

Review

# Conversion of End-of-Life Household Materials into Building Insulating Low-Cost Solutions for the Development of Vulnerable Contexts: Review and Outlook Towards a Circular and Sustainable Economy

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**Abstract:** In a world increasingly aware of the environmental cost of the current production/consumption model, the use of sustainable practices to reduce our environmental impact as a society becomes imperative. One way to reduce this impact is to increase the reuse of materials that are considered, by current definitions of "waste", at their end of life. End-of-Life Household Materials (EoLHM) can be defined as household waste materials that still possess exploitable properties, thus making them suitable for reuse. There are several studies in the literature that address the recycling of these materials. When it comes to their reuse, unfortunately, only a limited number of studies are available. This paper aims to fill this gap by investigating the possibility to convert EoLHM, such as clothes or packaging, into low-cost thermal insulating materials for the improvement of the indoor thermal comfort in buildings, especially for households at risk of suffering from energy poverty. For this purpose, a comprehensive literature review and a qualitative analysis of both commercial and EoLHM are proposed. Commercial thermal insulating materials analysis is used as a reference to measure the performance of EoLHM. Important aspects to be considered when choosing suitable EoLHM for a smart conversion and reuse are also investigated. The most important outcome of this investigation is the comprehension that the conversion of EoLHM into insulating material is possible, and it implies a direct reduction in waste production, with environmental benefits and positive social implications. However, some aspects such as adaptability, life expectancy, collection and storage are, at present, in need of further thinking and development to make the EoLHM reuse and re-conversion processes viable on a large (neighborhood/city) scale.

**Keywords:** household end-of-life materials; building retrofitting; thermal insulation; commercial insulating material; vulnerable houses; circular economy

## 1. Introduction

The life cycle of a material has social, environmental and economic effects. The depletion of raw materials is one of the main reasons for the continuous growth of the ecological footprint. Ensuring sustainable models of production and consumption corresponds to Goal 12 of the United Nations Agenda 2030 [1]. This document states that the efficient management of our shared natural resources is an important target to achieve sustainable development. Sustainable models are complex and effective systems, which can be

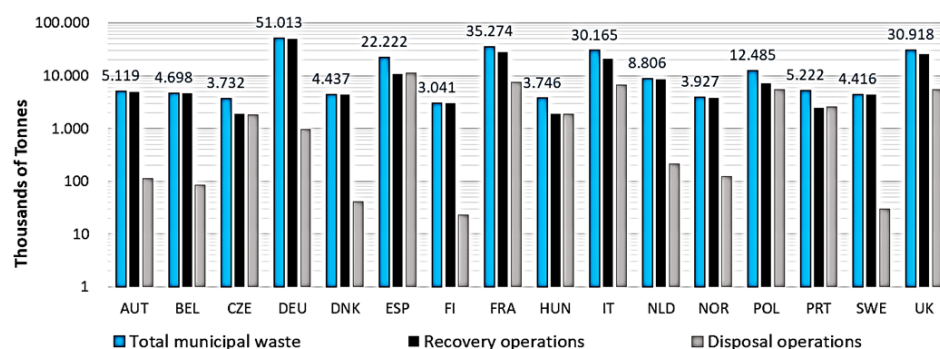
replicable and adaptable to different contexts. Production and consumption represent the application fields of these models. If, referring to a certain production, manufacturers play a key role, a certain degree of responsibility must be undertaken also by citizens, who are the final users. Everyone must play an active part of this process, switching to sustainable lifestyles. This paradigm shift highlights the limits of the classical model of linear economics. This model is coming to an end. The reason is clear: resources in our world are limited. We cannot, therefore, allow the raw materials, after their use, to become waste with negative consequences and impact on the environment. A possible solution is to close the loop and move on to the Circular Economy concept, recovering waste and making it the second raw material for a new production and consumption process. Today, several countries, through the 3R (reduce, reuse, recycle) principle, try to promote circular economy and sustainable manufacturing. Waste management thereby becomes a key phase of materials life cycle.

The amount of waste generated in each country is related to the urbanization, consumption types and pattern, household revenue and lifestyles. However, each country uses its own definition for measuring the packaging waste, and this makes the comparisons between countries difficult [2]. Despite EU and OECD (Organisation for Economic Co-operation and Development) efforts, regional and local policies continue to play a significant role in environmental protection, and the global quantity of waste production is increasing [3]. It is estimated that a person living in an OECD country produces 520 kg of household waste every year [4]. As regards packaging waste, the total generated quantity increased by 6.6 million tons from 2007 to 2017, and 173.8 kg of packaging waste was generated per inhabitant in Europe [5]. The most common types of packaging waste in the EU are made of paper and cardboard (41%), plastic (19%), glass (18%), wood (17%) and metal (5%).

Household end-of-life material (EoLHM) can be destined for reuse, recycling, and incineration, with or without energy recovery, or landfill. According to the survey by Eurostat [6], municipal waste includes household waste and waste similar in nature and composition to household waste: in Figure 1, it can be observed that municipal waste is destined for landfill and, in a small part, to recovery operations. Landfill is the most common practice in OECD countries (Figure 1). Except for reuse and recycling, the other disposal methods determine the material end-of-life with a consequent footprint. Indeed, new raw materials must be extracted and processed. Finished goods must be transported and supplied. The amount of recycled packaging depends on the material and on the country [2]. Waste is often shipped overseas (with additional emissions due to the transportation) towards regions where waste disposal rules are sometimes unclear. In these countries, waste is often mismanaged (not formally managed and includes disposal in dumps or open, uncontrolled landfills, where it is not fully contained) with consequences for the environment and the health of native people [7,8]; incorrect waste disposal and abandonment are critical, with consequent soil, air and water pollution. If recycling is energy-consuming, reuse (intended as the reuse of the object for the same purpose for which it was designed, or assigning the object to another use) is probably the option with the lowest environmental impact.

This article investigates how EoLHM can be reused for realizing thermal insulating panels destined to help people below the threshold of poverty or living in disadvantaged conditions to improve the indoor comfort in their houses. EoLHM have the advantage to be cheap (or even free), easy-to-find, and safe. Thus, EoLHM seem to be suitable to become low-cost solutions to enhance thermal indoor comfort conditions, and could be a viable alternative for people living under the poverty threshold. However, the conversion of household waste material into low-cost insulating material is possible as long as requirements such as mechanical resistance, stability, safety in case of fire, low thermal conductivity, low perforation vulnerability, building site adaptability, aging durability, and water resistance are fulfilled [9]. The main objective of the study presented in this paper is the state of the art regarding the reuse of EoLHM and, in particular, of packaging. The paper

presents and discusses information reported in the literature about thermal properties of EoLHM, with the aim to highlight the potential of these materials to be converted into insulating materials. The study is focused mainly on EoLHM that can be reused without any type of processing so that they are directly available to low-income people. Indeed, any treatment would entail costs that would affect end users, and consequently, vulnerable people would not be able to afford them. Since EoLHM are originally designed for a different purpose, it is difficult to find information about properties related to their insulation performance (for example thermal conductivity, heat capacity and density). The difficulty of obtaining information from the literature has highlighted that the approach proposed in this article is quite innovative and, to date, it has been adopted mainly in developing countries. The authors believe that this approach can and should also be imported into more developed countries to help the socially and economically vulnerable population. Moreover, the paper aims to highlight aspects that need to be investigated further to make the conversion from EoLHM to insulating material a common procedure. The paper is structured in four sections. In the Introduction, the content and motivation of this review on EoLHM reuse are stated; Section 2 illustrates aspects related to the production and disposal environmental impact of some materials (paper, cardboard, clothes, and plastic). Physical properties found in the literature concerning commercial insulating materials and technologies and EoLHM are reported in Section 3. Commercial thermal insulating materials analysis is used as a reference to measure the performance of EoLHM. In the Discussion, pros and cons of using commercial insulating materials and EoLHM for thermal buildings refurbishment are analyzed.



**Figure 1.** Municipal waste produced in 2018 in EOCED, and waste treatment [3]. Recovery indicates any operation whose objective is to use waste as a substitute for other materials to perform a particular function [10].

#### *Why EoLHM for Building Refurbishment?*

While the building design in the past was aimed at structural aspects only, it is now a multidisciplinary process that embraces socio-economic and environmental issues. According to the European Energy Poverty observatory [11], energy poverty occurs when a household suffers from a lack of adequate energy, that is, the lack of adequate warmth, cooling, lighting and energy to power appliances. In the EU, energy poverty affects more than 50 million families that cannot afford proper interventions to improve their dwellings energy performance [12]. There is a close correlation between poverty and precarious indoor comfort conditions, which are affected by age, education level, salary of the occupants, dwelling size, and age of the building [13,14]. Mainly elderly people, disabled people and long-term-unemployed are often forced to live in unhealthy spaces and in conditions of total discomfort, including conditions causing the death of the tenants. For example, in Spain, there are about 6000 excess winter deaths related to cold dwellings [15]. Since energy poverty is related also to social isolation, people living in poor neighborhoods should be involved in the renovation process to give them the possibility to have experience in the construction sector. The idea is that this could help marginalized people to find a job. Examples of the combination of engineering and social aspects are reported in [16–18]. One

of the test cases is the construction of a psychiatric hospital in Czech Republic: the hospital was built by people with mental diseases. In Germany, homeless and unemployed people were hired in a construction site and a certification proving the acquired knowledge was released, so that the people participating to the experiment could enter the work world more easily.

Given their huge quantity and presence in every part of the world, the reuse of EoLHM enables low-income people to refurbish their houses with free products in contexts where commercial insulating materials cannot be purchased. In addition, low-cost or even free insulating materials would incentivize buildings refurbishment, and it would facilitate the achievement of energy and environmental international goals [19,20], as buildings are responsible for approximately 40% of EU energy consumption and 36% of the CO<sub>2</sub> emissions [9,21]. Since about 35% of the EU's buildings are over 50 years old, and only about 1% of the building stock is renovated each year [22], revamping the existing building stock is a key factor.

## 2. Waste Materials in Details

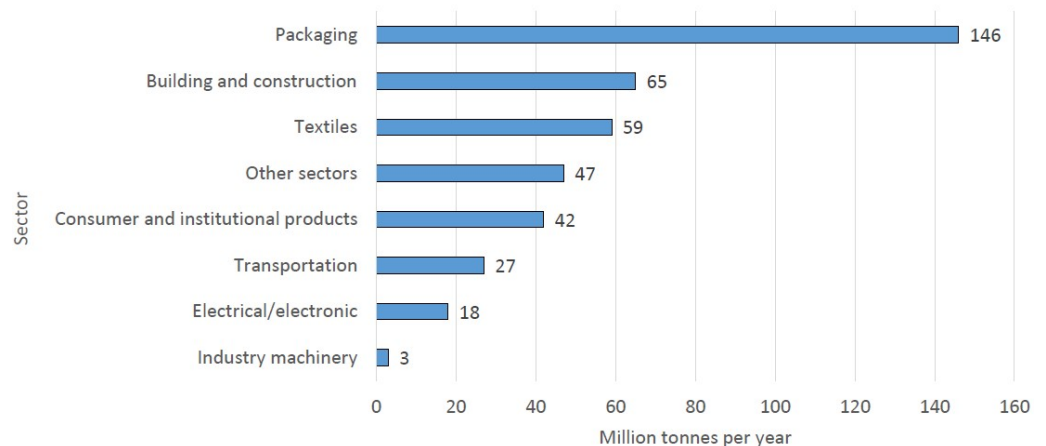
This section gives an overview of the environmental impact due to the production and disposal of some materials, the most suitable ones to be reused for the improvement of thermal comfort in buildings.

### 2.1. Textile Waste

The fashion industry has a significant environmental impact, as it is responsible for 10% of all greenhouse gas emissions and the 20% of waste water. Clothing items are discharged when damaged or no longer fashionable (the fast-fashion phenomenon). Textile waste includes products such as old clothes, carpets, tablecloths and pieces from the textile sector, and they can be made of several materials in different percentages. The yearly global production of textile waste is estimated to be about 92 million tons, but a growth of up to 134 million tons is expected by 2030 [23]. The destiny of waste clothes is second-hand life, charity, landfill or incineration for the production of electricity. In the USA, about 37 kg of clothes are discharged every year, and 13 million tons were destined for landfill or incineration in 2017 [23]. Due to heterogeneity of textile waste, and even if fiber recycling technologies do exist, just 12% of clothing is recycled: this is a very small percentage compared to paper (66%), glass (27%) or plastic bottles (29%) [24]. For example, according to [25], even though polyester is the material most present in the textile waste industry, in 2017, only 14% of it was recycled, while the rest was discarded to landfills.

### 2.2. Plastic

The production of plastic is increasing continuously: while in 1950, the estimated yearly production was 2 million tons, recently 380,000 million tons were exceeded [8]. As can be seen in Figure 2, plastic is used in several sectors, but the greatest percentage belongs to packaging, with 146 million tons produced in 2015 [8]. Plastic products include PVC (which causes several problems when disposed), PET, mainly used for beverage packaging and used in different forms, PE, PP and PS. The high contamination and heterogeneity of plastic waste entails problems in completing the closed-loop recycling process [26]. Therefore, even if plastic recycling is possible, the majority of plastic waste products are collected in landfills. According to [27], the poor management of plastic waste leads to about 8 million tons per year of plastic put into the oceans, with consequent damage to flora, fauna and humans. In sea water, plastic undergoes a fragmentation process, and the resulting particles are so small that they cannot be removed easily. Moreover, plastic, being durable and resistant to degradation, can travel long distances with a consequent movement of species to remote places. The study reported in [27] forecasts that by 2050, there will be more plastic than fish in the sea. Each country contributes to this disaster, the extent of which depends on the population size and the quality of the waste management system.



**Figure 2.** Primary global plastic production by industrial sector allocation in 2015 [8].

### 2.3. Paper and Cardboard

Paper and cardboard are produced from wood fiber, and despite their natural base, the production process is polluting and requires high quantities of water (about 5 L of water to make a sheet of paper) [28,29]. Discharge from paper mills adversely affects aquatic habitats and life, as well as the health of local communities [28,29]. However, the production of recycled paper has a lower impact on the quality of water and air [30]. To counteract the increase in plastic production, many of the most famous brands have decided to use paper and cardboard packaging rather than traditional plastic bags [28]. Indeed, more than half of the paper produced globally is destined to be turned into packaging, with 241 million tons of shipping boxes, cardboard bags and wrappers and other paper packaging produced annually [28,31]. Additionally, e-commerce has led to an increase in cardboard packaging that reached 65 billion in 2016 [28], and an increase of 20% in volume on annual basis from 2017 to 2021 is expected [32]. In [5], it is reported that about 70 kg per person of paper and cardboard waste was produced in 2017 in Europe. Although paper recycling is possible, it is a source of pollution due to the sludge produced during de-inking [30]: it represents the third largest industrial polluter to air, water, and land in the USA, and it releases over 100 million kg of toxic pollution each year.

### 2.4. Glass

Glass can be 100% recycled and transformed endlessly without loss of quality. In some countries, deposit-refund policies have encouraged the transition from one-way glass packaging to returnable packaging. As much as 74% of all glass bottles ends up in recycling bins, and about 30 billion bottles are transformed into new glass packaging [33]. Over the last 25 years, these actions led to a 70% reduction of CO<sub>2</sub> emissions and waste production.

### 2.5. Metal Packaging

Metal packaging, used as beer and soft drink cans, foil and closures [34], includes mainly products made of steel, which represent the 85% of the total amount, and the remaining 15% belongs to aluminum packaging. Since aluminum is not easy to be welded, it is used only for making seamless containers. The increase in the use of renewable resources in metal packaging production and the increase in the quantities of recycled material led to carbon savings between 20% and 39%, respectively [35]. By comparing the current data with those of 2006, it emerges that the water consumption of an average steel packaging unit has gone down 60%. According to [36], metal packaging is the most recycled packaging with 82.5% of steel packaging and 76.1% of aluminum beverage currently recycled in Europe.

### 3. Insulating Materials

It is common practice for the building industry to use insulating materials available on the market. In this section, the characteristics of commercial insulating materials and EoLHM are reviewed. Even though a direct comparison between these two categories of materials is not proposed, commercial materials are analyzed to give an overview of the performance that should be achieved by coupling EoLHM. The materials analyzed are listed in Figure 3. In this article, insulating materials deriving from agriculture are not analyzed because they are not directly available to disadvantaged people. If on the one hand industrial insulating materials properties are declared, on the other hand, the potential of EoLHM to insulate has not been extensively investigated.

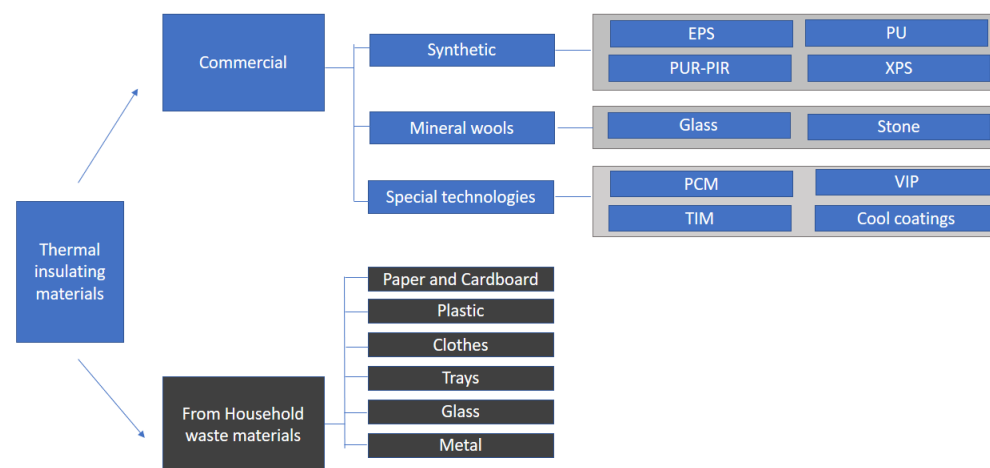


Figure 3. Materials analyzed in this paper.

#### 3.1. Commercial Insulating Materials and Technologies

According to Figure 3, commercial insulating materials have been categorized into mineral wool, synthetic polymers and special technologies. Synthetic materials are those obtained in a laboratory, whereas special technologies consider elements that guarantee thermal insulation by exploiting properties different from the thermal conductivity (cool coatings and PCM), or from assemblies of multiple elements fashioned from composite materials (VIP and TIM). Collected properties of commercial materials are reported in Table 1.

##### 3.1.1. Mineral Wool

Mineral wool is a generic name for a range of human-made non-metallic inorganic fibers. Mineral wool products are available in different formats such as rolls, rigid or semi-rigid panels and high density panels. Rock wool and glass wool are the most used products for thermal insulation of buildings. Rock wool is produced from igneous rock, whereas glass wool belongs to the MMVFs (Man-Made Vitreous Fibers) category and for its production, up to 80% of recycled glass is used [37]. Mineral wool products combine thermal insulation properties and good fire behavior. They are lightweight, relatively cheap and stable even after variations in temperature and humidity. Since they are not fragile and can be cut and perforated easily, mineral wools can be handled even by unskilled workers. In spite of this, they must be handled carefully to limit the fiber loss that may cause irritation and breathing problems. The European Certification Board [38] for mineral wool products ensures that, since they have a low bio-persistence, mineral wool products are naturally removed by the human body. Despite this, IARC decided not to make an overall evaluation because no statistical data were available. In particular, the safety of glass wool was for a long time called into question. Research showed that glass fiber can cause lung illness as asbestos [39–41]. However, even if fiberglass can irritate eyes, skin and the respiratory system, scientific evidence demonstrates that it is safe to manufacture

when safety measures are adopted [42]. For example, according to the American Lung Association, it should not be left exposed in an occupied area [39].

**Table 1.** Properties of the commercial insulating materials and technologies analyzed:  $c$  is the specific heat,  $\lambda$  is the thermal conductivity,  $\rho$  is the density.

Material	$c$ [kJ/kg·K]	$\lambda$ [W/mK]	$\rho$ [kg/m <sup>3</sup> ]
Rock wool	0.84 [43] 0.8–1 [45]	0.037–0.054 [44] 0.030–0.045 [46]	30–150 [44] 100–140 [47]
Glass wool	0.84 [43]	0.038–0.053 [44] 0.034–0.04 [46,47]	11–110 [44] 14–48 [47]
EPS (Expanded polystyrene)	2.134 [48]	0.040–0.056 [44] 0.031–0.037 [46] 0.026–0.033 [47]	23–30 [44] 20 [48] 35–56 [47]
XPS (Extruded polystyrene)	1.45–1.7 [45]	0.034–0.041 [44] 0.035 [46]	30–50 [44]
Polyurethane	1.3 [43] 1.4–1.5 [49]	0.032–0.034 [44] 0.022–0.040 [46] 0.02–0.03 [47]	30–70 [47]
PIR (Polyisocyanurate) and PUR (Polyurethane)		0.022–0.040 [46] 0.018–0.028 [46] 0.019–0.022 [47]	30–60 [50]
VIP (Vacuum Insulated Panels)		0.0035–0.008 [46] 0.005 [47]	
GFP (Gas Filled Panels)	1.290 [48]	0.010–0.035 [46] 0.001 [51] 0.038 [48]	
Aerogel	1.240 [48]	0.013–0.022 [46] 0.0208 [48] 0.013–0.038 [47]	3–80 [47]

### 3.1.2. Synthetic Materials

Synthetic materials can be cut and perforated easily, and since they are not fragile, they can be handled also by unskilled workers. The most used synthetic materials are polystyrene (PS), expanded polystyrene (EPS) and extruded polystyrene (XPS). PS is a synthetic polymer made from styrene, and in the market it can be found as EPS, which has an open structure, while XPS that has a closed structure. They are low-cost, lightweight, dimensional stable, non-toxic and non-irritant but flammable [47]. They provide good thermal resistance. Even though they are resistant to aging, they are sensible to direct sunlight [52]. This group includes also rigid polyurethane foams (PUR/PIR) produced through a chemical reaction between two base components in liquid form and an agent (such as pentane, air, nitrogen, carbon dioxide, in the percentage of 90–95%). Since their closed structure excludes the occurrence of water absorption and transportation, the thermal conductivity is not affected by the moisture content. They resist mold and decay, and their life expectancy is suitable for building applications. These materials are characterized by thermal resistance and dimensional stability, but UV radiation causes discoloring, and a low-level sanding effect. Their limited diffusion in the market is due to their higher price. Tests performed on animals indicate that exposure continuous to dust particles of polyurethane can cause lung infections, airway obstruction and fibrosis, while contact does not cause problems [53].

### 3.1.3. Special Materials and Technologies

Besides the materials described above, there are technologies whose aim is to regulate the entering of heat and light in buildings. These technologies guarantee thermal insulation

by exploiting properties different from the thermal conductivity or from assemblies of multiple elements fashioned from composite materials.

#### 3.1.4. PCM—Thermoresponsive Materials

Thermoresponsive materials react to thermal loads by changing their properties. This category includes several materials, but phase change materials (PCM) are the most common thermoresponsive technology for building thermal insulation. When exposed to a heat source, PCM's temperature increases until they change phase, and during this process, the heat is stored without increasing the temperature of the material. They can be installed on transparent or opaque surfaces to regulate the quantity of energy and the quantity of light entering the building [54]; they can also be coupled to light structures, integrated in concrete elements or shutter systems. Even though their performance is affected by several factors (such as the climate and operating conditions, the color of the wall and the degree of ventilation [55,56]), their application in buildings walls delays the heat transfer during summertime and, consequently, reduces energy demand peaks for air conditioning [57–60]. PCM are characterized by suitable phase-transition temperatures, high latent heat of transition, high density, small volume changes, low vapor pressure, long-term chemical stability, no toxicity and no fire hazard, good availability and low cost [61]. However, no PCM presents all these characteristics at the same time.

#### 3.1.5. Vacuum Insulating Panels (VIP) and Gas-Filled insulating Panels (GFP)

Vacuum insulating panels consist of an evacuated highly porous core enclosed in a case made of several metallic layers. They can be categorized into different types such as PUR-foam, polystyrene foam, expanded perlite, expanded cork, fumed silica and aerogels [62–65]. Gas-filled panels are similar to VIP, but their core consists of a baffled structure filled with gas. The function of the baffle in GFP (a cellular structure made of reflective layers) is to suppress radiation and convection, and to give structural resistance [51]. The gas contained in GFP must be non-toxic and non-flammable, and it must not condense at room temperature; suitable gases are air, argon, carbon dioxide, krypton and xenon. Flexible and non-flexible VIP and GFP can be found on the market: flexible panels have better performance and lower cost, but they cannot be used when structural strength is required. For both solutions, an aspect to be considered is the performance over time. GFP life expectancy is about 20 years [51], whereas for VIP, the core characteristics affects the panel life expectancy, which can reach 50 years [66]. However, the vacuum loss entails an increase in thermal conductivity ranging between 400% and 500% [67]. Since neither VIP nor GFP can be perforated, they need to be designed, manufactured and installed by skilled workers or incorporated into prefabricated structures [51]. Given their extremely low thermal conductivity, their installation must be performed carefully, trying to avoid thermal bridges and paying particular attention to the connections between the panels [64,67]. Their penetration in the construction market was limited by their high price and scarce adaptability [47,68].

#### 3.1.6. Transparent Insulating Materials (TIM) and Aerogel

Transparent Insulating Materials represent an interesting application when considering daylight because they offer a barrier to heat transfer and, at the same time, allow the passage of light. They are used as rooflights, membrane roofs and façades, exterior thermal insulation composite system, light-diffusion insulating panels, translucent wall elements, thermal insulation or curtain walls, or they are coupled to glazing systems [69,70]. The most famous material belonging to this category is Aerogel, known to be one of the best solid insulation materials. It is a synthetic ultralight material derived from a gel in which the liquid component for the gel has been replaced with a gas. Aerogel is lightweight and characterized by a very low thermal conductivity. Given its transparency, it is widely used as filler in transparent elements such as windows to obtain a more insulating and lighter structure compared to standard windows systems. Despite the fact that Aerogel products



are practical, they are very expensive [71]. Aerogel may generate dust, and even if it is not carcinogenic, protective gears must be worn when handled since it may cause irritation to eyes, skin, respiratory tract and digestive system [72].

### 3.1.7. Cool Coatings

Cool coatings, which are characterized by high reflectivity of the sunlight, are usually coupled to opaque or transparent surfaces to limit heat gains in buildings due to solar radiation. They can be natural, such as gravel, which is widely used on roofs in the Mediterranean area, or synthetic, such as foils, paint, shingles or panels [73,74]. Cool coating performance is closely related to the conditions of the surface on which they are installed, aging, building orientation and location [75]. According to [74], they can reduce the peak cooling demand for air conditioning in summertime by 11–27%, and tests performed in 27 cities showed that the solar gain reduction in wintertime is less substantial than the cooling load reduction in wintertime. Therefore, their use is positive on the annual energy balance. It was shown that the application of cool coating is more beneficial for old, poorly or non-insulated buildings and, in some cases, it is more beneficial than windows replacement and roof insulation [76–78].

### 3.2. Insulating Materials and Systems from EoLHM

In this Section, EoLHM properties found in the literature are reported. In particular, the thermal conductivity, the density and the specific heat of these materials have been investigated. However, aspects related to their mechanical resistance are also discussed. The properties reported here are the result of an extensive research of data in the literature; in fact, few studies have dealt with the reuse of EoLHM. Collected properties of EoLHM are reported in Table 2 respectively.

**Table 2.** Properties of household waste materials:  $c$  is the specific heat,  $\lambda$  is the thermal conductivity,  $\rho$  is the density.

Material	$c$ [kJ/kg·K]	$\lambda$ [W/mK]	$\rho$ [kg/m <sup>3</sup> ]
Recycled textile fibers	1.2–1.6 [45]	0.036–0.053 [46] 0.03–0.053 [45]	30–50 [45]
Tablecloths		0.033 [79]	53.31 [79]
Woven fabric waste	0.052–0.0603 [80]	0.044 [81]	440
Non-woven fabric sub-waste		0.103 [81]	122.5 [81]
Linter		0.039 [46]	
Polyester and polyurethane	0.24 [43]	0.041–0.053 [82]	203–491 [82]
Paper	1.25–1.65 [83]	0.08–0.18 [83]	625–1190 [83] 625–1190 [83]
Low density paper copy	0.24 [43]	0.08 [83]	625 [83]
Glossed coated paper	1.25 [83]	0.1756 [83]	1190 [83]
Cardboard	1.8 [84] 1.8 (flute) [84]	0.1 [84] 0.22–0.047 [85] 0.052–0.060 [86]	520 (linear.) [84] 49–74 (flute) [84]
Tetra-Pak		0.06 [46]	
Recycled PET	1.2 [45]	0.034–0.039 [46]	32–85 [45]
Glass and recycled glass	0.83–1 [45]	0.80 [46] 0.031–0.05 [45]	100–450 [45]

### 3.2.1. Textile Waste

Given their low thermal conductivity and low-cost production, thermal insulation performance of textile waste, such as tablecloths [46], textile tablecloths mixed to linter [79], polyurethane [82] and polyester [82,87], has been investigated with a view of using them as insulation for buildings [88]. In particular, thermal conductivity of woven and non-woven fabrics has been investigated. Weaving numerous threads together perpendicularly to each other creates woven fabrics. Non-woven fabrics are long fibers that have been bonded together using some sort of heat, chemical, or mechanical treatment [89]. It was found that the thermal conductivity of woven fabric waste is comparable to that of EPS, XPS and mineral wool, whereas woven fabric sub-wastes are comparable to vermiculite and expanded perlite [81]. According to [90], non-woven fabrics made of polyester offer higher thermal resistance than polypropylene. Since it was found that thermal conductivity values are suitable for building insulation, waste cuttings from different polyester fabrics without shredding the fabric were used as thermal insulation in [87]. In [91], a numerical study showed that a layer made of acrylic and wool inserted in a masonry wall implies a temperature reduction amplitude and a heat flux reduction of about 77% all year for Morocco's climate conditions.

### 3.2.2. Paper and Cardboard

Density, heat capacity and thermal conductivity of different types of paper sheets were analyzed in [83]. An insulating panel made of two external layers of recycled polyethylene fibers and an internal layer made of waste paper was designed in [92]. Different cardboard design options were identified in [93], and acoustic performances, transportability, lightness, cost and recyclability were evaluated: the most performing configuration identified is made of two honeycomb panels filled with cellulose fiber. To evaluate the conservation status of the beer during transport by trucks, thermal and acoustic performances of beer packaging were investigated in [94]. The comparison of the thermal performance of two types of packaging, one made of cardboard only and one made of cardboard coupled to an aluminum foil, showed that the second sample has a better performance over time [94]. Cost and practical implication of cardboard panels installed on ultra-low-cost houses in South Africa made of ordinary corrugated iron was investigated in [85]: it was shown that a panel 20 mm thick entails money savings after one winter. Tetra-Pak is a material typically made of paperboard (75%) and low density polyethylene (10–25%) [95], and the thermal conductivity of panels made of this material when coupled to wool fiber waste was investigated in [96]. According to [97], panels made of Tetra-Pak, food packaging films and candy polyethylene wrappers could have the potential to produce binderless value-added composite panels.

### 3.2.3. Plastic

Given their wide availability and the environmental problems related to their abandonment, numerous studies have investigated the possibility of reusing plastic bottles as building elements. PET bottles were used for building low-cost houses in Nigeria that cost 65% less than a standard house [98] and for insulating bivouacs and buildings at high altitude [99]. In Guatemala, schools were built with abandoned plastic bottles filled with plastic bags and other trash inserted into a metal frame and covered with concrete [100]. Thermal and mechanical properties of walls made of plastic bottles filled with different materials were investigated in [98,101]. Bottles filled with water showed better thermal performance but a lower mechanical resistance than bottles filled with sand [98]. In tests performed on bottles positioned horizontally, the best thermal performance was measured (from best to worst) for bottles filled with air, with dry sand, with common bricks, and with saturated sand, respectively [101].

### 3.2.4. Egg-Boxes and Trays

Egg-boxes and trays are treated separately because what distinguishes them is not their chemical composition, but rather their shape. In fact, egg-boxes are made with different materials including plastic, recycled paper, cardboard and expanded polystyrene. Even though mainly the acoustic performance of egg-boxes has been investigated in the literature [34,102,103], several studies focused on their mechanical properties [104–106]. Egg-boxes' mechanical properties are more affected by shape than material [104], and greater mechanical resistance belongs to cardboard (even if strongly affected by humidity), followed by polystyrene and expanded polystyrene [105].

### 3.2.5. Metal Packaging

Aluminum cans were coupled to polystyrene and cardboard in [107], but only the acoustic performance of the panel was investigated.

### 3.2.6. Glass Packaging

Glass packaging includes bottles and jars that are used for drinks and food. Tests performed on five types of waste glass bottles showed that they can be used as supplementary building materials with excellent mechanical properties [108]. Heineken [109,110] designed square beer bottles to be interlocked, and they were used to build houses in the Caribbean islands.

## 4. Discussion

With the aim to highlight their pros and cons, the materials analyzed are compared from several points of view. Different aspects have been considered for commercial materials and for EoLHM, as shown in Figures 4 and 5.

	Cost	Installation/ Adaptability	Life expectancy	Resistance to moisture	Maintenance	Danger
Mineral wools	●	●	●	●	●	●
EPS, XPS, PIR, PUR	●	●	●	●	●	●
VIP, GFP	●	●	●	●	●	●
Thermoresponsive materials (PCM)	●	●	●	●	●	●
TIM (Aerogel)	●	●	●	●	●	●
Cool coatings	●	●	●	●	●	●

● GOOD                      ● AVERAGE                      ● WEAK

**Figure 4.** Qualitative analysis of commercial insulating materials properties: green identifies good properties, yellow identifies average properties and weak properties are presented in red.

	Thermal insulation	Installation/ Adaptability	Life expectancy	Resistance to moisture	Quantity/ Availability	Ease of storage
Textile waste	●	●	●	●	●	●
Paper/Cardboard	●	●	●	●	●	●
PET Bottles	●	●	●	●	●	●
Egg boxes/trays	●	●	●	●	●	●
Metal cans	●	●	●	●	●	●
Glass bottles	●	●	●	●	●	●

● GOOD                      ● AVERAGE                      ● WEAK

**Figure 5.** Qualitative analysis of EoLHM properties: green identifies good properties, color identifies average properties and weak properties are presented in red. The dot indicates that the properties depend on the material.

Regarding the commercial materials, the following aspects are evaluated: cost, installation and adaptability, life expectancy, maintenance, resistance to humidity and possible harm to human health. The item “Cost” considers the cost related to material, labor and equipment necessary to the installation. This study investigates the possibility of using such materials in disadvantaged contexts. This means that if a material must be purchased, it is not optimal as the people who live in these realities generally have no economic resources to buy these products. In particular, technologies that cost more than 40 Euro/m<sup>2</sup> or whose installation requires a design are considered not exploitable. The item “Ease of installation and adaptability” considers whether the shape of the material can be easily adapted to existing structures, and also the possibility to drill the material without compromising its thermal performance. For example, if a material can be installed indoors without the aid of scaffolding or special equipment, it is considered suitable. Materials that require particular care or supporting structures or must necessarily be installed externally are considered less appropriate or unsuitable. The entry “Life expectancy” evaluates the material performance over time, whereas the entry “Maintenance” evaluates whether maintenance (for example cleaning) is necessary for preserving the material performance. The item “Resistance to moisture” evaluates whether the performance of the material is affected by the level of humidity. Finally, short-term risks (such as irritation) and long-term risks (such as disease) to people’s health are considered by the item “Danger”, and this item has been defined according to the information reported in the literature.

Given that EoLHM are designed for a different purpose than thermal insulation, aspects related to the possibility of converting them into insulating materials have been considered. The following aspects have been evaluated: thermal insulation, installation and adaptability, moisture resistance, life expectancy, quantity/availability and ease of storage. The item “Thermal insulation” takes into consideration the thermal resistance offered by the considered EoLHM: for this reason, both the thermal conductivity and the thickness have been evaluated. In addition, when possible, the possibility of filling EoLHM with different materials has been considered. For the item “Ease of installation and adaptability”, the approach described for the commercial materials has been adopted. The item “Moisture resistance” considers whether condensation phenomena can lead to deterioration, or if it should be avoided to prevent the formation of mold. Connected to this item there is also “Life expectancy”, which also evaluates the resistance of the materials to possible collisions. If the EoLHM collection takes place at domestic level (each tenant

collects EoLHM), the minimum number of elements is not negligible. As the collection of numerous EoLHM requires time and space, the item “Quantity/Availability” considers the number of elements necessary to insulate a reference 10 m<sup>2</sup> wall (2.70 × 3.7 m), whereas the item “Ease of storage” considers whether the storage requires a big space and/or protection from humidity.

#### 4.1. Commercial Insulating Materials

Commercial insulating materials have the advantage to be available in different shapes and thicknesses and, since their properties are declared by the producer, the identification of the most suitable material is easy to be made. However, there are some aspects, such as cost and installation procedure, that are not negligible: their price and the required skills make these elements not always suitable for disadvantaged contexts, characterized by limited financial resources and technical skills. Mineral wool products are cheap and their installation does not require skilled personnel because they can be cut and perforated easily. Due to the fact that they are made of fibers, they do not offer a strong vapor barrier [43,44], and an additional barrier must be considered when they are installed indoors. They must be handled carefully because they can irritate skin and cause problems to the respiratory system [39–42]. Properties of PUR, PIR, XPS and EPS are comparable, but PUR and PIR are much expensive. Synthetic materials can be cut easily, handled and perforated without problems, and are easy to be installed. Given their stiffness, they do not show problems related to fiber loss. However, they can be exposed to limited level of humidity and they should be protected from direct sunlight which causes superficial crumbling. VIP and GFP offer high thermal resistance in a limited thickness but a critical point is their price [47,68]. Moreover, they must be installed by skilled people and after a careful evaluation of the context. Since they are not easily deformable, they are not suitable in constructions with many openings. PCM are not so widely spread, and their application is generally limited to structures where the effect of solar radiation is strong. Their choice and installation requires a careful design and expert personnel. Cool coatings are a good solution in hot climates, however their application is limited to external surfaces and they cannot be applied in historical contexts where the appearance of the external façade must be preserved [73–75]. Since they are cheap, available in many formats and easy to install, their application at the top of very old buildings can be considered. Their very limited cost allows their installation also in very poor contexts.

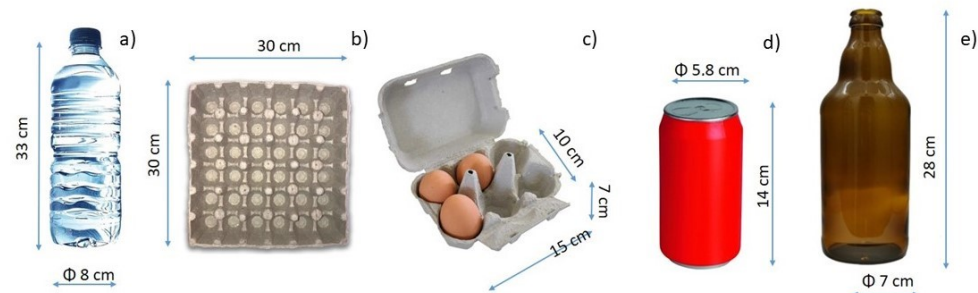
#### 4.2. Insulating Materials from EoLHM

Textile wastes have good thermal insulating properties, are easily available and are easy to cut. Given their typical surface, a limited number of clothes may be necessary for the thermal insulation of a 10 m<sup>2</sup> wall. However, since they do not have structural resistance, they must be confined in rigid systems conceived during the design phase that should compensate for their flammability. Their collection and storage is not problematic. Clothes do not suffer when exposed to moisture, even if prolonged exposures can give rise to mold processes and an increase of the thermal conductivity.

Cardboard is cheap, available in large quantities, thermal insulating and it can be used for structural purposes when loads are limited [85,86]. However, there are critical aspects to be considered such as the limited resistance to moisture and flammability [84]. The same considerations are valid for paper, even if paper should not be considered for structural purposes.

Plastic packaging includes a wide range of products. In particular, PET bottles are light and not fragile. To increase their thermal resistance, they can be filled with other materials characterized by low thermal conductivity and low stiffness such as clothes. PET bottles are largely available, and the conversion of bottles from waste to a thermal insulation material candidate could limit their abandonment. However, they can neither be shaped nor be stacked easily, especially when positioned vertically. Shape and size of plastic bottles vary a lot. Therefore, the number of elements to insulate a wall depends on the positioning of

the bottles, which can be done vertically or horizontally. Figure 6a shows the dimensions of a 1.5 L plastic bottle: to insulate the 10 m<sup>2</sup> reference wall, 378 plastic bottles positioned vertically and 1990 bottles positioned horizontally are required. If positioned horizontally, the structure is more stable but its thickness reduces the living space significantly, which is a not negligible aspect in dwellings where the living space is limited.

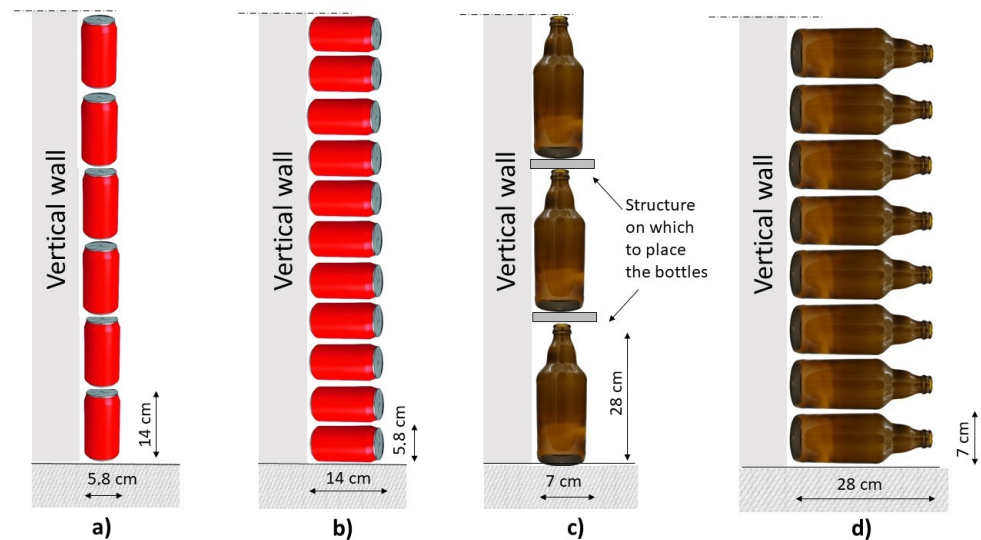


**Figure 6.** Dimensions of the EoLHM considered in the analysis reported in Section 4: (a) plastic bottles [111], (b) egg-box trays [112], (c) egg-box [113], (d) metal can [114], (e) glass bottle [115].

Regarding egg-boxes, even if their limited thickness does not provide enough thermal resistance, their structure makes them suitable to be filled with fibrous materials such as clothes. However, for both cardboard and egg-boxes made of paper, a barrier should be provided to limit the humidity exposure, and treatments for increasing their resistance to fire should also be considered. If used as containers, plastic egg-boxes should be considered when there are problems related to humidity. Their adaptability is poor, because they can break when cut, especially those made of plastic. Although different egg-boxes shapes and sizes can be found on the market, numerous elements are required for insulating the reference 10 m<sup>2</sup> wall: more precisely, 111 egg trays depicted in Figure 6b and 635 egg-boxes depicted in Figure 6c are required.

Aluminum cans show good mechanical resistance, and they are widely available. Given their shape, they can be filled with low-thermal-conductivity materials, and they can also be easily stacked also without a supporting structure. They are very lightweight, do not show problems from humidity exposure and their flammability is negligible, although the release of harmful substances at high temperatures should be evaluated. By considering cans whose dimensions are reported in Figure 6d, to insulate the reference wall, 1231 elements positioned vertically as in Figure 7a and 3786 elements positioned horizontally as in Figure 7b are necessary.

Glass packaging has structural and moisture-exposure resistance, but at the same time, they are fragile and not easily stackable. Since they have scarce adaptability, it is necessary to provide a system that allows the bottles' arrangement as proposed in Figure 7c. As for plastic bottles, glass bottles can be filled with fibrous material in order to provide higher thermal resistance. An important aspect is the weight of the elements. By considering the dimensions reported in Figure 6e, 510 elements positioned vertically are necessary to insulate the reference wall, for a total weight of about 250 kg. By positioning the bottles horizontally as shown in Figure 7d, 2600 elements are necessary and their weight is 1250 kg.



**Figure 7.** Possible stacking configurations of cans and bottles: cans positioned vertically (a) and horizontally (b), glass bottles positioned vertically (c) and horizontally (d).

If commercial materials are suitable for ordinary building interventions, they are not in disadvantaged contexts where people cannot afford these technologies and do not have the technical knowledge for making a correct and effective installation. However, from this analysis, it emerges that EoLHM can be used for thermal insulation. Since none of the EoLHM analyzed present all the characteristics for building retrofitting, they should be coupled wisely. Although some of them present weak thermal insulation properties, they can be easily filled and used to trap loose materials: for example, plastic bottles can be filled with clothes and enclosed in a cardboard structure. Moreover, there are some aspects related to the adaptability to be considered in the design phase and that can be solved by providing a self-bearing structure that should cope with the system flammability. Since a large number of elements must be collected in order to carry out interventions even on small surfaces, EoLHM collection and storage should be done at the neighborhood or at a city level by means of an extensive collecting system. Given that EoLHM are not designed to be converted into insulating materials, packaging manufacturers should design these objects to facilitate their installation in their second life or to improve some of their properties. Since a large number of elements must be collected to be able to carry out interventions even on surfaces of modest size, their collection and storage should be done at the neighborhood or city level. If this type of intervention were standardized, an extensive collecting system must be organized.

#### 4.3. Steps to Encourage and Facilitate the Conversion of EoLHM into Insulating Materials

The conversion of EoLHM into insulating material can promote the circular economy and give disadvantaged people the opportunity to renovate their homes and improve their living conditions. To allow a wiser and circular use of resources, more studies must be conducted to determine EoLHM's properties and to identify interventions able to make them more suitable to be used as insulating elements. Future research should consider manufacturers of household materials. Involving these stakeholders in the end-of-life design of their products could be the way to maximize the potential of raw materials. One of the goals could be to develop their products to facilitate their installation in second life or to improve some of their properties in order to better exploit their properties. Encouraging and promoting effective partnerships between public, public-private and civil sectors is also one of the goals of Objective 17 of the 2030 Agenda [1]. These partnerships could help to overcome some of the issues highlighted in the study on the collection and storage of household waste for reuse.

## 5. Conclusions

The study investigated the possibility of converting end-of-life household materials (EoLHM) into low-cost insulating materials. A large number of articles related to the properties of commercial insulating materials and EoLHM has been analyzed. The limited number of articles found in the literature related to reuse has highlighted the necessity of bringing some innovation in this sector. From the information so collected, tables that qualitatively evaluate important aspects in the choice of insulating materials have been proposed to highlight the potential of EoLHM and the aspects that need to be improved to achieve the performance of commercial materials. The conversion of EoLHM into insulating materials is possible, and it must be stimulated, in order to push the circular economy and discourage the abandonment of EoLHM. However, there are some aspects, such as the collection and storage of the materials to be used, that need to be further investigated. Since a large number of elements must be collected in order to carry out interventions even on small surfaces, EoLHM collection and storage should be done at the neighborhood or at city level by means of an extensive collecting system. Furthermore, some of these materials (such as glass bottles) are poorly adaptable or offer poor thermal resistance/insulation (such as egg-boxes). Nevertheless, the peculiarities of each material can be exploited to create insulating panels composed of several materials. Egg-boxes can, for example, contain materials characterized by low thermal conductivity but without structural stiffness (such as clothes). Given the wide availability of these materials, these solutions should be used to renovate buildings in disadvantaged contexts. If properly trained, people living in these realities could implement the interventions directly. Indeed, the realization of insulating panels made of EoLHM does not require particular skills and tools. In spite of this, an introduction to the thermal insulation in buildings and its principles is very important to show how to make these panels. On the other hand, a course or set of guidelines should be defined to make participants aware of the best practices. A further benefit of a possible collaboration between professionals and people living in these contexts can be a better integration of the marginalized population and the creation of work opportunities.

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## Abbreviations

The following abbreviations are used in this manuscript:

EoLHM	End-of-Life Household Materials
EPS	Expanded Polystyrene
EU	Europe
GFP	Gas Filled Panels
OECD	Organisation for Economic Co-operation and Development
PCM	Phase Change Materials
PE	Polyethylene



PET	Polyethylene terephthalate
PIR	Polyisocyanurate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
TIM	Transparent Insulating materials
UV	Ultraviolet
VIP	Vacuum Insulated Panels
XPS	Extruded Polystyrene

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