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Review

The Application of Sheep Wool in the Building Industry and in the Removal of Pollutants from the Environment

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Abstract: The presented review is focused on a brief overview of the scientific works on the use of sheep wool outside the textile industry that were published in recent years. The focus of the information is the on construction industry, which is a significant consumer of heat- and sound-insulating materials. With its properties, sheep wool can compete very well with insulators made from non-renewable resources. Other building elements can also be combined with wool, as long as they are used in appropriate conditions. Due to its chemical and physical structure, wool is extremely suitable for the adsorption removal of pollutants from the living and working environment, in native or modified form. Wool can also be used in recycling processes. However, each application must be preceded by an investigation of the optimal conditions of the given process, which offers researchers inspiration and interesting topics for research.

Keywords: sheep wool; construction; isolation; adsorption; pollutant

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1. Introduction

The success of goods on the market has different time cycles, the boom alternates with recession. The periodicity of these phases is individualized for each product and depends on many variables. Even in the case of sheep wool, the specificity of each phase depends on several factors, such as the characteristics of the country related to the breeding conditions of the sheep, the legislative support for sheep farming, the fiber quality depending on the breed of the sheep, and many others. However, the most important factor is the current demand for specific goods. Today, along with sheep meat and milk, wool is not only less desirable, but has become an unwanted waste. The reason is the competition from synthetic fibers and the collapse of several textile companies focused on the processing of sheep wool. Unmarketable wool increases the costs for breeders to shear, store and legally dispose of wool waste as a hazardous animal waste. Its handling is governed by the regulation of the European Commission [1].

Sheep breeding is of considerable importance for food production, employment and landscaping. According to Eurostat [2], pastures in Europe (excluding those in England) occupy almost 60% of usable agricultural land. If a certain part of the obtained volume of wool is used for traditional textile production, there is still a lot of space for other uses of the remaining wool.

It is gratifying that researchers have also begun to deal with non-textile uses of wool. The impetus was the environmental crisis, the consequences of which the world is already feeling. The saving of non-renewable resources and a deeper focus on biomaterials is a direction of research with enormous potential. In this field, several significant results are shown, but only a small fraction of them have already found applications in practice. A certain hinderance can be the need to scour the wool at the beginning of each wool application, which is connected with the consumption of water and compliance with the legislative requirement to clean it until it is free of harmful chemicals. One hope for more gentle wool scouring is an ultrasonic bath [3]. Another limiting factor is the insufficient resistance of wool against various factors such as microorganisms and moths. These are tasks waiting to be solved and implemented, preferably without the use of chemicals.

The foundation of wool is biopolymer keratin [4]. Its chemical and physical structure is an admirable work of nature. Its ingenious structure enables research to be developed in many directions.

The presented study briefly summarizes the solved problems associated with the application of wool in the construction industry and in environmental protection for the recent period without the intention of a detailed analysis.

2. Wool in the Construction Industry

2.1. Thermal and Acoustic Insulation

Thermal insulating properties of wool are the reason why sheep fleece has been used since ancient times to protect the human body and dwelling from the cold. The sound-insulating ability of the wool has proven to be another added value. Wool is a renewable resource and is practically available regionally. Therefore, its transport over shorter distances lowers emissions from transport means.

At the time of the climate crisis, the use of the insulating properties of wool is the challenge of the day. The thermal insulation of buildings is one of the biggest consumers of thermal insulation materials. Not only the legislative instruments of states, but also individual citizens should react to this fact. Zhao et al., in a mini-review [5], analyzed the situation of plastic consumption in the construction industry. Globally, buildings or construction consume 18–19% of plastics, which is right behind the consumption of packaging materials (40%). Therefore, it is not surprising that 5% of plastic waste comes from construction waste. Although, in some respects, plastics have better insulating parameters, their other properties such as their worse water absorption, flammability, non-biodegradability, etc., are problematic. From an environmental point of view, they are accompanied by more harmful effects, starting with the consumption of non-renewable resources, energy-intensive production processes, as well as the disposal of plastic waste. In this area, plastic waste is either burned for energy purposes accompanied by emissions, or recycled. Recycling technologies develop slowly because plastic waste is usually not homogeneous enough. In addition, composite materials present complications for recycling. Starkova et al. [6] dealt with the effect of the environmental degradation of wool, which can affect the life cycle and useful life of sheep wool fibers. They investigated the influence of moist air and UV radiation individually and synchronously using the two-parameter Weibull distribution [7]. Tests of the elastic modulus and strength of the fibers showed individual reductions in mechanical degradation characteristics (moisture-saturated fibers up to 43%, UV aging up to 50%), but the simultaneous action of both factors had an even worse effect. The study [6] is a demonstration of the applicability of the Weibull distribution for predicting the service life of sheep wool.

The evaluation of thermo-insulation materials can be based on various aspects, namely, the origin of the material, its chemical composition, physical properties (strength parameters, density, heat and sound transmission), availability, processability, convenient handling, biodegradability versus stability, fire resistance, moisture resistance, resistance to bacteria and fungi, or recyclability. The price is very important. This is documented by the fact that the cited source [8,9] shows that, in the years 2000–2020, the number of publications dealing only with the price of insulating materials dominated over others, where this was a combination of the costs, energy used, and emissions of insulating materials. In addition to sheep wool, the range of materials used includes cork, cellulose, rock wool, polystyrene, perlite, coconut husks, cotton waste, bagasse, rice husks, textile waste, woven fabric, polyurethane, polystyrene, aerogels, phase change materials, and nano insulation materials [8]. The wool's thermal conductivity λ is 0.04 W/m·K, which is only slightly more than that of expanded polystyrene (EPS), polyurethane (PUR) and cellulose insulation (0.038–0.033 W/m·K).

If sustainability were considered a key feature, in terms of the necessary input of energy, natural insulators mean 95% less energy consumption than conventional mineral wool [10,11]. Since wool fibers are crimped, they shape millions of small airbags that trap air and help to create a thermal barrier.

A significant advantage of sheep wool is its thermal and moisture buffering. Ahmed et al. [12], when testing the moisture absorption and thermal conductivity of sheep wool, found that sheep wool is able to absorb water at a capacity of up to 30–35% of its own weight, i.e., 0.30–0.35 kg of water/kg of dry wool. As the authors state, with up to 20% of its weight in absorbed moisture, sheep wool does not change its thermal conductivity. This is an important advantage, because it retains its thermal insulation ability even in a partially wet state. In construction, wool functions as a carrier of air humidity between the external and internal environments, and thereby maintains a favorable interior atmosphere. This prevents the micro-condensation of moisture on the cold wall and limits the occurrence of mold. Mineral insulators do not have such a sorption property. They can capture only a 1–1.5 wt.% of moisture, because they do not have as much of a complex organic structure as biopolymer keratin. Florea and Manea [13] also emphasize the stabilization of relative humidity in the interior as an advantageous feature. The corresponding mechanism is the hysteresis of the adsorption–desorption process; with increased environmental humidity, the wool adsorbs moisture, and with decreasing humidity, moisture desorption occurs. When water is adsorbed, the fiber swells, which increases the surface area of the fiber and makes it more accessible for adsorption.

Bosia et al. [14] also report, in addition to good results for the thermal and sound insulation of soft mats made of 100% sheep wool as well as semi-rigid panels made of sheep wool (70–80%) with (20–30%) polyester fibers, the favorable absorption of formaldehyde. The stiffness obtained through the partial fusion of the polyester fibers allows for their application in walls, while soft mats are suitable for pitched roofs.

As mentioned above, natural materials are also becoming a proper alternative to traditional synthetic ones for sound absorption treatments. There is no doubt that the excellent sound- and thermal-absorbing ability of sheep wool is caused by micro-cavities (pores) in its physical structure. Berardi and Iannace [15] tested several natural materials including sheep wool in terms of sound absorption. They compared the results obtained using existing theoretical models with measured results. During experiments in the area of audible frequencies (200–2000 Hz), they found that at medium and high frequencies with a relatively homogeneous character, the value of the sound absorption coefficient for sheep wool is high ($\approx$0.95). The sound absorption significantly increases with the wool thickness layer, especially at a middle frequency. On the other hand, this comparison showed the limits of the theoretical models originally defined for porous materials with homogeneous fibers when they are applied to natural materials; the theoretically predicted data calculated from the two models were 46% worse than those of the experimentally measured ones.

The good sound-absorbing properties of wool were also confirmed by the research of del Rey et al. [16], performed on seven sheep samples with different wool compositions and densities. It was shown that at medium and high frequencies, sheep wool has a suitable and comparable sound absorption to that of mineral wool or those of recycled polyurethane foams.

El Wazna et al. [17] dealt with the evaluation of a non-woven waste fabric for thermal insulation materials. They tested four non-woven wastes based on acrylic and wool made using a needle-punched technique. Important factors in determining the flow through non-woven materials such as the dependence of the thermal conductivity and the air permeability on the porosity and density of the anisotropic structure, the character of the fibers random distribution as well as tortuosity of the conductive channels were measured. The thermal conductivity was comparable and even better to that of conventional insulating materials (glass wool, mineral wool, EPS). The non-woven fabric made from scoured wool showed the lowest conductivity.

Table 1 gives a comparison between some physical properties of sheep wool and those of selected petrochemical-based materials.

Table 1. A comparison of selected physical properties of sheep wool with those of other petrochemical-based materials (adapted from [9]).

Insulation Type	Density	Thermal Conductivity	Specific Heat Capacity	Sound Absorption Coefficient
Notion (unit)	ρ (kg/m^3)	k (mW/mK)	c_p (J/g°C)	α (−)
Sheep wool	10–20	38–54	1.3–1.7	0.056–1.12
Rubber	500–930	100–140	–	0.2–0.8
Polystyrene fibres	15–60	34–39	1.2	0.61–0.75
Granulated Rubber	550	135	–	00.96
Expanded Polystyrene	18–50	29–41	1.25	0.22–03.65
Extruded Polystyrene	32–40	32–37	1.45–1.7	0.2–0.65
Polyurethane	30–160	22–35	1.3–1.45	0.67 or 0.8

The application of sheep wool as a thermal- and sound-absorbing material in buildings can be hindered by the fact that the wool is attacked by moths or other parasites. Therefore, it is necessary to first treat the wool appropriately chemically. However, the effect of the applied insecticide is not permanent and working with it exposes people to harmful substances unless the work environment is properly managed. Resolving this shortcoming of wool is a challenge for further research.

In addition to other determining properties of wool, its behavior during fire is important from a safety point of view. Thanks to its chemical structure, which includes a high content of nitrogen and moisture, wool has a fire resistance. Several parameters are standardized for assessing flammability, one of which is the Limiting Oxygen Index (LOI). It is defined as the minimum concentration of oxygen in a mixture of oxygen and nitrogen that is needed to support the flaming combustion of a material. According to the LOI, wool is classified as "Slow burning" (Table 2) based on its LOI of 25.2 [18].

Table 2. The classification of the selected materials' flammability based on the Limiting Oxygen Index (Adapted from [18]).

Fiber	LOI	Classification
Flax	17.4	LOI < 20.95–Flammable
Cotton	18.4	
Polyester	20.6	
Wool	25.2	21 < LOI < 28–Slow burning

Wool ignites only at a temperature of about 560 °C. It is important that wool does not melt or drip during a fire, i.e., it does not spread fire, but it does char [12].

2.2. Composites

The physical–mechanical properties of wool are not very extraordinary in terms of their strength and ductility. However, in combination with other suitable materials, they can find applications, e.g., in the construction industry.

For soil strengthening and stabilization, Galán-Marín et al. [19] prepared a composite composed of clay, the alginate from cell walls of brown algae, and wool fiber with a length of 10 mm. In the clay matrix, alginate acted as a binder instead of using cement or lime, and the sheep fiber acted as a reinforcement. A wool content of more than 0.25% turned out to be unsatisfactory. Low-length wool proved to be better. Probably, it is more difficult to incorporate the fibers of higher-quality, coarser wool homogeneously. With the optimal composition of the composite, the compressive strength was measured using the three-point method at 4.44 MPa. According to the authors, the mentioned composite still needs to be studied in terms of its optimal fiber length, its orientation, water resistance, moisture absorption and desorption, as well as its microstructure, including the bond between the components.

Also, Parlato et al. [20] recommend the use of waste wool for soil compaction for building components. Following the authors, the addition of natural fibers to soil improves its tensile strength, ductility, impact resistance, toughness, and reduces its drying shrinkage. Based on the statistical analysis of the experimental results using the Weibull distribution [7], a strong correlation of the diameter of the fibers with the mechanical properties was found.

The study of Mounira et al. [21] compares the thermal insulation properties of adobe blocks made in three variants: clay, clay+3% wool and clay+5% wool. In terms of thermal conductivity and heat spread, the composite with 5% wool proved to be the best. With a wall thickness of 30 cm, this composition also had the lowest thermal transmittance, which means the smallest heat leakage from the house. The testing of other parameters showed that increasing the wool content reduces the depth of the heat flow, increases its density and dampens the external heat flow more. Measuring the heat energy consumption for heating a house containing the tested composites showed that the heat consumption decreases if the clay is replaced by a clay–wool composite.

The effort to utilize wheat straw and sheep wool, with these being the most widespread agricultural by-products, was led by Statuto et al. [22] to prepare adobe bricks from clay mixed with plant or animal fibers. The property testing was supposed to give an answer as to whether the bricks can be used as a building element for bio-buildings. The measured mechanical properties, especially the compression strength, pointed to the difference between the two types of bricks. The adobe bricks prepared with sheep wool showed significantly higher mechanical parameters than those incorporating wheat straw. On the other hand, the adobe brick with wheat straw exhibited a lower shrinkage than that of adobe bricks made without any fiber additive.

Atbir et al. [23] prepared experimental composites of clay and several layers of wool by placing wool fibers in one direction and in a transverse direction in a brick form on a layer of moistened clay. The fiber content in the composites was in the range of 0–4.5%. The composite with 4.5% wool showed the best thermal and bending characteristics. It was interesting to observe that the raw specimens broke via only one vertical cracking, but reinforced composites were unimpaired. Such results are encouraging for applications in thermal insulation.

In order to improve the fracture toughness in tension and prevent the formation of cracks, fiber-reinforced cement mortars are used in the construction industry. These are fibers from synthetic polymers such as polyethylene, polyvinyl chloride, etc., or from inorganic materials, e.g., glass, carbon, steel, etc. The fracture toughness is improved by increasing the amount of fibers and the ratio between the length and the diameter of the fibers. Recently, plant fibers such as bamboo and hemp have also been used to reinforce the mortar. Fantilli et al. [24] decided to investigate, for the first time, the use of wool as an animal fiber for reinforcement in cement mortars, in a 1% amount. The results of the measured properties were compared with the results for mortar reinforced with hemp. In some cases, they used both wool and hemp with a surface previously treated with atmospheric plasma. The presence of treated and untreated wool in the mortar increased the flexural strength and ductility. In this way, not only the mechanical but also the ecological properties of the mortars were improved.

Also, Tiza et al. [25] investigated the addition of 1% wool or bamboo fibers to cement mortar. In the case of non-plasma-treated wool or bamboo, the addition of 1% wool to the cement mortar increased the flexural strength by 18%, and in the case of bamboo, by 23%, but the cracking of the mortar increased by 300%. One of the other advantages of sheep wool fibers is that they fill the empty space between the particles in the concrete due to their disordered fiber orientation, where the submerged fibers create voids by moving the particles away. In fresh mixtures, the parameters of the self-compacting concrete and the fluidity of the mixtures were deteriorated, which the authors attribute to the increased content of fibers and their size. From an ecological point of view, the comparison of energy consumption is interesting; sheep wool consumes less than 15% of the energy used to manufacture glass wool. This data can be corrected according to the wool scouring method.

Alyousef et al. [26] tried to improve the compatibility of wool (with a 70 mm fiber length) and cement by immersing the wool in 35% salt water. Composites of concrete and wool were prepared with natural (contents of 0–6%) and modified (contents of 0–0.15%) wool. In all cases, the compressive strength decreased, but the tensile and flexural strength values of the concrete, and thus its ductility, improved. If a fiber content of more than 6% was applied, the properties of the concrete deteriorated. The decrease in compressive strength was smaller for the sample with the modified wool. The addition of wool worsened the workability of the mixture.

Also, Jóźwiak-Niedźwiedzka and Fantilli [27], in a review of composites based on cement and wool, stated that such materials have great potential due to their sustainability and eco-friendliness. The influence of the pH of the cement matrix on sheep fibers deserves attention. High cement alkalinity and high humidity can gradually cleave keratin disulfide bonds, thereby reducing the ability of fibers to bridge surface cracks and shortening the life of the composite. Future research should focus on improving the strength and the fracture toughness in bending as well as increasing the fiber content in these composites.

Dénes et al. [28] set out to assess not only the thermal insulation properties of sheep wool but also their reinforcement. Besides wool, the following materials were selected to be compared: polystyrene, polypropylene, and polyacrylonitrile. The comparative analysis confirmed that sheep wool has similar properties to those of polystyrene; however, the differences between the two materials are more numerous. As expected, the performance of wool fibers as reinforcement in concrete is, overall, inferior to that of polypropylene. The conclusion was that wool can replace, to some extent, the hydrocarbon-based products. In a follow-up work, the authors, Dénes et al. [29], investigated the thermal and acoustic conductivity of two types of composites made of wool, on which they applied an acrylic-polyurethane resin and a natural rubber latex as a binder using different methods and in different quantities. The following analysis included the determination of the following parameters: the microstructure, chemical composition, water absorption, attack of microorganisms, water vapor permeability, hygrothermal adsorption characteristics and sound absorption (125–2000 Hz) of the samples. It was found that all the samples prepared and analyzed in this study fulfilled the national criteria for thermal and acoustic insulation over the considered frequency range. The wool–resin sample showed high sound absorption over the whole frequency range analyzed, while the wool–latex sample was more efficient at high frequencies. As expected, the weak side of the composites was their low resistance against the attack of microorganisms and their performances in water-related tests [29].

Bousshine et al. [30] dealt with the acoustic and thermal characteristics of some renewable materials of vegetable (date palm trunk, petiole, pinnate leaves, bunch, and fiber mesh, reed, esparto, olive tree, fig tree, and wood sawdust) and animal origin (chicken feathers, sheep wool). Testing showed that the majority of the studied materials indicated good acoustic and thermal performances. However, the main drawback of sheep wool is its low resistance to parasites or mites. That is why it is necessary to chemically treat it before using it in construction.

Urdanpillet et al. [31] prepared biocomposite samples by mixing sheep wool with a soy protein isolate at 80 °C with a wool content in the composite of 7, 10, 15, or 20 wt.%. The samples were dried through freeze-drying. The biocomposite had a suitable fibrillar microstructure and favorable acoustic absorption properties at a wide range of frequencies from 100 to 5000 Hz. Measured sound absorption coefficients above 0.9 are similar to those of acoustic absorbers available on the market, such as glass wool and polyurethane foams. The additional wool supplement resulted in a more amorphous structure according to XRD analysis, probably due to the hydrogen bonds between the soy protein and the wool.

Wool fiber-reinforced thermoplastic composites possess comparable properties with lignocellulosic fiber-reinforced thermoplastic composites. However, there is still not enough knowledge about the important prerequisites for achieving the desired properties, such as the quality and quantity of the fibers in the thermoplastic matrix, the fibers' compatibility, dispersion, orientation, etc. According to the current knowledge of Tanjung and Zulkepli reported in [32], the incorporation of wool fibers into thermoplastic matrices generating composites is always accompanied by a deterioration of the strength parameters compared to those of virgin thermoplastic polymers. Therefore, in connection with the environmental requirements to save non-renewable resources, it can be expected that in the foreseeable future, more numerous studies leading to a deep understanding of essential phenomena will be published.

Ilangovan et al. [33] prepared a hybrid composite with a polypropylene matrix, wool and poultry feathers as reinforcements individually and as blends in various proportions. The ratio of reinforcement/matrix (w/w%) was kept constant at 80/20. The testing of the tensile properties, thermal conductivity, sound absorption, and flame resistance of the composites showed that reinforcing with sheep wool provided higher tensile and flexural strength compared to using the feathers. When combining wool and feathers in a 50/50 ratio and with 80% reinforcement, the composites indicated a high sound absorption coefficient throughout the 1000 to 6000 Hz range depending on the proportion of wool and feathers. A flame resistance of V1 and a thermal conductivity of 0.630 W/m·K was obtained for the composites. By varying the ratio of wool and feathers, it is possible to achieve different properties according to the specified requirement.

Using the Vacuum-Assisted Resin Transfer Molding (VARTM) process, Sharma et al. [34] made an epoxy-based polymer composite-filled waste sheep wool fiber. Following the results, a strong matrix–fiber interaction was demonstrated. The composite showed better mechanical and thermal characteristics for insulating building components. The study revealed that non-woven needle-punched (N) animal fiber polymer composites exhibit good interfacial adhesion between the fiber and matrix with lower void contents and higher tensile strengths. Also, waste animal fiber-woven and felt polymer composites exhibited better hardnesses and low thermal conductivities.

Pennacchio et al., in the article [35], in addition to the physical properties related to the thermal and acoustic insulation parameters of wool, rock and glass wool and composites with hemp, also dealt with the energy consumption of individual insulation materials. A comparison of the data in Table 3 makes the environmental impact of the evaluated insulators visible.

Table 3. The life cycle impact assessments of the insulation materials used in the comparison analysis. Environmental indicator: Cumulative energy demand (non-renewable). Adapted from [35].

Insulating Material	Primary Energy (MJ) Calculated for Functional Unit = Mass per 1 m^2 of Insulation Materials to Get an R-Value (Insulation) = 2.5 m^2 K/W				
	Raw Material Supply	Raw Material Transport	Insulation Material Production	Packaging	Total
100% wool *	0	8.02	54.63	2.55	65.20
80% wool + 20% PET	38.05	8.54	43.89	4.93	95.41
50% wool + 50% hemp	13.95	24.57	147.35	16.77	202.64
Rock wool	46.16	5.83	143.93	8.70	204.62
Expanded PS	232.42	5.79	47.25	4.12	289.58
Glass wool	56.43	9.25	254.38	0.00	320.06

Note: * wool from a local source.

The environmental point of view also resonates in the work of Quintana-Gallardo et al. [36]. They state that the building industry is responsible for one-third of the total carbon emissions in the world. The reason is the fact that building materials come from non-renewable sources and their life cycle is associated with significant carbon emissions [37]. Compared to gypsum–cardboard panels, the use of biocomposite panels has a significantly lower environmental impact, although at the cost of worse acoustic parameters. However, where acoustic insulation for high airborne insulation is not necessary, biocomposite panels either with cellulose or sheep wool as an adsorbent can be a suitable and sustainable choice.

Alyousef [38] tried to modify wool by immersing it in a 35% saline solution for 24 h. The purpose of this operation was to eliminate impurities and increase the surface friction of the fibers, which was supposed to improve the adhesion of the fibers to the cement matrix. The effect of such a modification was compared with the application of wool without pre-soaking. After mixing both types of fibers into the concrete in amounts of 0.5, 1, 1.5, 2, and 2.5%, the samples were tested. Samples with 2.5% untreated wool showed a slightly lower compressive strength and modulus of elasticity, but, on the other hand, significantly better sound insulation and noise reduction was measured in the area of 2000 Hz, regardless of the fiber portion. As expected, samples with modified wool gave slightly higher strength values. However, higher portions of fibers in the concrete had a negative effect on the strength parameters due to the random dispersion of fibers in the matrix, while the acoustic properties improved.

Altin and Yildirim [39] even built an authentic three-room house, which they used to compare their proposed new insulation board made of boron-doped sheep wool with rock wool and EPS. The comparison of insulation performances showed that rock wool gave the best results in ambient and surface temperature tests, EPS provided the best insulation in the moisture test. When testing the sound insulation, the rock wool and EPS absorbed sound at very close decibel levels, while the boron-doped sheep wool insulation material provided a higher level of sound insulation. It was concluded that the boron-doped sheep wool insulation material did not bring significant advantages over stone wool and EPS.

The effect of sheep wool incorporated in the amount of 0, 3 and 5% in epoxy, polyurethane, and polyester matrices on the damping of mechanical vibrations, sound absorption, light transmission and electrical conductivity was investigated by Vasina et al. [40]. Like other authors, he found that the physical properties are significantly influenced by the wool content. Testing via a nondestructive method of forced oscillations showed that an increased concentration of sheep wool in polymer–sheep wool composites reduced their mechanical stiffness while, at the same time, producing a shift in the first resonance frequency peak position towards lower excitation frequencies. Enhanced sound absorption properties were also related to an increased wool concentration in the composite, which is interpreted as a consequence of a higher conversion of acoustic energy into heat. The sheep wool content affected the direct current (DC) electrical conductivity only in the polyurethane–sheep wool composites. Here, the electrical conductivity significantly increased compared to that of the virgin polyurethane resin, so the presence of wool worsened the electrical-insulating level. The composite with 3% wool had the highest electrical conductivity, while this effect was negligible in the case of the epoxy–sheep wool and polyester–sheep wool composites. Woolen fibers significantly worsened the light transmission of the composites, with the worst being that for the epoxy–sheep wool composite with 5% wool, namely being approximately 46% worsened, compared to the virgin epoxy resin.

Bahij et al. [41] examined the adhesion properties between non-woven plastic sheets and cement mortar for two mortar mixtures: (1) mixtures without superplasticizer with three different water–cement ratios (w/c) of 0.45, 0.50, and 0.55, and (2) mixtures with reduced amounts of water and three various percentages of superplasticizer of 0.0%, 1.11%, and 2.17%. Along with mechanical tests, bond tests, interferometry and microscopic analyses were performed. It was observed that the non-woven sheets had a strong adhesion to the cement mortar without using any adhesive materials.

The work of Caven and Bechtold [42] offers guidance on how wool fibers can be separated into individual, required components by applying minimal or no chemical or physical actions. The cuticle can be separated from the cortex through a combination of chemical and mechanical attacks.

3. Sheep Wool as an Adsorbent

3.1. The Removal of Chromium (Hexavalent/Trivalent)

The application of the adsorption properties of wool is mainly associated with the removal of toxic substances from the aquatic environment. Judging by the number of publications, the most attention was paid to chromium, whose variant, Cr(VI), is rich in toxic effects. Cr(VI) salts are oxidizing, carcinogenic, teratogenic and ecotoxic, and dangerous not only for humans, but also for animals, plants and microorganisms, while Cr(III) is not toxic. Cr(VI) is found in the form of anion in solutions with a low pH. In addition to pH, the adsorption of Cr(VI) on wool is influenced by its contact time, the initial concentration of Cr(VI) and the bath liquor ratio to wool mass. Jumean et al. [43] studied the effect of contact time on the adsorption process of Cr(VI) on sheep wool and, at the same time, monitored the possible change in the oxidation state of chromium. In the first phase, the process took place for a short time (0–3 h) and in the second, for a long phase (0–165 h). The results provided interesting insights. The adsorption after a short-term contact amount fitted the Langmuir model and the removal of Cr(VI) from the solution did not exceed 90%. The presence of reduced Cr(III) species was not detected. After long-term contact, the removal of Cr(VI) was more than 99%. The content of the total Cr fit the Freundlich model, but not the Langmuir model. Based on measurements of the wool surface free and loaded with Cr(VI) using FTIR and Electron Dispersive X-ray Spectroscopy (EDS), the authors proposed a two-step chromium removal mechanism as follows:

$$\text{Cr(VI)aq} + \text{wool} \rightarrow \text{Cr(VI)} - \text{wool complex} \rightarrow \text{Cr(III)} - \text{wool complex} \rightarrow \text{Cr(III)aq} + \text{wool} \quad (1)$$

In the first step, Cr(VI) is rapidly adsorbed onto the wool, and during longer contact, Cr is catalytically reduced to Cr(III) and desorbed into the solution, from which Cr(III) can be precipitated at a pH = 10.

Ray et al. [44] followed up on the findings from work [43] and found that the affinity of wool to Cr(VI) changes with contact time and pH. In a short contact time of 25 min at a pH = 2.0, the Cr(VI) from the solution was adsorbed on the wool without a change in the oxidation state. With a long contact time of at least 5 days and a pH = 1.5, the catalytic reduction of adsorbed Cr(VI) to Cr(III) took place. Cr(III) was desorbed from the wool, and after adjusting the solution to a pH = 10, Cr(III) was precipitated as hydroxide.

Also, following the findings from work [43], Badrelzaman et al. [45] performed the optimization of the same process at a pilot plant based on semi-batch adsorption cycles. This process, including regeneration, was verified on real wastewater from an electroplating company.

An analogous process was used by Khamis et al. [46] on the removal of Alizarin red S (ARS) dye from wastewater via adsorption on sheep wool. Under optimal conditions of a pH = 2, a contact time of 90 min, and an adsorbent dosage of 8.0 g/L, an ARS removal of more than 93% was achieved and the result was the same even after increasing the temperature to 50 °C. The experimental results fit both the Freundlich and Langmuir isotherms, but fit the Frendlich isotherm a little better. The authors used wool with adsorbed ARS for the adsorptive removal of Cr(VI). Ingeniously designed experiments and analysis results from FTIR and HPLC showed that while the ARS on the wool was oxidized, Cr(VI) was simultaneously reduced to Cr(III). This actually resulted in the regeneration of ARS, which was released into the solution. Such a cyclic regeneration of ARS with a simultaneous removal of toxic Cr(VI) is an interesting promise for the removal of organic pollutants from wastewater.

The possibility of using wool for the adsorption of both modified and unmodified forms of the dyes rhodamine6G (R6G) and Cr(VI) is presented in the study by Meenarathi et al. [47]. It was a rather complex procedure, the result of which was the extension of the side branches of the keratin chain through the condensation reaction and the formation of Schiff bases. The linked chains are sterically more favorable with active points for adsorption. As a result, the resulting sorptivity increased significantly for both

R6G and Cr(VI). As the authors [47] declare, the long-term goal is the use of appropriately modified wool fibers for membrane applications. In addition to the positive increase in sorptivity, the procedure used also has a negative aspect, namely that it required a number of operations and chemicals (e.g., ε-caprolactone monomer, oxydianiline, stannous octoate, sodium borohydride, glacial acetic acid, vanadium pentoxide, sodium hydroxide, chloroform, tetrahydrofuran, sodium bicarbonate, acetone, triethylamine, and diethyl ether). In routine operation, the number of chemicals can probably be narrowed down. Only a detailed analysis can evaluate the soundness of such a modification and its impacts on the environment.

The possibility of the preparation of membranes combining keratin with other components gives chances for many variations. Jin et al. [48] prepared a keratin/PET nanofiber membrane and tested its performance in Cr(VI) adsorption. They studied the adsorption at different ratios of components and found that optimal sorptivity is achieved with a 50% proportion of keratin and in solution with a pH = 3. At a higher keratin content, the membrane was more hydrophilic, had greater porosity and amino groups were more protonated. The highest adsorption of such a composite membrane was 75.86 mg/g, while that of the pure PET nanofiber membrane showed only 27.27 mg/g. As indicated by the analysis results from FTIR and XPS, the active adsorption sites were disulfide bridges and amino groups. The adsorption interaction with amines was electrostatically based, and in the case of disulfide bonds, it was a redox mechanism in cystine oxide.

More recent information on Cr(III) adsorption is mostly focused on sheep wool irradiated with an accelerated electron beam, which was first reported by Porubská et al. [49]. According to the absorbed dose of energy by the wool in the range (0–400 kGy), the main effects of this modified wool are the breaking of disulfide bonds, and the oxidation of the formed S-radicals through S-sulfonate, cystine monoxide, and cystine dioxide to the end product, cysteic acid. The wool's exposure changed the point of zero charge (ZPC) from a pH = 6.85 for natural wool to a pH = 6.20 for the irradiated sample with an absorbed dose of 410 kGy. The value of the isoelectric point (IEP) of natural wool at a pH = 3.35 changed only slightly for all exposed samples, namely to a pH = 3.40 [50]. Batch sorption experiments with Cr(III) also gave different results. The sorptivity of wool increased with increasing Cr(III) concentrations. Contrary to expectation, wool with a lower absorbed dose of energy showed higher sorptivity than wool with a high dose, but it was higher than that of natural wool. On the basis of the FTIR spectra, the authors concluded that the resulting chromic salts–carboxylates and cysteinates form complexes with ligands (-NH_2, =NH, -OH) available on the fiber surface. At lower doses, less cysteic acid is formed in the keratin and the resulting salts do not yet cover the entire fiber surface, allowing Cr(III) cations to diffuse into the subsurface layers. Higher-absorbed doses produce more cysteine acid, and thus, more complex salts are formed. These occupy a larger portion of the surface, thereby preventing the entry of additional Cr(III) cations. Moreover, the possibility of coordinating one Cr(III) salt molecule with ligands from several keratin chains leads to crosslinking, which makes diffusion even more difficult [51]. The results from the sorption experiments of a simple Cr(III) solution were subjected to fitting with ten models of adsorption isotherms. The corresponding dependencies were shown by the models of Freundlich, Temkin, Halsey, Harkins-Jura and Jovanovic for all or almost all dosed samples [51].

3.2. The Removal of Other Species Using Wool

Compared to Cr(III), Cu(II) has a greater tendency to form complexes. The study [52] analyzes, in detail, the reasons for the fluctuation of the sorptivity of both natural and electron beam-irradiated wool (Figure 1).

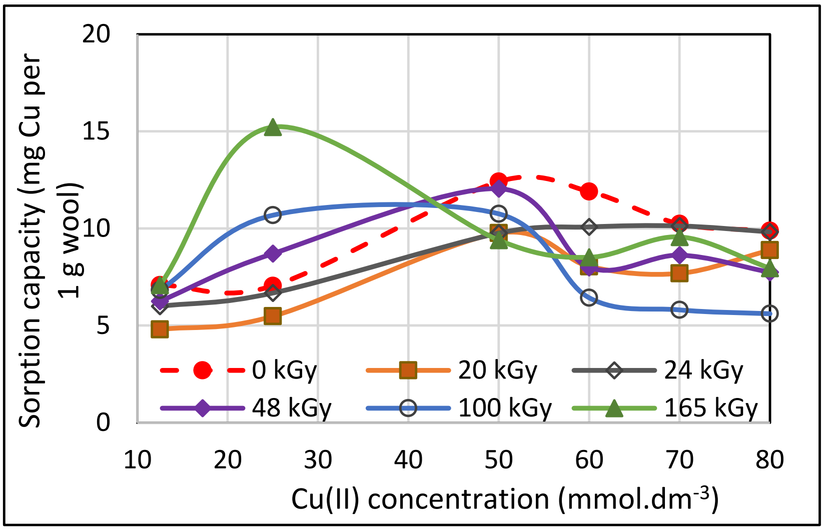

Figure 1. The variations of Cu(II) sorption onto irradiated sheep wool depending on the concentration and absorbed dose [52].

On the basis of the difference in the spectra recorded using FTIR and ATR spectroscopy, it was found that there was the formation of Cu(II) complexes of carboxylic and cysteic acids with ligands coming from various keratin macromolecules. Namely, metal cations (Lewis acids) form normal salts through a substitution mechanism; these salts coordinate with functional groups having free pairs of electrons and these ligands may not always come solely from the same chain.

The testing of Cu(II) adsorption on wool with absorbed doses ranging from 0 to 165 kGy provided data for its fitting to 10 isotherm models. Various compositions and architectures of the Cu(II) complexes were specified to be responsible for different isotherm model fittings. The copper cation showed adherence to Langmuir, Flory–Huggins, and partially Redlich–Peterson models. The latter clearly distinguished the native wool from the modified ones [53].

The study of Co(II)'s adsorption on both natural and electron beam-modified wool yielded several common features with Cu(II) and Cr(III). All mentioned cations are complex-forming. In the analysis of Co(II)'s fitting for 10 models of adsorption isotherms [53], agreements with the Langmuir, Flory-Huggins and Redlich-Peterson models were shown. When comparing the results with those of the models applied for Cr(III), it was found that none of the 10 models were adequate for both Cr(III) and Co(II). On the contrary, the simultaneous non-fitting to all dosed samples was observed for the Elovich and partially Dubinin-Radushkevich models.

Regarding the influence of wool moisture during electron beam irradiation on the obtained sorption properties, Braniša et al. [54] conditioned wool samples for 10 days at ambient relative humidities (RHs) of 10%, 53%, and 97%. In this state, the samples were exposed and absorbed doses of 0–109–257 kGy. The corresponding sorptivity was demonstrated for Co(II) adsorption. Since it was previously found that the development of the structure of the irradiated wool, especially the transformation of S-oxidized products to cysteic acid, is also dependent on the time interval from exposure [55], adsorption experiments with Co(II) were performed after 2 and 100 days (Figure 2).

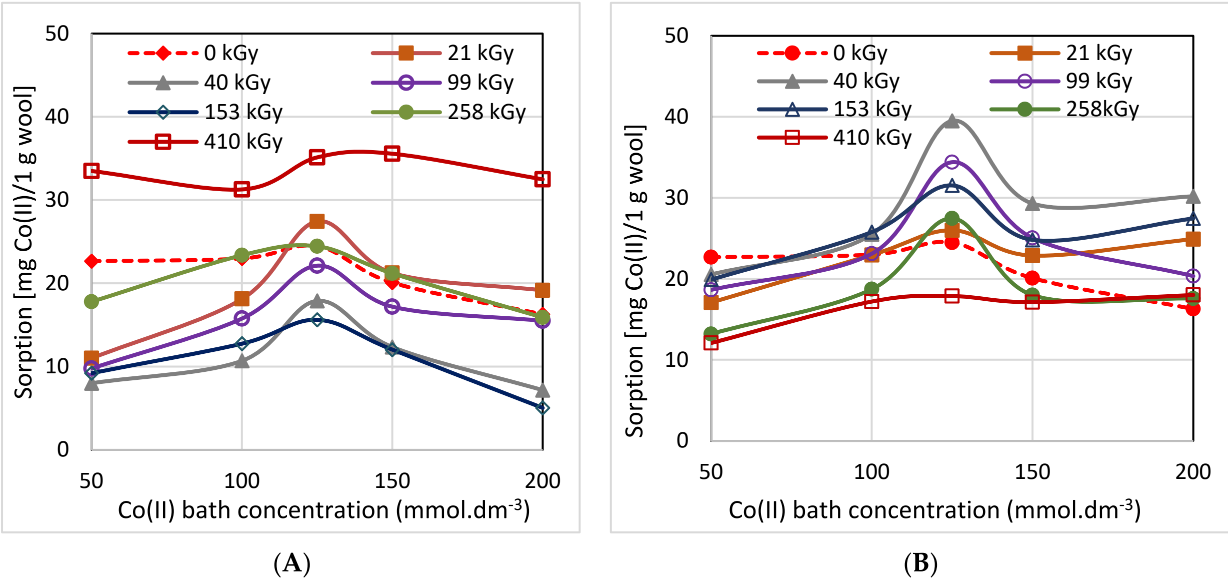

Figure 2. The variation of the sorption of Co(II) on the wool samples depending on the initial bath concentration measured (**A**) 2 days and (**B**) 100 days after irradiation [55].

In practical terms, a one-component solution rarely occurs. Adsorption from a binary solution is a more complicated problem, which explains the small number of works dealing with the competitive adsorption of components. Braniša et al. [56] described the competitive adsorption of Cr(III) and Cu(II) from a binary solution on electron beam-modified wool of 0–24–100 kGy at the same concentration of each component in a solution from 15 to 35 mmol $\cdot$ dm^{-3}. It turned out that the partners influenced each other to the extent that the order of sorptivity of the components changed with the dose. Thus, optimally dosed wool could provide a special adsorbent suitable to control the preferential sorption of some cations from binary solutions. These adsorption data were used to analyze the fitting of 10 adsorption isotherm models, when the adsorption results of each cation from single solutions were compared with the corresponding data of both cations from the binary system [57]. It was shown that the competing cation significantly changes the fitting of the selected isotherms and that even the simultaneous fitting of the same cation in a single and binary solution is rare.

Enkhzaya et al. [58] demonstrated how modified sheep wool can be used for the improved adsorptive separation of Cu(II) and Au(III). The wool was modified with NaOH, Na_2S, $NaHSO_3$, and $NaBH_4$ solutions. Each modification affected the Au(III) adsorption individually in the order of Na_2S-treated wool > $NaBH_4$-treated wool > NaOH-treated wool > $NaHSO_3$. The reducing effect of the Na_2S caused disulfide bonds to be broken, so different concentrations of the Na_2S solution were tested. At that time, the secondary structure of the keratin was already changed from an α to a β conformation. Chemical changes were monitored using FTIR and XPS. The adsorbed amount of Cu(II) increased with the concentration of the modifying Na_2S. The XPS indicated that the binding of Cu(II) occurs through the oxygen on the carboxyl group, while Au(III) was bound to the amine nitrogen and sulfur of the thiol groups. The experimental results fit the Langmuir isotherm better than the Freundlich isotherm.

Olawale et al. [59] investigated the thermodynamics and the mechanism of adsorption of some heavy metals on wool. It was confirmed that the adsorption is highly dependent on the conditions of this separation, mostly on the pH and temperature of the environment. The Pb adsorption on both adsorbents was an endothermic process. Using statistical physics, it was shown that the adsorption of heavy metals represents a multi-interaction mechanism. The results of these calculations essentially confirmed the correctness of the Cu(II) adsorption mechanism on the wool reported in [52], namely, that the cation forms a complex with the ligands donated by the side functional groups of keratin, which is a multi-interaction event. In the case of multi-component solutions, a competitive action must be taken into account, especially if the Cr(VI) ion is present. The authors [59] state that the performance of keratin biosorbents can surpass even the activated carbons described in the literature.

As found by Zimmerman et al. [60], the total surface charge of natural sheep wool is negative under normal conditions. Thus, the wool cannot be expected to be attractive to negatively charged particles in a solution. Respecting this fact, Porubská et al. [61] modified the wool by dipping it in hydrochloric acid or citric acid, which protonated the wool. The effect was subsequently demonstrated on the adsorption of nitrate anions (NO_3^-) from solutions with a concentration of (20–100) mg $\cdot$ dm^{-3} of nitrate, when the increasing initial concentration also increased the adsorption. The best result was shown by the wool treated with 0.01 M of HCl, which adsorbed the nitrate anion in an amount up to 5 mg/g. The measured results fitted the Freundlich, Temkin and Halsey isotherms from the eight tested models very well. Such a simple method of nitrate pollutant removal can be used for contaminated local wells, which is a fairly common case in small rural farms with livestock.

In addition to the ability of sheep wool to remove heavy metals and some organic substances from polluted water, there is not much information about the possibility of eliminating human viruses from wastewater using filtration. The study of Pang et al. [62] describes experiments using wool-packed glass columns (30 cm long, 3.5 cm in diameter) at a flow rate of 7.3–7.5 mL/s, the aim of which was to capture three types of viruses of different sizes on the column. The result was compared with the non-reactive water tracer NaCl. It was found that the mass recovery ratios of the viruses to NaCl were 0.62–0.63 for norovirus, 0.64–0.65 for adenovirus and 0.40–0.42 for rotavirus. The results were better than those of polyester, polypropylene and river sand filters. This indicates that wool has great potential as an alternative filter medium for treating drinking water, especially under drinking water's shortage and the need for simple practical solutions.

In addition to moisture, wool can also absorb some harmful gases, both through physical and chemisorption mechanisms. These are the nitrogen oxides from the burning of fossil fuels or the formaldehyde released from furniture adhesives. When they accumulate in the interior, they pose a danger to humans. Mansour et al. [63] summarized analytical results concerning the absorption of volatile organic compounds (VOCs), specifically gaseous formaldehyde, toluene, limonene and dodecane, using different wool types. Wool exposed to formaldehyde gas achieved a mass gain of 4. 9%, and after desorption in a formaldehyde-free environment, the mass of the wool decreased to 102.9% of its original mass. This indicates a volume of chemically bound formaldehyde of 2.9% and a physically bound 2% of the original wool mass. The absorption of the other mentioned VOCs was measured. The breed Swaledal absorbed (in ng/dm^3) 191 $\pm$ 32 of toluene, 325 $\pm$ 13 of limonene and 186 $\pm$ 15 of dodecane. In the case of physisorption, these findings may be related to the different size of the surface area of the absorbing wool determined by the wool fiber thickness of the given breed and the dimensions of the absorbate molecule. Hegyi et al. [64], when testing four types of non-woven mattresses composed of a mixture of 90% sheep wool yarn and 10% binding polymer fibers, analyzed these materials for their thermal insulation efficiency, water vapor permeability and formaldehyde sorption. They confirmed improving the air quality inside the rooms by reducing the formaldehyde concentration. Based on the residual amount of formaldehyde in the test chamber after 24 h from the end of the test, the authors formulated the conclusion that under constant conditions and a without further introduction of formaldehyde, the desorption of formaldehyde at 24 h is very low (only 13% of the adsorbed amount) and the chemisorption mechanism prevails over physisorption.

An overview of the topics covered can be seen in Table 4.

Table 4. Summary of the topics covered.

Section	Topic	Authors
Section 2.1	***Thermal and acoustic insulation***	
	Plastics' consumption in the construction industry.	Zhao et al. [5]
	The effect of the environmental degradation of wool.	Starkova et al. [6]
	Weibull distribution.	Naik and Fronk [7]
	The distribution of publications related to the price of insulating materials.	Ijjada and Nayaka [8]
	A comparative analysis of building insulation.	Kumar et al. [9]
	The necessary input energy for natural insulators and conventional mineral wool.	Volf et al. [10]
	The mechanism of wool thermal insulation.	Database [11]
	The thermal- and moisture-buffering of wool.	Ahmed et al. [12]
	The humidity adsorption mechanism, the hysteresis of the adsorption–desorption process.	Florea and Manea [13]
	The thermal and sound insulation of soft mats made of wool and polyester fibers.	Bosia et al. [14]
	The testing of several natural materials for sound absorption; a comparison of experimental and theoretical results.	Berardi and Iannace [15]
	The sound-absorbing properties of wool.	del Rey et al. [16]
	The thermal conductivity of wool compared to that of conventional insulating materials.	El Wazna et al. [17]
	The Limiting Oxygen Index of wool.	Silva-Santos et al. [18]
	The fire characteristics of wool.	Ahmed et al. [12]
Section 2.2	***Composites***	
	Wool as a reinforcement in clay.	Galán-Marín et al. [19]
	Waste wool for soil compaction for building components.	Also Parlato et al. [20]
	The thermal insulation properties of adobe blocks made of clay and wool.	Mounira et al. [21]
	Adobe bricks from clay mixed with plant or animal fibers.	Statuto et al. [22]
	Adobe bricks from clay and wool fibers oriented transversely; their thermal and bending characteristics.	Atbir et al. [23]
	Wool fibers in cement mortars.	Fantilli et al. [24]
	Wool fibers in cement mortars; an ecological point of view.	Tiza et al. [25]
	Immersing wool in salt water; composites of concrete and wool; their compressive strengths, tensile and flexural strengths.	Alyousef et al. [26]
	Composites based on cement and wool.	Jóźwiak-Niedźwiedzka and Fantilli [27]
	The thermal insulation properties of sheep wool; a comparison with synthetic fibers.	Dénes et al. [28]
	The thermal and acoustic conductivity of composites made of wool and acrylic-polyurethane resin and natural rubber latex.	Dénes et al. [29]
	The acoustic and thermal characteristics of some renewable materials including wool.	Bousshine et al. [30]
	A biocomposite prepared by mixing sheep wool with a soy protein isolate.	Urdanpillet et al. [31]
	The incorporation of wool fibers into thermoplastic matrices generating composites.	Tanjung and Zulkepli [32]
	A hybrid composite with a polypropylene matrix, wool and poultry feathers.	Ilangovan et al. [33]
	An epoxy-based polymer composite-filled waste sheep wool fiber.	Sharma et al. [34]
	The thermal and acoustic insulation parameters of wool, rock and glass wool and composites with hemp; their energy consumption.	Pennacchio et al. [35]
	The responsibility of the building industry for one-third of the total carbon emissions in the world.	Quintana-Gallardo et al. [36]
	Biocomposite panels have significantly lower environmental impacts.	Nußholz et al. [37]
	Immersing wool in a saline solution, increasing the surface friction of the fibers and the adhesion to the cement matrix.	Alyousef [38]
	A comparison of boards made of boron-doped sheep wool with those made of rock wool and EPS.	Altin and Yildirim [39]

Table 4. *Cont.*

Section	Topic	Authors
	The incorporation of sheep wool in epoxy, polyurethane, and polyester matrices; the damping of mechanical vibrations, sound absorption, light transmission and electrical conductivity.	Vasina et al. [40]
	An examination of the adhesion properties between non-woven plastic sheets and cement mortar.	Bahij et al. [41]
	How wool fibers can be separated into individual components.	Caven and Bechtold [42]
Section 3.1	***The Removal of chromium (hexavalent/trivalent)***	
	The effect of contact time on the adsorption process of Cr(VI) on sheep wool; the possible change in the oxidation state of chromium.	Jumean et al. [43]
	Changes in the oxidation state of adsorbed Cr with wool contact time and pH.	Ray et al. [44]
	The optimization of wool regeneration; designing a pilot plant.	Badrelzaman et al. [45]
	The removal of Alizarin red S (ARS) dye adsorbing on wool from wastewater; the simultaneous regeneration of ARS and removal of Cr(VI).	Khamis et al. [46]
	The adsorption of both modified and unmodified forms of the dyes rhodamine6G (R6G) and Cr(VI).	Meenarathi et al. [47]
	A keratin/PET nanofiber membrane tested in Cr(VI) adsorption.	Jin et al. [48]
	The effect of an accelerated electron beam on wool.	Porubská et al. [49]
	The adsorption of Cr(III) on (non)irradiated wool.	Braniša et al. [50]
	The fitting of ten models for Cr(III) adsorption isotherms.	Braniša et al. [51]
Section 3.2	***The Removal of other species using wool***	
	An anomalous sorption of Cu(II) on natural or electron-irradiated sheep wool.	Porubská et al. [52]
	The fitting of ten models for Cu(II) adsorption isotherms.	Porubská et al. [53]
	The effect of wool moisture during electron beam irradiation on Co(II) sorption.	Braniša et al. [54]
	The effect of irradiation lapse on Co(II) sorption.	Braniša et al. [55]
	The competitive adsorption of Cr(III) and Cu(II) from a binary solution.	Braniša et al. [56]
	Competitive cation adsorption on electron-irradiated wool changes the fitting of adsorption isotherms for single-component solutions	Porubská et al. [57]
	The adsorptive separation of Cu(II) and Au(III) on wool modified with NaOH, Na_2S, $NaHSO_3$, and $NaBH_4$.	Enkhzaya et al. [58]
	The application of statistical physics to examine the thermodynamics and mechanisms of adsorption of some heavy metals on wool.	Olawale et al. [59]
	Testing the total surface charge of natural sheep wool.	Zimmerman et al. [60]
	The adsorption of nitrate anions on modified wool.	Porubská et al. [61]
	The capture of three types of viruses of different sizes on the wool-packed column.	Pang et al. [62]
	The adsorption of VOCs on wool	Mansour et al. [63]
	The ad/absorption of formaldehyde on wool.	Hegyi et al. [64]

4. Conclusions

The non-textile use of sheep wool in the field of construction provides a great scope for research. The expected tasks should include the research of thermal and sound insulation elements with an emphasis on ingenious and cheap design solutions, the production technology and high insulation efficiency. Aiming to protect wool against moths without chemicals is a big and probably difficult challenge, but a very necessary one. The solving of this problem may condition the expansion of wool's application. Today, this is the weakness of using wool. The identification of polymer–wool composites suitable for mechanically less-demanding applications such as being used as lightweight, fire-resistant, eco-friendly, and biodegradable materials is certainly interesting. The technical solution for the preparation of homogeneous mortar mixtures containing wool with optimal fiber lengths will be very welcome in the construction industry. It will be especially useful for improving the compatibility of wool with a selected matrix.

The adsorption and absorption properties of wool can be optimally used to eliminate or separate selected components in the process of recycling or improving the living or working environment. "Custom" wool modification can produce surprisingly good results. One can expect studies focused on wool modification using radiation technologies, especially irradiation with an accelerated electron beam.

Sheep wool has the potential to be turned from a waste into a sought-after and useful renewable material.

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References

1. Regulation (EC) No 1069/2009 Laying Down Health Rules as Regards Animal By-Products and Derived Products Not Intended for Human Consumption and Repealing Regulation (EC) No 1774/2002 (Animal By-Products Regulation). Available online: https://eur-lex.europa.eu/EN/legal-content/summary/animal-by-products-not-intended-for-human-consumption.html (accessed on 8 April 2024).
2. Statistical Atlas, Eurostat Regional Yearbook. 2023. Available online: https://ec.europa.eu/statistical-atlas/viewer/?mids=BKGCNT,BKNUTS2,C13M02,CNTOVL&o=1,1,1,0.7&ch=C01,ENV,C13&center=49.97812,19.97593,3&lcis=C13M02& (accessed on 8 April 2024).
3. Czaplicki, Z.; Matyjas-Zgondek, E.; Strzelecki, S. Scouring of Sheep Wool Using an Acoustic Ultrasound Wave. *Fibres Text. East. Eur.* **2021**, *29*, 44–48. [CrossRef]
4. Giteru, S.G.; Ramsey, D.H.; Hou, Y.; Cong, L.; Mohan, A.; Bekhit, A.E.D.A. Wool keratin as a novel alternative protein: A comprehensive review of extraction, purification, nutrition, safety, and food applications. *Compr. Rev. Food Sci. Food Saf.* **2023**, *22*, 643–687. [CrossRef] [PubMed]
5. Zhao, J.R.; Zheng, R.; Tang, J.; Sun, H.J.; Wang, J. A mini-review on building insulation materials from perspective of plastic pollution: Current issues and natural fibres as a possible solution. *J. Hazard. Mater.* **2022**, *438*, 129449. [CrossRef] [PubMed]
6. Starkova, O.; Sabalina, A.; Voikiva, V.; Osite, A. Environmental Effects on Strength and Failure Strain Distributions of Sheep Wool Fibers. *Polymers* **2022**, *14*, 2651. [CrossRef] [PubMed]
7. Naik, D.L.; Fronk, T.H. Weibull Distribution Analysis of the Tensile Strength of the Kenaf Bast Fiber. *Fibers Polym.* **2016**, *17*, 1696–1701. [CrossRef]
8. Ijjada, N.; Nayaka, R.R. Review on properties of some thermal insulating materials providing more comfort in the building. *Mater. Today Proc.* **2022**, *58*, 1354–1359. [CrossRef]
9. Kumar, D.; Alam, M.; Zou, P.X.W.; Sanjayan, J.G.; Memon, R.A. Comparative analysis of building insulation material properties and performance. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110038. [CrossRef]
10. Volf, M.; Diviš, J.; Havlík, F. Thermal; moisture and biological behaviour of natural insulating materials. *Energy Procedia* **2015**, *78*, 1599–1604. [CrossRef]
11. Swiss Centre for Life Cycle Inventories. The Ecoinvent Database. 2015. Available online: http://www.ecoinvent.org/database/ (accessed on 8 April 2024).
12. Ahmed, A.; Qayoum, A.; Mir, F.Q. Investigation of the Thermal Behavior of the Natural Insulation Materials for Low Temperature Regions. *J. Build. Eng.* **2019**, *26*, 100849. [CrossRef]
13. Florea, I.; Manea, D.L. Analysis of Thermal Insulation Building Materials Based on Natural Fibers. *Procedia Manuf.* **2019**, *32*, 230–235. [CrossRef]
14. Bosia, D.; Savio, L.; Thiebat, F.; Patrucco, A.; Fantucci, S.; Piccablotto, G.; Marino, D. Sheep Wool for Sustainable Architecture. *Energy Procedia* **2015**, *78*, 315–320. [CrossRef]
15. Berardi, U.; Iannace, G. Acoustic characterization of natural fibers for sound absorption applications. *Build. Environ.* **2015**, *94*, 840–852. [CrossRef]
16. Del Rey, R.; Uris, A.; Alba, J.; Candelas, P. Characterization of Sheep Wool as a Sustainable Material for Acoustic Applications. *Materials* **2017**, *10*, 1277. [CrossRef] [PubMed]
17. El Wazna, M.; El Fatihi, M.; El Bouari, A.; Cherkaoui, O. Thermo physical characterization of sustainable insulation materials made from textile waste. *J. Build. Eng.* **2017**, *12*, 196–201. [CrossRef]
18. Silva-Santos, M.C.; Oliveira, M.S.; Giacomin, A.M.; Laktim, M.C.; Baruque-Ramos, J. Flammability on textile of flight crew professional clothing. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *254*, 052006. [CrossRef]

19. Galán-Marín, C.; Rivera-Gómez, C.; Petric, J. Clay-based composite stabilized with natural polymer and fibre. *Constr. Build. Mater.* **2010**, *24*, 1462–1468. [CrossRef]
20. Parlato, M.C.M.; Cuomo, M.; Porto, S.M.C. Natural Fibers Reinforcement for Earthen Building Components: Mechanical Performances of a Low Quality Sheep Wool ("Valle Del Belice" Sheep). *Constr. Build. Mater.* **2022**, *326*, 126855. [CrossRef]
21. Mounir, S.; Khabbazi, A.; Khaldoun, A.; Maaloufa, Y.; El Hamdouni, Y. Thermal Inertia and Thermal Properties of the CompoSite Material Clay-Wool. *Sustain. Cities Soc.* **2015**, *19*, 191–199. [CrossRef]
22. Statuto, D.; Bochicchio, M.; Sica, C.; Picuno, P. Experimental development of clay bricks reinforced with agricultural by-products. In Proceedings of the 46th International Symposium "Actual Tasks on Agricultural Engineering", Opatija, Croatia, 1 March 2018; p. 595.
23. Atbir, A.; Cherkaoui, M.; El Wardi, F.Z.; Khabbazi, A. Improvement of thermomechanical characteristics of multilayer biomaterial of and clay. *Mater. Today Proc.* **2022**, *58*, 1331–1336. [CrossRef]
24. Fantilli, A.P.; Sicardi, S.; Dotti, F. The use of wool as fiber-reinforcement in cement-based mortar. *Constr. Build. Mater.* **2017**, *139*, 562–569. [CrossRef]
25. Tiza, T.M.; Singh, S.K.; Kumar, L.; Shettar, M.P.; Singh, S.P. Assessing the potentials of Bamboo and sheep wool fiber as sustainable construction materials: A review. *Mater. Today Proc.* **2021**, *47*, 4484–4489. [CrossRef]
26. Alyousef, R.; Alabduljabbar, H.; Mohammadhosseini, H.; Mohamed, A.M.; Siddika, A.; Alrshoudi, F.; Alaskar, A. Utilization of Sheep Wool as Potential Fibrous Materials in the Production of Concrete Composites. *J. Build. Eng.* **2020**, *30*, 101216. [CrossRef]
27. Jóźwiak-Niedźwiedzka, D.; Fantilli, A.P. Wool-Reinforced Cement Based Composites. *Materials* **2020**, *13*, 3590. [CrossRef] [PubMed]
28. Dénes, O.; Florea, I.; Manea, D.L. Utilization of Sheep Wool as a Building Material. *Procedia Manuf.* **2019**, *32*, 236–241. [CrossRef]
29. Dénes, T.-O.; Iştoan, R.; Tămaş-Gavrea, D.R.; Manea, D.L.; Hegyi, A.; Popa, F.; Vasile, O. Analysis of Sheep Wool-Based Composites for Building Insulation. *Polymers* **2022**, *14*, 2109. [CrossRef] [PubMed]
30. Bousshine, S.; Ouakarrouch, M.; Bybi, A.; Laaroussi, N.; Garoum, M.; Tilioua, A. Acoustical and thermal characterization of sustainable materials derived from vegetable, agricultural, and animal fibers. *Appl. Acoust.* **2021**, *187*, 108520. [CrossRef]
31. Urdanpilleta, M.; Leceta, I.; Guerrero, P.; de la Caba, P.K. Sustainable Sheep Wool/Soy Protein Biocomposites for Sound Absorption. *Polymers* **2022**, *14*, 5231. [CrossRef]
32. Tanjung, F.A.; Zulkepli, N.N. Chapter 9—Thermoplastic polymer/wool composites. In *Wool Fiber Reinforced Polymer Composites*, 1st ed.; Sabu, T., Seiko, J., Eds.; Woodhead Publishing: Sawston, UK, 2022; pp. 155–179. [CrossRef]
33. Ilangovan, M.; Navada, A.P.; Guna, V.; Touchaleaume, F.; Saulnier, B.; Grohens, Y.; Reddy, N. Hybrid biocomposites with high thermal and noise insulation from discarded wool, poultry feathers, and their blends. *Constr. Build. Mater.* **2022**, *345*, 128324. [CrossRef]
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. *Mater. Today Proc.* **2023**, *in press*. [CrossRef]
35. Pennacchio, R.; Savio, L.; Bosia, D.; Thiebat, F.; Piccablotto, G.; Patrucco, A.; Fantucci, S. Fitness: Sheep-wool and hemp sustainable insulation panels. In Proceedings of the Energy Procedia 111 8th International Conference on Sustainability in Energy and Buildings, Turin, Italy, 11–13 September 2016.
36. Quintana-Gallardo, A.; Alba, J.; del Rey, R.; Crespo-Amorós, J.E.; Guillén-Guillamón, I. Life-Cycle Assessment and Acoustic Simulation of Drywall Building Partitions with Bio-Based Materials. *Polymers* **2020**, *12*, 1965. [CrossRef]
37. Nußholz, J.L.K.; Rasmussen, F.N.; Milios, L. Circular building materials: Carbon saving potential and the role of business model innovation and public policy. *Resour. Conserv. Recycl.* **2019**, *141*, 308–316. [CrossRef]
38. Alyousef, R.R. Enhanced acoustic properties of concrete composites comprising modified waste sheep wool fibers. *J. Build. Eng.* **2022**, *56*, 104815. [CrossRef]
39. Altin, M.; Yildirim, G.Ş. Investigation of usability of boron doped sheep wool as insulation material and comparison with existing insulation materials. *Constr. Build. Mater.* **2022**, *331*, 127303. [CrossRef]
40. Vasina, M.; Straznicky, P.; Hrbacek, P.; Rusnakova, S.; Bosak, O.; Kubliha, M. Investigation of Physical Properties of Polymer Composites Filled with Sheep Wool. *Polymers* **2024**, *16*, 690. [CrossRef] [PubMed]
41. Bahij, S.; Omary, S.; Belhaj, E.; Steiner, V.; Feugeas, F. Peeling Force Required for the Detachment of Non-Woven Plastic Tissue from the Surface of Mortar Prisms. *Polymers* **2023**, *15*, 4286. [CrossRef]
42. Caven, B.; Bechtold, T. Reverse engineering of wool fibre into its constituent components as functional additives to form wool based structures. *Procedia Eng.* **2017**, *200*, 128–134. [CrossRef]
43. Jumean, F.H.; Khamis, M.I.; Sara, Z.A.; AbouRich, M.S. Concurrent Removal and Reduction of Cr(VI) by Wool: Short and Long Term Equilibration Studies. *Am. J. Anal. Chem.* **2015**, *6*, 47–57. [CrossRef]
44. Ray, P.; Sabri, A.M.; Ibrahim, T.H.; Khamis, M.I.; Jumean, F.H. Design and optimization of a batch sequential contactor for the removal of chromium(VI) from industrial wastewater using sheep wool as a low-cost adsorbent. *Desalin. Water Treat.* **2018**, *13*, 109–113. [CrossRef]
45. Badrelzaman, M.; Khamis, M.I.; Ibrahim, T.H.; Jumean, F.H. Scale-Up of Self-Regenerating Semi-Batch Adsorption Cycles through Concurrent Adsorption and Reduction of Cr(VI) on Sheep Wool. *Processes* **2020**, *8*, 1092. [CrossRef]
46. Khamis, M.I.; Ibrahim, T.H.; Jumean, F.H.; Sara, Z.A.; Atallah, B.A. Cyclic Sequential Removal of Alizarin Red S Dye and Cr(VI) Ions Using Wool as a Low-Cost Adsorbent. *Processes* **2020**, *8*, 556. [CrossRef]

47. Meenarathi, B.; Agathian, K.; Anbarasan, R. Modification of wool fibre's structural properties as a cheap adsorbent for the elimination of Cr6+ and Rhodamine6g dye from aqueous solution. *Int. J. Biol. Macromol.* **2023**, *253*, 127160. [CrossRef] [PubMed]
48. Jin, X.; Wang, H.; Jin, X.; Wang, H.; Chen, L.; Wang, W.; Lin, T.; Zhu, Z. Preparation of keratin/PET nanofiber membrane and its high adsorption performance of Cr(VI). *Sci. Total Environ.* **2020**, *710*, 135546. [CrossRef]
49. Porubská, M.; Hanzlíková, Z.; Braniša, J.; Kleinová, A.; Hybler, P.; Fülöp, M.; Ondruška, J.; Jomová, K. The effect of electron beam on sheep wool. *Polym. Degrad. Stab.* **2015**, *111*, 151–158. [CrossRef]
50. Braniša, J.; Kleinová, A.; Jomová, K.; Malá, R.; Morgunov, V.; Porubská, M. Some Properties of Electron Beam-Irradiated Sheep Wool Linked to Cr(III) Sorption. *Molecules* **2019**, *24*, 4401. [CrossRef] [PubMed]
51. Braniša, J.; Jomová, K.; Lapčík, L'.; Porubská, M. Testing of electron beam irradiated sheep wool for adsorption of Cr(III) and Co(II) of higher concentrations. *Polym. Test.* **2021**, *99*, 107191. [CrossRef]
52. Porubská, M.; Kleinová, A.; Hybler, P.; Braniša, J. Why Natural or Electron Irradiated Sheep Wool Show Anomalous Sorption of Higher Concentrations of Copper(II). *Molecules* **2018**, *23*, 3180. [CrossRef]
53. Porubská, M.; Jomová, K.; Lapčík, L'.; Braniša, J. Radiation-modified wool for adsorption of redox metals and potentially for nanoparticles. *Nanotechnol. Rev.* **2020**, *9*, 1017–1026. [CrossRef]
54. Braniša, J.; Kleinová, A.; Jomová, K.; Weissabel, R.; Cvik, M.; Branišová, Z.; Porubská, M. Sheep Wool Humidity under Electron Irradiation Affects Wool Sorptivity towards Co(II) Ions. *Molecules* **2021**, *26*, 5206. [CrossRef] [PubMed]
55. Braniša, J.; Jomová, K.; Kovalčíková, R.; Hybler, P.; Porubská, M. Role of Post-Exposure Time in Co(II) Sorption of Higher Concentrations on Electron Irradiated Sheep Wool. *Molecules* **2019**, *24*, 2639. [CrossRef]
56. Braniša, J.; Koóšová, K.; Lendelová, K.; Porubská, M. Competitive Adsorption of Cr(III) and Cu(II) on Electron Beam Irradiated Sheep Wool from Binary Solutions Can be Controlled by the Absorbed Dose. *ACS Omega* **2022**, *7*, 38015–38024. [CrossRef]
57. Porubská, M.; Koóšová, K.; Braniša, J. Competitive Cation Adsorption on Electron-Irradiated Sheep Wool Changes the Fitting of Adsorption Isotherms for Single-Component Solutions. *Processes* **2023**, *11*, 502. [CrossRef]
58. Enkhzaya, S.; Shiomori, K.; Oyuntsetseg, B. Effective adsorption of Au(III) and Cu(II) by chemically treated sheep wool and the binding mechanism. *J. Environ. Chem. Eng.* **2022**, *8*, 104021. [CrossRef]
59. Olawale, S.A.; Bonilla-Petriciolet, A.; Mendoza-Castillo, D.I.; Okafor, C.C.; Sellaoui, L.; Badawi, M. Thermodynamics and Mechanism of the Adsorption of Heavy Metal Ions on Keratin Biomasses for Wastewater Detoxification. *Adsorpt. Sci. Technol.* **2022**, *2022*, 7384924. [CrossRef]
60. Zimmerman, B.; Chow, J.; Abbott, A.G.; Ellison, M.S.; Kennedy, M.S.; Dean, D. Variation of Surface Charge along the Surface of Wool Fibers Assessed by High-Resolution Force Spectroscopy. *J. Eng. Fiber. Fabr.* **2011**, *6*, 61–66. [CrossRef] [PubMed]
61. Porubská, M.; Cvik, M.; Jomová, K.; Branišová, Z.; Braniša, J. Nitrate removal from aqueous solution by way of adsorption on modified sheep wool. *Surf. Innov.* **2022**, *10*, 68–75. [CrossRef]
62. Pang, L.; Lin, S.; Krakowiak, J.; Yu, S.; Hewitt, J. Performance analysis of sheep wool fibres as a water filter medium for human enteric virus removal. *J. Water Proc. Eng.* **2022**, *47*, 102800. [CrossRef]
63. Mansour, E.; Curling, S.; Stéphan, A.; Ormondroyd, G. Absorption of volatile organic compounds by different wool types. *Green Mater* **2016**, *4*, 1–7. [CrossRef]
64. Hegyi, A.; Bulacu, C.; Szilagyi, H.; Lăzărescu, A.-V.; Meiţă, V.; Vizureanu, P.; Sandu, M. Improving Indoor Air Quality by Using Sheep Wool Thermal Insulation. *Materials* **2021**, *14*, 2443. [CrossRef]