% in volume, the flexural strength increased by 18% and the fracture toughness by 300%. In the same way, if an equivalent mass of cement mortar is substituted by 10 g of wool treated with atmospheric plasma (1% in volume) the flexural strength increase by 23% and the fracture toughness by 300%. Fantilli [27] also stated that the sustainability of cement mortar improves by decreasing the cement quantity and substituting polymeric fibers with sheep wool. They indicated that additional tests must be performed with the aim of optimizing the composition of cement mortar by reducing the cement quantity and increasing the fiber amount without consequences for workability and mechanical performances of the composite matrix.

Other research activities were focused on the incorporation of sheep wool fibers in cement mortars or in cement-lime mortars, with the aim to improve the thermal and mechanical performance of mortars. As a result of performed tests, the use of sheep wool fibers reduces susceptibility of cracking when compared with the mortars realized without reinforced fibers [28].

Statuto et al. [29] performed compression tests on two different types of reinforced adobe clay, one mixed with 3% by weight of sheep wool and one with 3% by weight of wheat straw. The compressive strength of adobe bricks reinforced by sheep wool fiber was considerably higher than compressive strength measured for adobe clay reinforced with wheat straw.

In their study, Stirmer et al. [30] compared compressive strength, flexural performance, thermal insulation and density on different mortar mixtures prepared with Portland cement, crushed sand 0/4 mm, lime, expanded clay, metakaolin and chemical admixtures, sheep wool fibers (in amounts of 3, 5 and 9% per mortar mass, respectively). Obtained results showed that the addition of sheep wool fibers reduced the mortar density and improved thermal insulation properties, but caused a decrease in the mechanical properties, in particular compressive strength was decreased. Sheep wool fibers tend to degrade due to the reaction of wool with alkalis contained in cement composite.

They stated that sheep wool fibers are suitable for restoration of traditional buildings because sheep wool composition blends with original mortar.

In a recent study, Alyousef et al. [31] investigated workability, compressive strength, tensile strength, and flexural strength of concrete specimens prepared by using ordinary Portland cement, natural sand, crushed stone chips and reinforced with sheep wool fibers. Specimens were prepared by changing the quantity of sheep wool fibers by weight in the mix concrete design: 0%, 0.5%, 1%, 1.5%, 2%, 3%, 4% and 6%. Based on experimental results they stated that best performances are achieved with 2–3% content of sheep wool. Cardinale [32] evaluated the possible use of sheep wool fiber to increase thermal and mechanical performances on cement mortar panels. The aim was to optimize sheep wool percentage inside the panels to obtain best performances. Among the different mixed combinations, it was found that the best results could be reached with 2% of sheep wool. Mobili et al. [33] proposed an interesting use of sheep wool as a reinforcement fiber for a prefabricated clay sandwich panel for the exterior enclosure. This panel results from a combination of different materials such as clay soil, water, calcium alginate and sheep wool fibers. Sheep wool is incorporated to improve resistance to compression, bending and shearing and reduce shrinkage. Moreover, in this case, sheep wool also contributes to the absorption of water vapor.

A study performed in Romania investigated the inclusion of sheep wool fibers and fly ash—a residue from power plants or from incineration of solid materials—in a concrete mix. The aim was to evaluate the influence of these components, sheep wool and fly ash, on mechanical performances of concrete such as tensile strength, compressive strength, ductility and post-cracking behavior. They also emphasized the importance of using locally available resources in order to reduce pollution and improve sustainability [34].

3. Other Uses of Sheep Wool Fiber

A study with the purpose to explore the effect of a liquid nitrogen (LN_2) pre-treatment of raw wool waste in an anaerobic digestion process was successfully carried out. Obtained results show that a pre-treatment with LN_2 could change the physical structure of sheep wool fiber, improving solubility and bioavailability for microbial degradation. As a conclusion to this research, the biogas potential of sheep wool was demonstrated [35].

Zheljazkov et al. [36] investigated the effect of sheep wool as an organic nutrient source for plants. They stated that the addition of wool, used as fertilizer and/or substrate, determines growth increments of up to 33%, especially for tomato and pepper plants.

Moreover, in the European market, depollution wool-based products could be found specific for the sustainable management of ports, marinas, water processing, and in general, treatment sites for water contaminated by oils and/or petroleum. These products, raw felt geotextiles made of 100% sheep wool, are oleo-absorbers useful for prevention of micro-spillages in the sea, capable of capturing, absorbing and biodegrading petrochemical hydrocarbons.

A study investigated biochar and sheep wool as potential reinforcements in polymeric composites. In detail, flammability, thermal and mechanical properties of composites were examined in this study. Biochar and wool as natural reinforcements in polymeric composites improve fire/flame resistant properties and mechanical properties [37].

Finally, because sheep wool contains more than 95% by weight of pure keratin, it could also be employed for the extraction of keratin in order to obtain innovative biopolymers [38].

Keratin regenerated from sheep wool, e.g., sheep wool organic waste deriving from farm or wool fiber by-products from textile processing, is biodegradable, biocompatible and self-extinguishing.

However, as the unreduced keratin solutions are stable, the extraction of keratin from wool requires the chemical modification of cysteine [39].

4. Building Components in Rural Constructions

Currently, sheep wool-based insulation products available in the global building market are:

- Soft mats made of 100% sheep wool, with thicknesses between 4 cm and 6 cm;
- Rigid or semi-rigid panels made of sheep wool (70–80%) and polyester fibers (20–30%), with thicknesses between 5 and 12 cm;
- Rigid panels made of 100% sheep wool [40];
- Loose-fill fibers.

With regard to clay or cement mortar-based adobes reinforced with sheep wool fibers, they are not currently commercialized and their possible applications are still at an experimental stage.

Sheep wool-based insulation products are mainly used for the thermal and acoustic insulation of roofs, partition walls, false ceiling roofs. In the construction sector the sheep wool fibers used to produce these building components are large and short, and these characteristics make sheep wool unsuitable for textile sectors and destined for disposal.

Rural buildings, residential or not, are usually built without a specific temperature control system. Below, some potential examples of critical issues that might arise from the use of sheep's wool-based insulation products are described.

4.1. Roofs

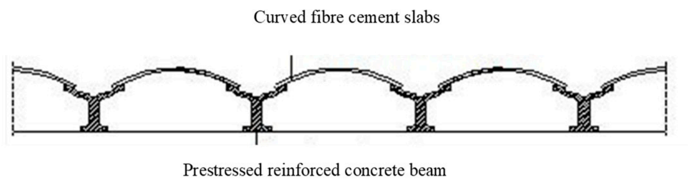
The employment of sheep wool as a thermal insulating material for roofs could represent a consistent advantage for some types of rural buildings where the control of microclimatic conditions is of relevant importance, with regard to their main functional destination (i.e., buildings for intensive animal breeding, buildings for agroindustry). Sheep wool fiber is suitable for thermal insulation because of its thermal parameters, reported in Section 2.1.

In buildings for intensive animal breeding, a proper thermal insulation of building components more exposed to solar radiation (e.g., external walls and roof) allows animals to be defended from heat stress, especially during the summer season. When the outside temperature and relative humidity rise above levels well tolerated by animals, the mechanism by which they disperse excess heat goes into crisis. For example, in extreme climatic conditions, dairy cows are unable to dissipate heat through sweating, and increase their breathing rate to high latent heat loss. Firstly, to decrease metabolic heat production, animals reduce both food intake and physical activity, and to disperse heat through their respiratory system they increase water consumption. This new metabolic set up causes a decrease in milk production, fat and protein concentration. These unhealthy conditions for animals can occur for the whole summer season if passive and/or active cooling systems are not efficient.

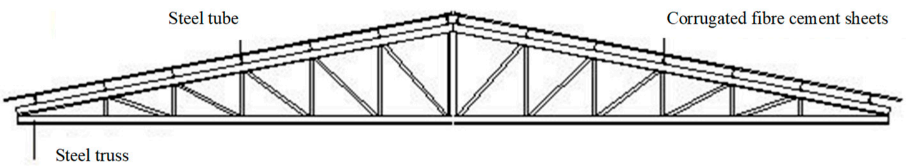
In buildings for intensive animal breeding, the load bearing structures of the roofs are frequently made with steel trusses, or in prestressed reinforced concrete, while the roof covering is generally made of fiber cement slabs. Rarely, in such buildings, are roof systems realized with wooden supporting structures and roofing tiles. This roof system is used in traditional rural buildings or in those recently built, or restored, that are included in protected areas subject to landscape constraint.

By considering the most widespread roof typologies, there are three different types of roof (Figure 3) built with:

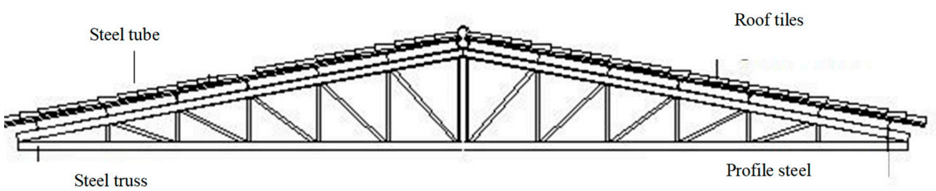
- A bearing structure in prestressed reinforced concrete, covered with curved fiber cement slabs (Figure 3a);
- A steel supporting structure covered with corrugated fiber cement straight sheets (Figure 3b);
- A steel supporting structure covered with brick tiles (Figure 3c and Figure 4).



Roof realized with supporting structure in prestressed reinforced concrete and roof covering in curved corrugated fibre cement slabs.
a)



Roof made with steel supporting structure and covering in corrugated fibre cement straight sheets.
b)



Roof made with a steel supporting structure and a roof covering in brick tiles.
C)

Figure 3. Main typologies of barn roof system.

Figure 4. Barn roof system realized with steel supporting structures and roofing tiles.

The application of the sheep wool insulation is different depending on the type of roofing structure. In some case, sheep wool insulation can be placed directly above the bearing structure. However, if the elements of the bearing structure are too far from each other, a secondary bearing structure could support the insulation layer (Figure 5). Suitable products that could be used for this are soft mats made of 100% sheep wool.

Figure 5. Example of sheep wool insulations on roof [41].

4.2. External and Internal Walls

Sheep wool is appropriate for thermal insulation of external walls made of brick or stone masonry, as well as concrete, either in warm and dry climates or in cold and humid climates. In case of a warm and dry climate, water evaporates from wool fibers and absorbs heat from the inside by keeping walls cool. In cold and humid climates, sheep wool absorbs water and prevents condensation in construction cavities by keeping the temperature above the dew point in damp conditions. The methodology to apply sheep wool-based insulation products differs from cavity walls or solid walls. If an external wall has a cavity, the insulation, semi-rigid panels or in loose-fill fibers, will be placed inside the cavity without preparing the internal wall surfaces, and the sheep wool thickness required will be the same as of the cavity to be filled. In new construction, to make sure that the insulation does not slip in the cavities, a net support could be required. Sheep wool insulation panels are simple to install as occurs for mineral wool panels. In solid walls, sheep wool insulation is placed on the indoor wall surface, with a secondary structure able to support it.

Thermal performances of the indoor environment could also be achieved by using sheep wool to insulate internal walls. In detail, sheep wool has a relevant capacity to control condensation due to water vapor diffusion parameters and hygroscopic properties (e.g., moisture diffusivity 1.2×10^{-5} $m^2\ s^{-1}$, hygroscopicity more than 35% of its own weight) [13]. Excess of air relative humidity is the main cause of mold which has detrimental effects to both the building structure and as a risk to human health. The main advantage of using sheep wool as an insulation material is its capacity to absorb the excess moisture without significant changes of its thermal performance, as occurs instead for mineral fiber insulations that deteriorate. Through a chemical process, called chemisorption, sheep wool is suitable to neutralize harmful and odorous substances such as nitrogen dioxide, sulphur dioxide, toluene, and formaldehydes. By using sheep wool insulation, indoor air quality (IAQ) and human and/or animal wellness improve.

In some rural buildings, such as flour mills, olive mills and wineries, the insulation of external walls is crucial to obtain optimal microclimatic conditions during the agroindustry processes. In detail, within the grain supply chain, one of the most important issues during the milling phase is to maintain constant the rheological characteristics of flours, semolina and wheat flours over time. In addition, inadequate hydration of the flours can determine further problems related to the accomplishment of specific regulatory requirements; the occurrence of risks for consumers from mold formation; and changes in grain characteristics that cause the systems to malfunction [42]. Furthermore, an appropriate thermal insulation could contribute to the improved thermal condition of flour mills during heat treatments for insect pest control [43]. Finally, since flour is an explosive material, an important aspect to be considered is the fire reaction of mill building materials. Sheep wool is a natural fiber that does not contribute to the propagation of flame and has a fire reaction class 'E' [8]. As a result of the high presence of nitrogen within its composition, wool is a self-extinguishing material that burns slowly and, in case of flame, sputtering is low.

With regard to olive mills, oil storage conditions (e.g., packaging material, oxygen, temperature, and light), modifications to both the fatty acid alkyl esters (FAEE) and other parameters (e.g., peroxide) may cause the production of low-quality extra virgin olive oils (EVOO). During the long term oil storage, high temperatures greater than 24 °C cause degradation of oil quality, meanwhile temperature lower than 8 °C improves rancidity [44]. Thermal control of the oil storage area could be improved by using passive solutions, and among them, insulation of internal partition walls by using sheep wool made panels or soft mats could represent a proper solution.

Finally, a great number of wineries located in the Mediterranean area lack specific temperature control systems to optimize wine storage and the ageing process. Also, in this case, sheep wool insulation could be used with the aim to obtain passive control of the indoor air temperature distributions and trends. Constant temperature and humidity levels inside wine production buildings could be achieved by an adequate internal insulation system, in addition to an external one. Wine aging practice is mostly influenced by air relative humidity and air temperature. If wine is stored in conditions that are too dry, the cork will shrink and cause leakage, if the air is too moist, mold and contamination may occur. To avoid these problems and to reach the optimum wine development condition, air relative humidity levels in wine aging cellars should be kept constant, about more than 70% [45]. Due to its hygroscopicity sheep wool is the most suitable natural insulation material to create these microclimatic indoor conditions. Furthermore, the wine production process is sensitive to temperature changes. The most ideal microclimate condition for wine storage and aging is a temperature range between 9 °C and 20 °C, with maximum air temperature fluctuation of 6 °C. If wine is exposed to too high temperature, i.e., more than 25 °C, for long periods of time, it may be spoiled and could develop bad off-flavors. In case of too cold temperatures, wine can freeze and expand, causing the pushing of cork or the bottle to crack. A wrong range of air temperature can also produce adverse chemical reactions that may cause wine faults. Moreover, wine should not be kept in a refrigerator since the cooling process often includes dehumidification which could dry the corks too quickly and allow oxygen to enter the bottle. For all these above issues, a passive control system of air temperature and humidity by sheep wool made insulation materials is a solution for the whole wine production process.

4.3. Concrete Slab Floor

In agro-industrial buildings, machine vibrations cause unpleasant conditions for both workers and processed products. For instance, during red wine production process, to limit changes in physicochemical properties of the stored wines, indoor vibrations should be minimized.

Sheep wool isolates better from vibrations compared to other materials, such as rock wool or fiberglass. In detail, sheep wool made materials, such as soft mats, could be employed for the acoustical insulation of concrete slab floors. This kind of building solution should be carried out in agro-industrial buildings such as olive oil mills, pasta factories, flour mills, and, especially, when the production process is not only limited to short periods, but is extended over the whole year. Sheep wool made insulation materials, i.e., loose fibers or soft mats, should be applied directly on concrete slabs by using a wooden secondary bearing structure. This type of building intervention, when carried out on existing buildings determines an increase of about ten centimetres of the floor level because of the thicknesses of both the sheep wool soft mats and the wooden secondary bearing structure.

5. Critical Analyses on the Reuse of Sheep Wool Fibers and Future Research Developments

This critical analysis on the reuse of sheep wool in building components references its long term performance and availability.

Long term performance of natural materials should be considered because of their biological composition. With regard to sheep wool, the most critical disadvantage is its vulnerability to fungal and insect attacks. Mold growth on the surface of sheep wool made materials is a potential allergenic powered by dust particles. The most common kind of wool molds that cause allergy and asthma are: Alternaria alternate, Stachybotrys species, Acremonium species, Penicillium (biverticillata), Fusarium species. However, despite high hygroscopicity of sheep wool, laboratory tests showed that mold growth durability and susceptibility of common mold strains is low [10].

Another critical aspect to be considered for sheep wool reuse is its potential pathogenic bacteria load that is a critical point for breeders because it must be disposed as special waste with heavy financial and management costs. In fact, the European Hygienic-Sanitary Regulation concerning animal by-product management, i.e., storage and disposal, considers sheep wool as an agricultural by-product only if it is submitted to some specific treatments, even a simple washing, in order to lower its potential pathogenic bacterial load [46,47]. So, before any use, greasy sheep wool must be washed, and in some cases carded. Additionally, to prevent attacks by fungal and insects, especially moths, a treatment with biocide (e.g., acid boric) should be required. Sometimes, during the manufacturing process of sheep wool panels, highly toxic anti-moth products are used, such as permethrin, that reduce the sustainable reuse of sheep wool.

Lastly, sheep wool made insulation materials available on market are produced by few manufacturers. In Italy, these products are manly made of wool imported from foreign countries such as Austria or New Zealand [27]. For this reason, sheep wool made insulation products are generally more expensive than conventional insulating. Since the sustainability of sheep wool made products depends on the availability and geographical location of greasy sheep wool, specific analyses should be carried out on a territorial scale to investigate its possible re-use on a short supply chain.

Therefore, as part of a Ph.D. carried out within the International Doctorate in Agricultural, Food and Environmental Science of the University of Catania (Italy), with the aim of studying possible alternative uses of agricultural waste, i.e., sheep wool, a methodology was put forward to locate and quantify the availability of sheep wool in an area of southern Italy, strongly characterized by the breeding of dairy sheep, whose fleece is not suitable for the textile industry. In Italy, the number of sheep is around 7.4 million with the largest number in Sardinia (3,301,837), Sicily (906,069), Lazio (743,823), and Tuscany (422,734) (Table 5).

Sicily is the region in Italy with the second highest number of sheep, after Sardinia. By analyzing data supplied by the National Zootechnical Registry (January 2019) of the Italian Ministry of Health, the number of sheep in Sicily was geo-referenced and quantified on a province scale to obtain the geographical areas where the production of this by-product is higher, and the problem of its disposal is potentially relevant (Figure 6).

Future development of this research activity will be focused on the production of earthen adobes and panels made with raw earth and crushed sands, reinforced by sheep wool fibers. Raw earth buildings, warm in the winter and cool in the summer, are widespread in the world, also in regions very different for climate and land configuration. These constructions are important for a sustainable development of the building sector, with a low impact for the ecosystem, although high levels of seismicity could limit their use in Italy, where technical regulations only allow for raw earth buildings if they are associated with wooden bearing structures [48].

During the research study, the mechanical and thermo-acoustic performances of sheep wool made building components will be compared with that provided by similar ones obtained by using other natural fibers (e.g., hemp and straw). Self-supporting adobe clay, reinforced with sheep wool, will be manufactured and tested by changing wool content and fibers disposition.

Based on the achieved results, the possible use of these components in rural building such as agro-industrial buildings and animal housing, will be investigated [49]. These kinds of rural buildings are mainly made of conventional materials (e.g., concrete, steel, and plastic), and have a high negative environmental impact. The use of locally available, renewable raw materials, such as raw earth and natural animal or vegetal fibers, could improve the sustainability of rural buildings [50].

Table 5. Consistency of the Italian sheep population divided by region in the year 2017. (Data provided by the BDN of the Zootechnical Registry established by the Ministry of Health at the CSN of the "G. Caporale" Institute of Teramo "IZS).

Italian regions	Number of sheep
Valle d'Aosta	2215
Liguria	13,588
Friuli Venezia Giulia	23,221
Trentino Alto Adige	92,732
Emilia Romagna	59,907
Molise	71,279
Veneto	75,988
Umbria	116,898
Lombardia	129,869
Piemonte	135,172
Marche	150,538
Abruzzo	202,959
Campania	213,870
Basilicata	248,456
Puglia	264,675
Calabria	269,456
Toscana	422,734
Lazio	743,823
Sicilia	906,069
Sardegna	3,301,837

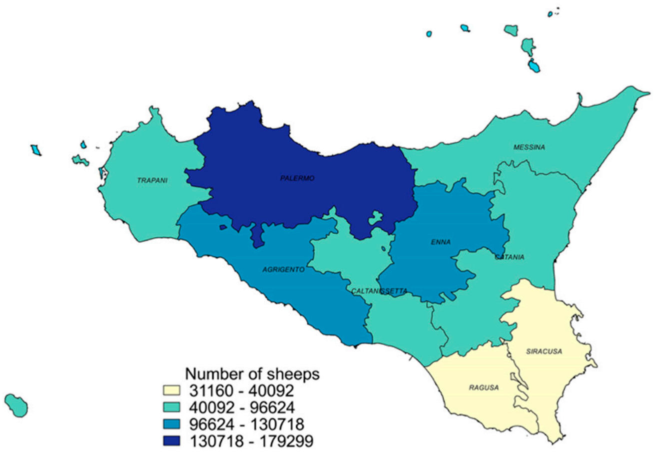


Figure 6. Number of sheep in Sicily localized and quantified on a provincial scale.

6. Conclusions

A holistic assessment of sustainability and energy efficiency in buildings must consider primary energy demand, CO_2 reductions, and ecological properties of the building materials, traditional or not.

In this research work, an organized framework is proposed with the aim of providing information suitable to optimize passive conditioning systems that could be also extended to rural buildings not mentioned here.

Some mechanical and thermal-physical insulation properties of sheep wool fibers and their combinations as reinforced fibers for composite were investigated.

From the results found, it is demonstrated that sheep wool fibers are suitable to be used in insulation applications, since they exhibit low thermal conductivity (between 0.034–0.067 W/mK) and high thermal resistance (between 2.5–2.6 m^2/WK). Other results recognized in the literature show that sheep wool fibers are also adequate for acoustical insulation due to the sound absorption coefficient around 0.77 Hz, measured for a sample panel of 60 mm thickness and a density between 18–23 kg/m^3. Moreover, sheep wool exhibited convenient hygroscopic properties, its water absorption is more than 35% in weight, making it suitable to balance indoor air humidity.

If used as reinforced fiber for composite, sheep wool improves tensile and compressive strength of specimens, and especially flexural strength by reducing susceptibility of cracking.

It is a challenge to use sheep wool fiber to improve thermal efficiency of buildings, especially in rural buildings.

The valorization of the locally available materials, such as agricultural co-products or by-products, and their use on rural buildings plays a crucial role, especially in agricultural areas. This is in accordance to the past tradition when the only possibility for farmers was to use local materials.

Since a sustainable reuse of agricultural co-products or by-products depends on their availability and geographical location, in the last part of this paper, a case study was chosen in order to carry out a methodology to locate and quantify the availability of sheep's wool. The area analyzed was Sicily, a region in south Italy, characterized by the high number of dairy sheep. In Sicily, the number of sheep is more than 900,000 and by considering an annual wool production of 1.5 kg from a single animal, it could be plausible to produce 1,350,000 kg of raw wool yearly.

In the future, research activities will be carried out with the aim of investigating mechanical and physical properties as well as the potential use of earthen adobes and panels made with raw earth, crushed sands and reinforced by sheep wool fibers.

Despite this, the utilization of natural insulation materials, such as sheep wool, is not yet widespread, and in some cases, is limited to the laboratory stage.

Moreover, aspects concerning whole manufacturing process to convert raw wool into building materials, such as the correct scale required for a really sustainable production of sheep wool insulation products, should be further investigated.

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