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Low-impact thermal insulation materials for sustainable retrofitting: potentialities and barriers from a literature review

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Abstract. The present study provides both an updated overview of the most recent studies about low environmental impact materials for building retrofitting and meta-analyses of the most important features, such as the thermal conductivity, allowing to evaluate their insulation potential against the diffused and recurrent conventional competitors. Specifically, 466 case studies about materials derived by co-production, wastes of other products and recycled ones have been selected and their thermal performances have been analysed. The materials have been clustered into homogeneous classes: lose materials and foams; structural materials; panels; finishing materials. The results show that some low environmental impact materials are characterized by thermal performances which can position them as materials able to contribute to building decarbonization, but little information can be found about other characteristics which can be crucial when the built environment is considered, such as durability, fire resistance, costs, and load resistance. Yet, these latter aspects may be investigated further when the material is considered to enter the prototyping phase whether in the academic or market context.

The present study provides a base for discussion about the use of more environmentally friendly thermal insulation materials which in the coming years might represent a valid option for sustainable building renovation.

Keywords: sustainable materials; embodied carbon; energy efficiency; building retrofitting; environmental impacts

1. Introduction

In the EU, 85% of buildings were built before 2000 and 75% of them are characterised by poor energy performances [1]. Therefore, building refurbishment is urgent to achieve a fully decarbonised building stock by 2050 [2]. To this aim, the choice of thermal retrofitting materials is crucial since their massive use would further increase the already impressive amount of materials — 50% of the globally extracted resources — used by the building sector [3]. It is, therefore, key to both decrease building energy use and environmental pressure due to the exploitation of natural resources. To this end, the use of waste-based materials or by-products can be beneficial for the manufacture of building materials with thermal insulation performance and would also contribute to the reduction of waste production.

Globally, 2.01 billion tons of municipal solid waste are generated yearly, and this share is expected to reach 3.40 billion tons by 2050 [4]. However, this is only a share of total global waste, which does not consider the other sectors whose weight varies considerably country by country. Taking Italy as an example, in 2020 construction waste accounted for 66.08 million tons; 28.95 M t for households; 26.53 M t for manufacturing; 1.63 M t for electricity, gas, steam and air conditioning supply; 1.34 M t for mining and quarrying; 348,501 t for agriculture, forestry and fishing [4]. Municipal solid waste (i.e., households) were mostly made of 39% biowaste; 19.1% paper and cardboard; 11.9% glass; 8.8% plastic; 5.3% wood [5]. These national statistics are in line with the overall waste picture of EU, where in 2020 construction and demolition works by their own accounted for 37.5% of total waste [6] which means about 1800 kg per capita, mostly made of concrete, bricks, wood, glass, metals and plastic. As for municipal solid waste, in the same year in the EU it accounted for over 500 kg per capita [7], which are largely collected separately.

Given that waste represents an environmental and economic issue, current policies and regulations are trying to convert it into a positive resource by applying circular economy principles. In particular, at EU level this applies increasingly more to renovation works [8]. Indeed, there are promising approaches, studies and experimentations that deal with waste-based materials for constructions, either bio-waste or not. The main concepts behind are the development of industrial symbiosis network and processes [9,10] and urban mining platforms [11]. In Italy some worth mentioning good practices are spreading in this field, mapped under the general umbrella of the Italian Circular Economy Stakeholder Platform (ICESP) [12]. For example, the Italian research project MaterSOS aimed at developing materials for constructions, such as concrete, mortar, tile adhesive, ceramic for interior and exterior cladding, and glazes, by innovating the formulations of traditional materials with a recycling rate of more than 60% and reducing the energy consumption of production processes [10]. Another project addresses the production of thermal insulation panels with recycled content, by upcycling polyurethane panels used as freezer and fridges packaging [13]. Others use agricultural waste to this end, such as rice by-products for building construction blocks [14]. Notably, also closed loop within the construction sector are developing, as the use of secondary materials from the glass fiber industry to new insulation materials [15]. Similar good practices and initiatives are mapped within the European Circular Economy Stakeholder Platform [16], but still several technical and non-technical barriers to their actual implementation exist [10,17]. Although the Waste Framework Directive [18] tried to overcome relevant legislative barriers, partly through the introduction of the end of waste criteria [19], other knowledge gap and procedural issues hamper CE to take place in Constructions yet. Among these, it is frequently mentioned a low level of detail about waste flows and reprocessing opportunities, as well as market constraints and a limited understanding of stakeholder in this field [9].

Within such a framework, the present study aims at providing an updated overview of recently published literature on building materials manufactured with waste or by-products and at exploring some of their most important characteristics such as thermal performances, physical and acoustic properties, water vapor resistance, reaction to fire, and durability, to name a few. This works lays the ground for mapping most promising materials to be developed and launched within the Italian construction market.

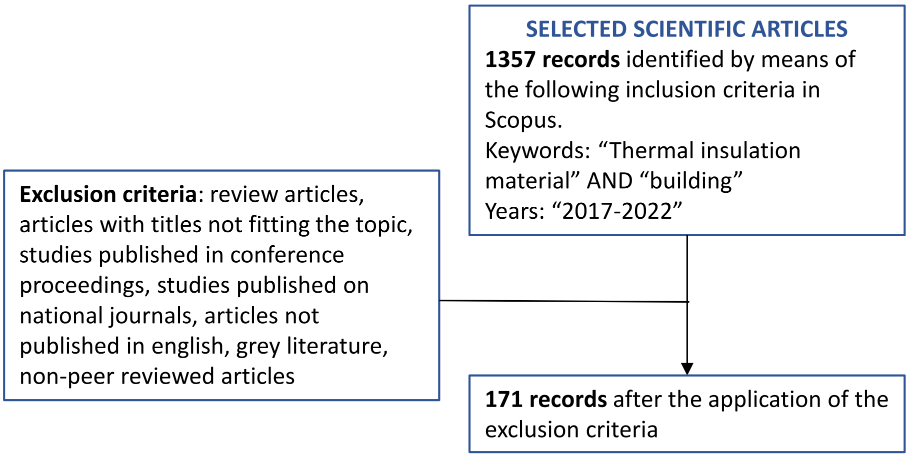
The present study is part of a larger research project named OFFICIO (“Ottimizzazione Filiere oFf-site per la rIqualifiCazione dell’ambIente cOstruito”, i.e., “Optimization of Off-Site supply chains for the renovation of the built environment”, aiming at characterizing the Italian production and supply chain of Off-Site Construction (OSC) solutions for building energy retrofitting, providing guidelines for its development and energy optimization.

OSC is a new approach to creating and renovating the built environment by reducing the intensity of activities carried out in the construction site and locating it mostly in the factory, a controlled environment in which higher standards of process efficiency, quality and safety can be achieved [20]. Although OSC is still at a relatively early stage of implementation in many countries, this emerging construction technique has increasingly attracted attention in recent years, from both academics and practitioners, due to its potential in achieving better project performance. In Italy its implementation is still at a very early stage, partly due to the high fragmentation of the market and supply chain, needing a deeper study and the development of tools to facilitate its integration, optimization, and implementation.

One of the project's tasks focuses on the identification and characterization of low-impact thermal insulation materials, specifically considering materials derived by co-production, wastes of other products and recycled ones, that could be selected, among others, to contribute making OSC supply chains more efficient and sustainable.

2. Materials and Methods

The published literature on the use of recycled, re-used materials or by-products for the manufacturing of materials or products with thermal insulation properties has been investigated to provide an updated overview of the most recent findings about potentially sustainable materials. Specifically, Scopus has been used to select the scientific literature published from 2017 until the end of 2022 responding to the keywords "thermal insulation material" and "building". To join the selected keywords the Boolean "AND" has been used. Figure 1 shows the procedure used to select literature including the exclusion criteria.



SELECTED SCIENTIFIC ARTICLES
1357 records identified by means of the following inclusion criteria in Scopus.
Keywords: "Thermal insulation material" AND "building"
Years: "2017-2022"

Exclusion criteria: review articles, articles with titles not fitting the topic, studies published in conference proceedings, studies published on national journals, articles not published in english, grey literature, non-peer reviewed articles

171 records after the application of the exclusion criteria

Figure 1. Flow diagram depicting the process of selection of the literature.

After a first screening, out of the 171 records, some of them reporting on multiple case studies, the authors selected 466 case studies fitting the topic. For each case study the authors retrieved identification data into an Excel spreadsheet. Specifically:

- the title of the article
- the digital object identifier (DOI)
- the material on which the case study is focused
- the country where the study is carried out—in particular, whenever the waste product used for the manufacturing of the new building material is typical of the country or of a region, the authors recorded data about the country of origin of the material and the kind of product (i.e., fibrous, closed cells, etc.).

Moreover, the authors collected physical and thermal data, namely:

- density,
- thermal conductivity (i.e., the heat flow that passes through a unit area of a 1 m thick homogeneous material due to a temperature gradient equal to 1 K),
- specific heat capacity, which expresses the ability of a material to store heat, and thermal diffusivity that describes the propagation of thermal waves within a material.

- Furthermore, since the behavior of building materials in case of fire may be responsible for safety issues, this aspect has also been investigated.
- Durability is a key parameter when environmental performances are concerned. Specifically, when a material has a short lifetime, it must be replaced several times in a certain time horizon. Consequently, its environmental impact is calculated as the impact over the product service life multiplied by the number of material replacements within the chosen time horizon. Thus, a material with a low environmental impact and a short service life might have a high environmental impact over a certain time horizon. Contrariwise, a material with a long lifespan and a higher environmental impact might have a lower environmental impact than the previous case. Therefore, whenever possible, the authors also collected durability data.
- Eventually, information has also been retrieved about: the kind of waste or by-product from which the recycled material comes from, cost, recyclability of the newly developed material at the end of its life cycle, whether the newly developed material is manufactured and tested as boards, loose material or foam, whether the newly developed material emits harmful substances, and about the stage of the conducted research.

3. Results

3.1. Data analyses

Figure 2 depicts the analysed data about the newly developed materials and shows that 69% of the case studies focus on the use of textile, agricultural and animal fibres (e.g., [21–25]). Besides, just 1% of the materials explore the use of organic non-fibrous materials such as spent coffee grounds and mussel shells (i.e., [26–28]), and aerogel from wood waste [29,30]. Pyrolytic wastes like industrial and carbonised wastes have been included in 7% of the case studies (e.g., [31–34]) and 22% of the investigated case studies focused on the use of inorganic wastes ([22,35–42]).

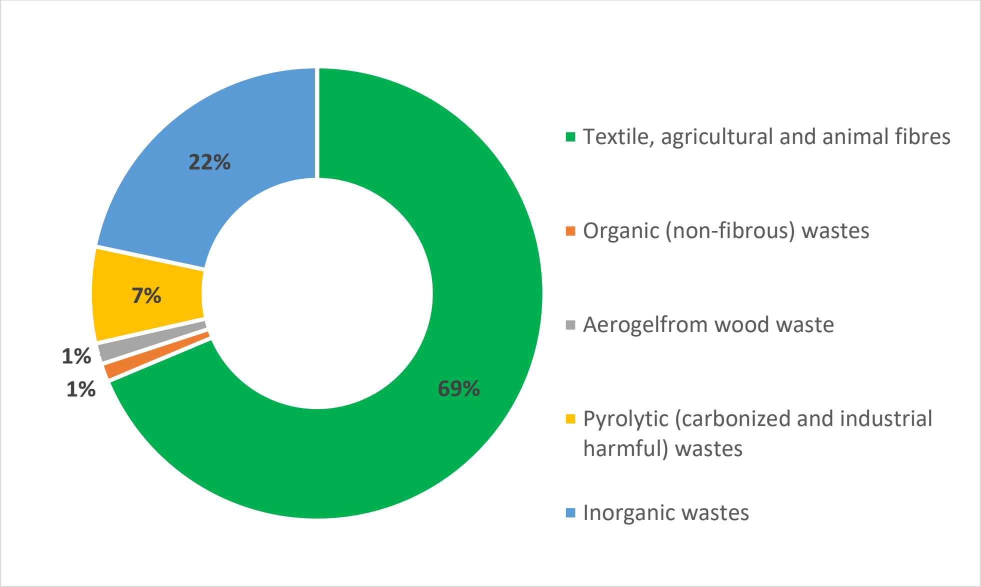


Figure 2. Data distribution of the wastes used for manufacturing the newly developed materials.

The literature review shows that the case studies concern either globally available wastes or locally available ones. With approximately 63% of the case studies focused on local wastes. The use of these latter can contribute both to a better waste management and to shorten the supply chain of the newly developed materials with consequent positive environmental effects. Among the selected case studies, those carried out in Morocco focus on agricultural wastes and wastes from the food industry such as hemp and date palm fibres (i.e., [43,44]), groundnut shells [45] as well as wastes from the textile industry like raw wool [43] and acrylic [46]. A study carried out in Algeria — one of the main producers and exporters of olive oil globally [47] — explores the thermo-mechanical performance of olive pomace lightweight concrete [48]. Sheep wool wastes have been used to manufacture composite thermal insulation panels in a study carried out in Romania [49], a country producer and exporter of sheep and goat meat[50]. Studies based on the use of wastes available in Italy significantly focused on paper pulp originated from recycled paper and cardboard, coffee pods and sawdust powder [51], granulated cork, rice husk, and coffee chaff [52].

By the analysis of all the collected data related to the case studies it results that almost all the case studies are characterized both in terms of density and thermal conductivity. Only 5.36% (i.e., [53,54,23,37,39,55,56]) and 1.28% (i.e.,[57–59]) of the case studies omit information about density and thermal conductivity, respectively. As far as specific heat capacity and thermal diffusivity are concerned, little information is provided by the scientific articles; in particular, just 9.65% (i.e., [34,38,45,46,51,59–64]) and 13.3% (i.e., [24,25,27,33,45,51,60,61,65–67]) of the case studies report data about specific heat capacity and thermal diffusivity, respectively. Few data can also be found about the fire resistance of the selected case studies; in this regard just 5.36% (i.e., [30,36,54,68–70]) report information about fire resistance. Among them, two articles (i.e., [36,68]) provide a qualitative evaluation, four articles (i.e., [36,69,54,70]) show the extinction time, and one article [30] provides information about the amount of residual material remaining after the ignition.

Information about water vapor diffusion resistance has been provided in just 3.6% of the case studies (i.e., [49,62,71,72]). Contrariwise, the compressive strength of the materials has been investigated in about 44% of the case studies.

Key information to evaluate the environmental and economic sustainability of the developed materials such as durability, cost and recyclability has been omitted in most of the examined case studies. Specifically, just two articles provide information about costs (i.e., [30,73]). Also information about the emission of harmful substances is lacking in all the articles except one (i.e., [54]). As regards whether the conducted research is basic or applied, none of the studies explicitly report such information, therefore, the authors have deduced it whenever possible. Specifically, 102 case studies have been judged being applied research. Similarly, none of the reviewed articles reports on barriers to the development and implementation of the materials.

3.2. Thermal performance

All the materials from the investigated case studies have been clustered into homogeneous classes: loose materials and foams, aerogel, structural materials, panels and boards, finishing materials. For each material the thermal conductivity has been investigated and depicted in Figure 3.

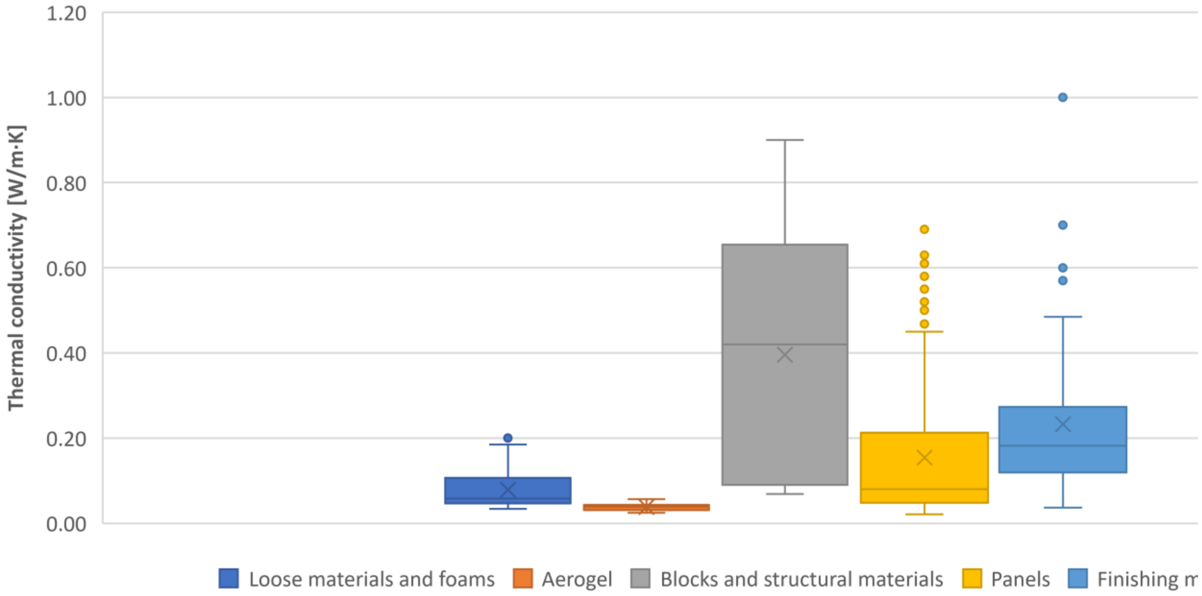


Figure 3. Thermal conductivity of the selected case studies.

Whenever a study provided a range of thermal conductivity, the lowest value has been chosen and reported in the box plot since the lowest value is the most promising value of an infant technology that can be further enhanced in the coming years. Besides, whenever the study presents thermal conductivity values for samples of assorted sizes, the value related to the most comparable size to the real scale application has been chosen.

Figure 3 shows that the average thermal conductivity for loose materials and foams equals 0.08 W/m·K and a minimum value of 0.03 W/m·K; the average value for the aerogel equals 0.039 W/m·K with a minimum of 0.024 W/m·K. Besides, Figure 3 shows that, compared to the other materials, higher variability in thermal conductivity characterizes the case studies about blocks and structural materials. Specifically, the thermal conductivity varies from 0.069 to 0.9 W/m·K and the average value equals 0.039 W/m·K. The thermal conductivity of panels and boards manufactured with recycled materials ranges from 0.021 to 0.45 W/m·K and an average value of 0.15 W/m·K; furthermore, among the thermal conductivity values, eight outliers can be found. As the finishing materials are concerned, the minimum thermal conductivity is 0.037 W/m·K, the highest value is 0.49 W/m·K and the average value equals 0.23 W/m·K; also for finishing materials Figure 3 showcases three outliers.

In the following, the authors thoroughly analyzed each category of materials.

Figure 4 displays the thermal conductivity values of loose materials and foams. Specifically, the loose materials and foams have been clustered according to the recycled materials they have been manufactured with: agricultural wastes, animal wastes, textile wastes, inorganic wastes, foams.

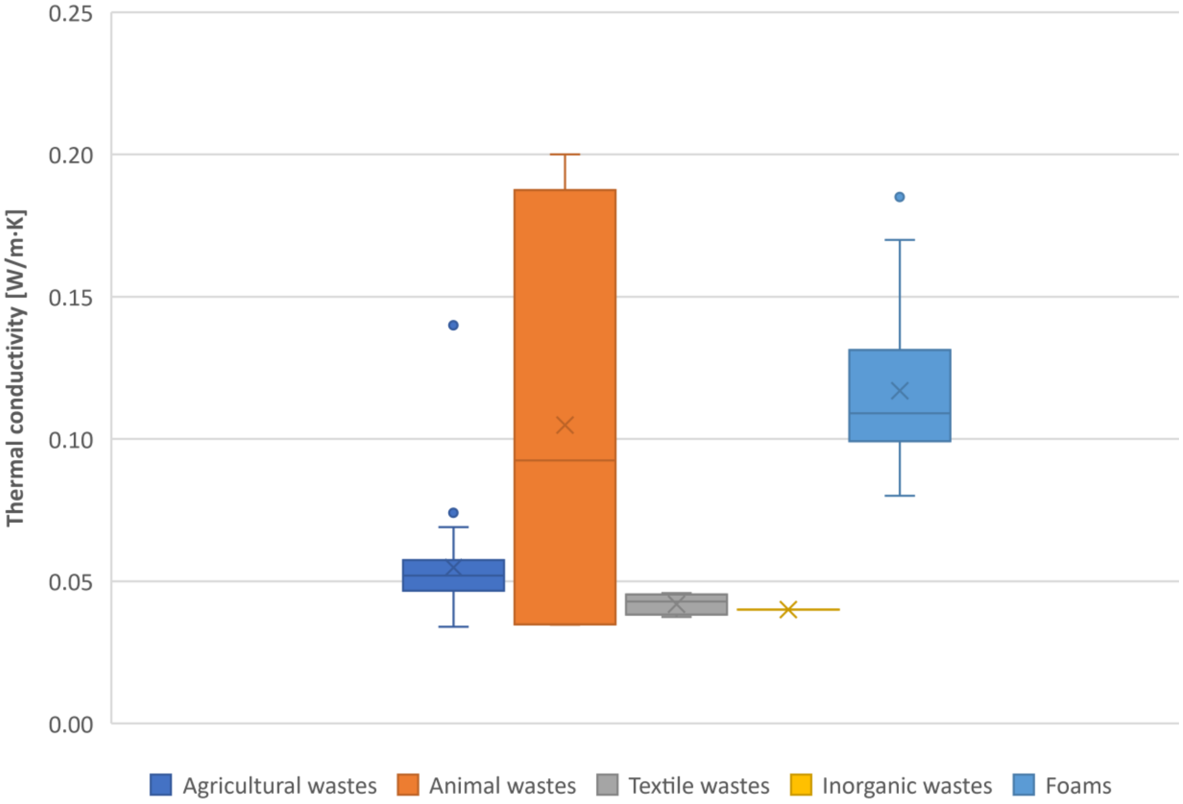


Figure 4. Thermal conductivity of loose materials and foams.

Loose materials derived from agricultural wastes are featured with the lowest thermal conductivity equal to 0.03 W/m·K and a maximum and an average value of 0.2 and 0.1 W/m·K, respectively (Figure 4). Besides, loose materials manufactured with animal wastes show the lowest variability with thermal conductivity values ranging from 0.03 to 0.07 W/m·K and an average value of 0.05 W/m·K. Loose materials manufactured with textile wastes are characterized by thermal conductivity variability ranging from 0.04 to 0.05 W/m·K. Among the reviewed studies, only one article (i.e., [42]) focused on loose materials derived from perlite recycled at the end of its use phase and finds that the thermal conductivity equals 0.04 W/m·K. Lastly, foams show a thermal conductivity ranging from 0.08 to 0.17 W/m·K with an average value equal to 0.12 W/m·K. Altogether, it results that the loose materials manufactured with agricultural and animal wastes have the best thermal performance. Specifically, the lowest thermal conductivity values are related to loose materials made with cellulose [74] and raw wool wastes [46].

As far as aerogel is concerned, all the reviewed studies focus on aerogels manufactured with cellulose derived from wood, therefore no further differentiations about the recycled materials from which the aerogel derives can be done. Consistently, it has been found that all the retrieved thermal conductivity data are characterized by limited variability and an average value equal to 0.039 W/m·K (Figure 3).

Figure 5 showcases the thermal conductivity values of structural materials. Specifically, the structural materials manufactured with spent coffee grounds [27], with straw fibres [75] and bricks made with demolition waste sludges [41] are characterized by the lowest thermal conductivity values equal to 0.09, 0.07-0.08 and 0.07-0.09 W/m·K, respectively. A higher thermal conductivity than the aforementioned materials has been found in the case studies of lightweight concrete with textile wastes [76] that exhibits a thermal conductivity ranging from 0.16 to 0.29 W/m·K with an average value of 0.22 W/m·K. Besides, fired clay brick with wooden furniture wastes [77] and those manufactured with sand and chars from coal [34] are characterized by a thermal conductivity ranging from 0.42 to 0.79 and from

0.52 to 0.90 W/m·K, respectively. Eventually, for the fired clay bricks manufactured with demolition waste sludges eleven case studies have been retrieved; nevertheless, all the retrieved thermal conductivity data converge towards a unique value equal to 0.48 W/m·K.

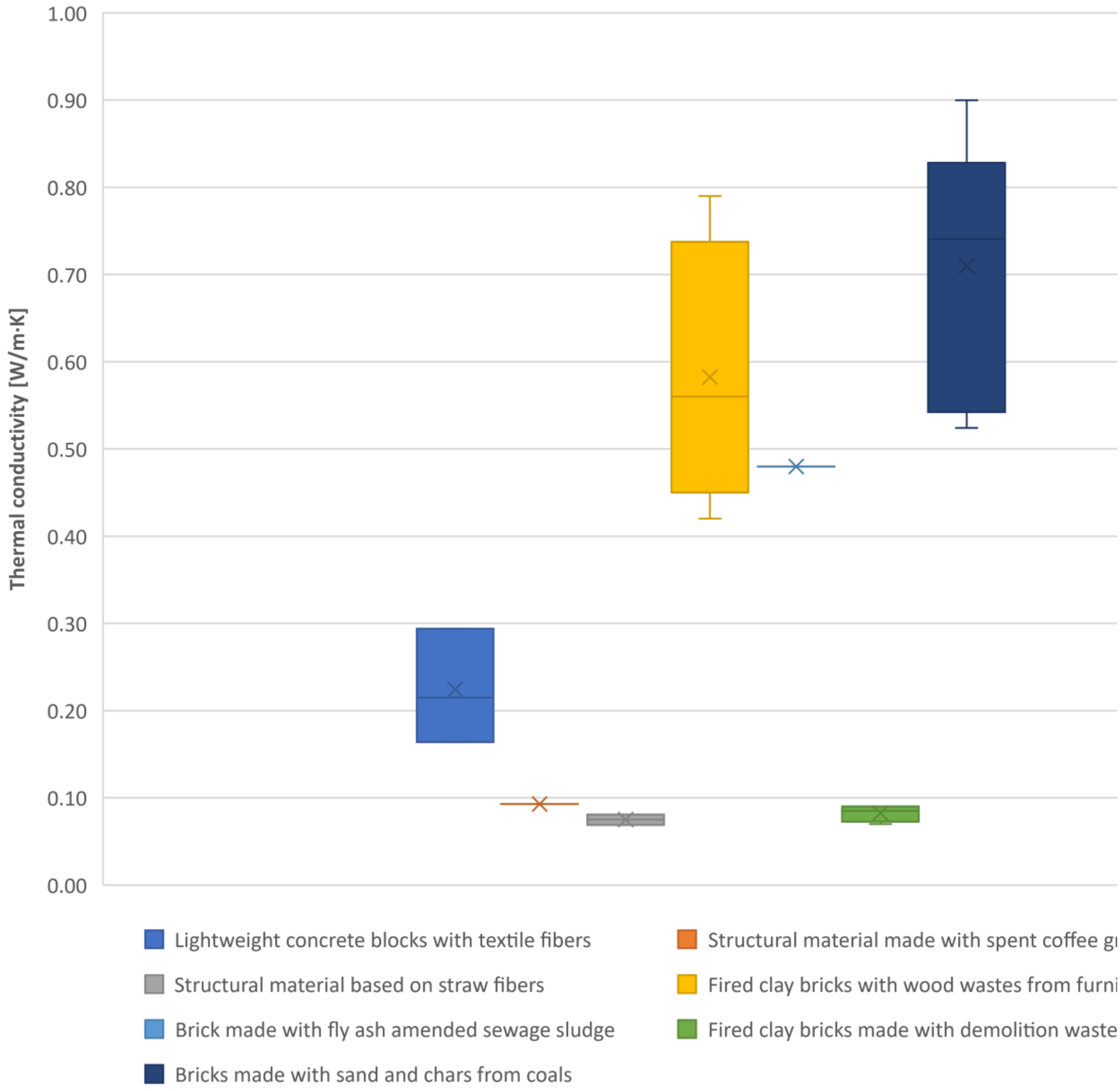


Figure 5. Thermal conductivity of blocks and structural materials.

The thermal conductivity values of panels and boards manufactured with recycled materials have been plotted in Figure 6.

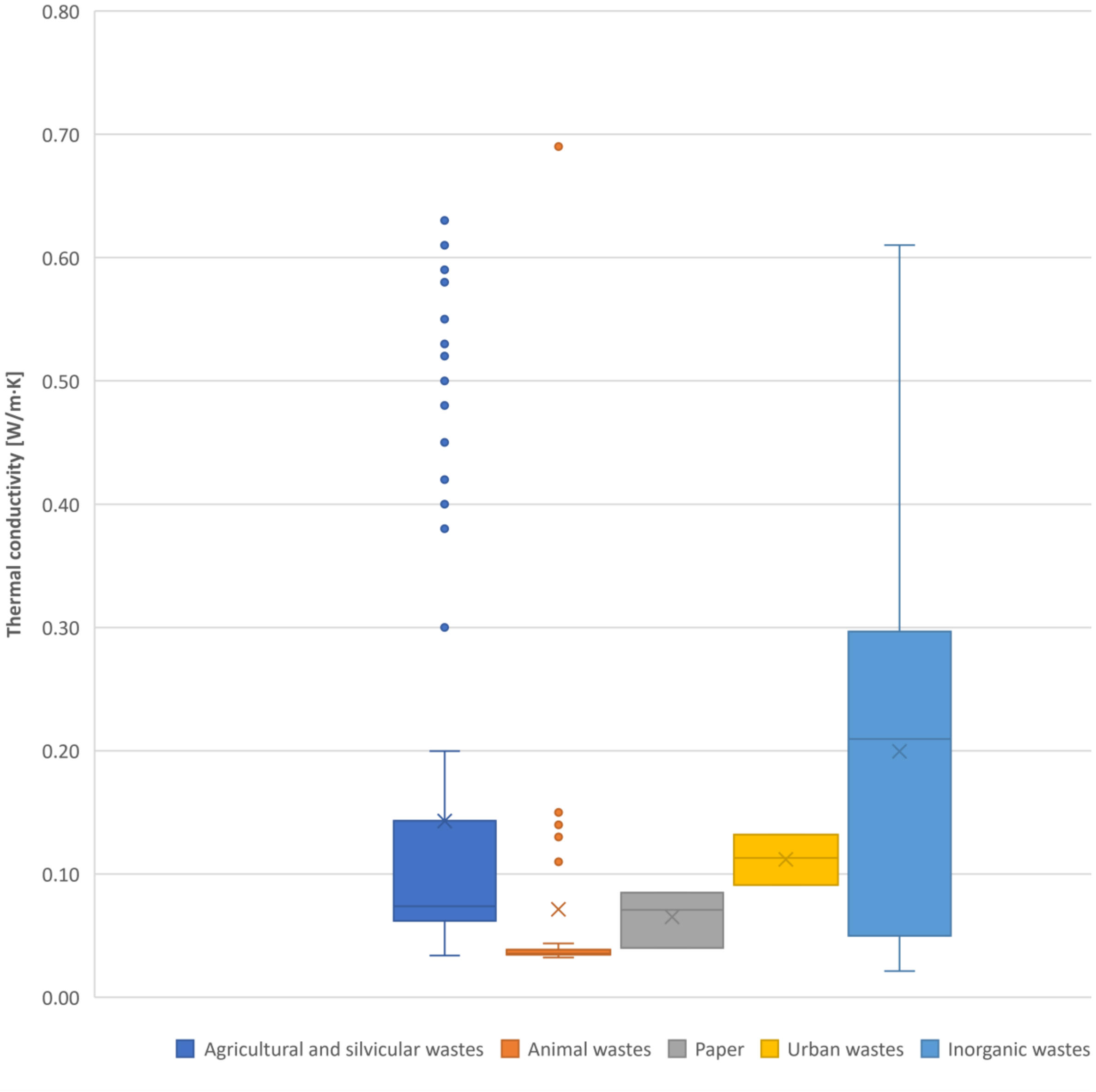


Figure 6. Thermal conductivity of panels/boards.

Figure 6 shows that the minimum thermal conductivity values for thermal insulation panels/boards manufactured with agricultural and silvicultural wastes, animal wastes, paper and inorganic wastes are similar and equal 0.02-0.04 W/m·K, contrariwise, the minimum thermal conductivity value related to panels and boards manufactured with paper wastes is considerably higher (i.e., 0.09 W/m·K). Furthermore, the boxplots show that panels made with agricultural wastes, animal wastes and inorganic ones are featured by a great variability in thermal conductivity values and those made of agricultural and animal wastes showcase numerous outliers. All the outlier values have been retrieved from two studies, the first one (i.e., [65]) focuses on the concrete panels with agricultural wastes and the second one focuses on gypsum boards (i.e., [58]). In both cases the great thermal conductivity is due to the high density of the panels. As far as the panels manufactured with animal wastes are concerned, the highest thermal conductivity value (i.e., 0.69 W/m·K) has been found in one case study focused on high density gypsum panels made with wool wastes [58]. The other outliers are related to the case studies of a single scientific article (i.e., [73]) focused on the manufacture of sandwich panels with different percentages of chicken feathers and resin.

As far as panels with inorganic wastes are concerned, the greatest thermal conductibility values are related to gypsum boards with Acrylonitrile Butadiene Styrene (ABS) [58] and to those manufactured with marble powder [40], both of them characterised by high density. Contrariwise, the most performing panels are characterized by low density values such as those produced with date palm fibres, hemp, corn and flax ([44,61,66,78,79]), sheep wool [49], and polyurethane wastes recycled after the end of their life cycle [37].

Figure 7 shows the thermal conductivity values of the finishing materials. Specifically, plaster, gypsum-based finish materials, lime and stucco exhibit lowest thermal conductivity values equal to 0.04 W/m·K, besides the lowest thermal conductivity of a composite material is 0.05 W/m·K. Denser materials are characterized by higher values of thermal conductivity; for instance, cement with 1% olive pomace shows a maximum thermal conductivity of 1 W/m·K [48], doubling the amount of olive pomace the thermal conductivity value is reduced to 0.3 W/m·K. Similarly, also geopolymers showcase a thermal conductivity ranging from 0.11 to 0.13 W/m·K, however, this range is populated by 5 values from the same number of case studies retrieved from just two scientific articles (i.e., [33,35]), therefore the reported values might not be representative enough.

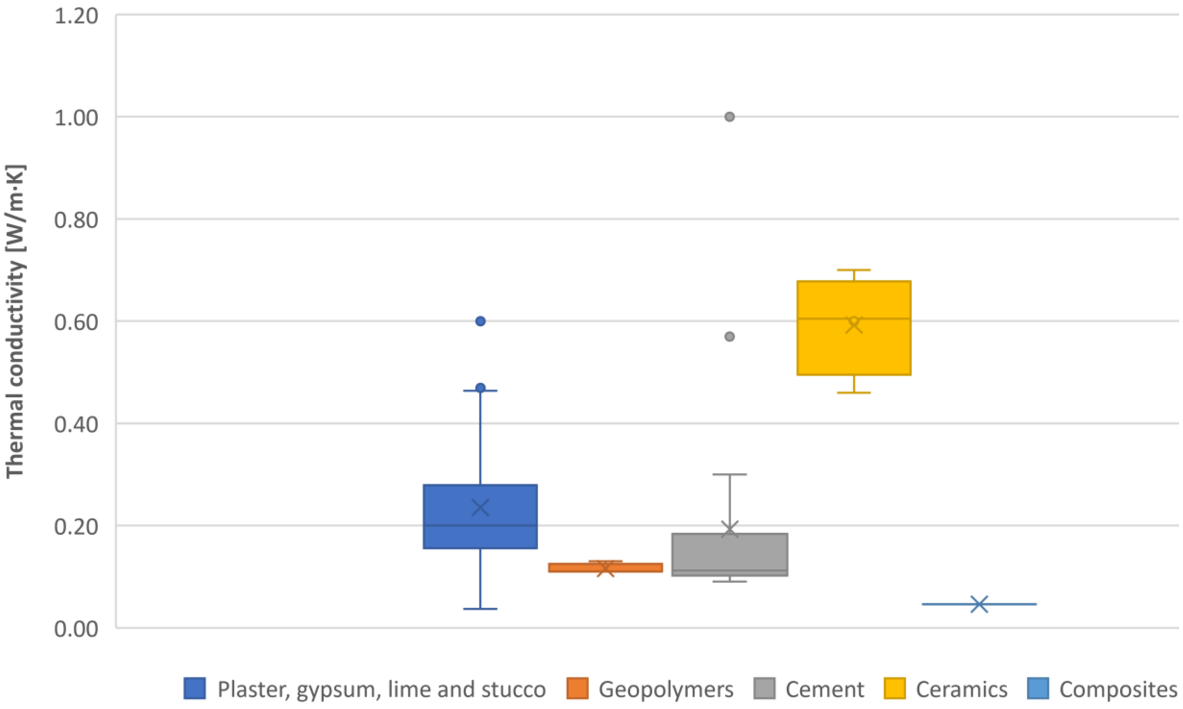


Figure 7. Thermal conductivity of finishing materials.

Eventually, also the case studies related to ceramics and composite materials have been analysed. It results that the thermal conductivity values related to ceramic with olive kernel flour and straw range from 0.5 to 0.7 W/m·K [53] and that just one article has been found for composite materials [80], therefore the value is excluded by any generalization.

4. Discussion

The analysis of the retrieved data shows that, among the loose materials, hemp shives, straw bales, wood sawdust and wastes, and reel straw—all of them characterized by a thermal conductivity equal to

0.05 W/m·K—have thermal performance similar to expanded perlite [81], a widely commercialized thermal insulator. Also peat, moss, chicken feathers, textile wastes from wool and acrylic, and perlite tailing show good thermal performance with a thermal conductivity of 0.04 W/m·K. Raw wool and cellulose have displayed a thermal conductivity of 0.03 W/m·K which is similar to stone wool, glass wool, expanded polystyrene, and extruded polystyrene [82–84]. Likewise, aerogels derived from wood show good thermal performance with thermal conductivity values ranging from 0.02 to 0.06 W/m·K. These latter values are comparable to those of polyurethane [85] and granulated aerogel [86]. The thermal conductivity of panels ranges from 0.02 to 0.69 W/m·K, with the lowest values related to panels with foam from polyurethane wastes. Among the retrieved thermal conductivity data, the panels manufactured with sheep wool are particularly promising since they are characterized by a thermal conductivity of 0.03 W/m·K. This value is similar to the thermal conductivity of stone wool, glass wool, expanded and extruded polystyrene [82–84]. Furthermore, in Italy, sheep wool is abundant and increasing its use would remove an important amount of waste [87,88].

Blocks and structural elements as well as finishing materials show thermal conductivity values from 0.07 to 0.09 and from 0.04 to 0.7 W/m·K, respectively. Such values are considerably higher than loose materials and panels since they are not thermal insulation materials tout court, nevertheless, the thermal performance of such structural materials may improve the thermal quality of a building.

Information about fire and water vapor resistance is mainly omitted and, when provided, it can hardly be used to compare case studies since it is very fragmented and inhomogeneous in terms of metrics. Anyhow, published research has shown that natural insulator materials absorb water vapor [89], which is the major cause of mould growth that, in turn, can damage natural materials such as hemp, sheep wool, straw, flax and cellulose both in terms of degradation and mechanical properties [90,91]. Nevertheless, vapor barriers can be applied to such materials when high vapor resistance is required [86]. Similarly, also fire resistance has been further investigated and results show that, according to European standard EN 13501–1, flax, hemp, straw bale, and sheep wool are classified as E (i.e., rank 6). "E" means that in the case of a very small fire (i.e., match fire) the material has acceptable reaction to fire (i.e., ignitability, flame spread). Such fire behaviour is the same in expanded and extruded polystyrene [92].

Lastly, among the reviewed literature, the lack of data about durability and cost is an important limitation for evaluating products' environmental and economic sustainability. More research should be carried out in this sense. Nonetheless, it has been found that natural materials are characterized by life span of about 80 years that is longer than the 50 years that have been esteemed for the petrochemical materials and their cost is pretty similar to that of petrochemical materials [93].

5. Conclusions

The present literature review has investigated the physical and thermal characteristics of newly developed materials derived by co-production, wastes of other products and recycled ones. The results of the analyses show that a large portion of such materials are promising in terms of thermal performance and are potentially characterized by low environmental impacts. The materials with the best thermal performance are the loose materials and panels made of agricultural and animal wastes and inorganic materials: specifically, raw sheep wool, polyurethane wastes, and hemp, to name a few. Nevertheless, among the screened scientific articles, no studies concomitantly investigate physical, thermal characteristics, durability, and costs of the newly developed materials, which represent a considerable gap hampering their market uptake Indeed, this aspect is detrimental since it hinders evaluating economic, environmental, and social impacts. However, studies investigating durability of newly developed materials with good thermal performance manufactured with wastes and by-products do exist in literature and suggest that such materials may have a higher durability than inorganic materials commonly found on the market.

Overall, it results that more systematic research is necessary to holistically assess the performance of newly developed materials manufactured with wastes and to include the evaluation of harmful substance release, thermal diffusivity for evaluating summer thermal performances, and recyclability potential. Furthermore, the in-situ evaluation of the thermal behavior may be beneficial for the correct assessment of the materials. Yet, the reviewed literature has shown that because of their good thermal performance and durability, materials manufactured with wastes and by-products might be a valid option when building retrofitting and decarbonization of the built environment is concerned.

Nevertheless, more aspects of such materials should be systematically investigated. Within the framework of the project OFFICIO, further research will be undertaken to evaluate whether the investigated materials with their specific characteristics can be used for the manufacture of OSC panels. In this respect, stakeholders such as associations and OSC producers will be interviewed and supporting information for the adoption of the materials with the best suitability to the OSC application will be shared with OSC manufactures interested in approaching such materials.

Author Contributions: Conceptualization, TS; methodology, TS; formal analysis TS; investigation TS, MB, LM, JG, EA writing-original draft preparation TS, MB, LM, JG, EA; writing-review and editing TS, MB, LM, JG, EA; visualization TS; supervision TS. All authors have read and agreed to the published version of the manuscript.

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