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Review

Incorporation of Waste in Thermal Mortars—A Literature Review

Amanda Barros [1], Eva Barreira [1,*], Lino Maia [1,2] and Maria Lurdes Lopes [1]

[1] CONSTRUCT, Department of Civil Engineering, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal; up202103253@edu.fe.up.pt (A.B.); linomaia@fe.up.pt (L.M.); lcosta@fe.up.pt (M.L.L.)

[2] Faculty of Exact Sciences and Engineering, University of Madeira, 9000-082 Funchal, Portugal

* Correspondence: barreira@fe.up.pt

Abstract: Innovation in construction plays a fundamental role in helping us face current challenges, namely the reduction in energy consumption, the mitigation of the effects of climate change, the depletion of resources, and the generation of waste. Regarding the built environment, improving the thermal properties of the building envelope is one of the growing needs to reduce energy consumption in the building sector. In this context, thermal mortars have been a trend in the construction industry in recent years due to their ability in reducing heat transfer through the building envelope. On the other hand, the addition of waste has been studied as an alternative to improve the thermal properties of mortars and reduce the consumption of primary materials in the construction sector. This work aims to carry out a detailed review regarding the incorporation of waste in thermal mortars through the application of scientometric data analysis and a systematic literature review. To this end, the different residues incorporated into thermal mortars and the various percentages and forms of incorporation were identified throughout the publications gathered in this review. The most studied properties regarding the thermal mortars with the addition of waste were also the subject of study. A comprehensive database of thermal mortars with the incorporation of waste is presented, in which the objectives of the studies, the wastes and forms of incorporation and the measured properties are highlighted. The main results of the analysed researches are deeply discussed and the gaps in this area of the knowledge are identified to point out new directions and possible perspectives for future studies in the field of thermal mortars incorporating waste.

Keywords: energy efficiency; insulation materials; sustainability; thermal mortars; waste

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1. Introduction

The contribution of the construction sector to the development of the global economy is an undeniable fact. However, its negative impact on the natural environment, marked by high energy consumption, intensive greenhouse gas emissions and large amounts of solid waste, is nowadays a major concern [1]. Since economic development is linked to the increasing number of dwellings and the consequent increase in energy consumption, it is of fundamental importance for the construction sector to develop from a technologic point of view and move forward to effective environmental solutions.

In fact, the residential sector is nowadays under attention for being responsible for approximately 40% of the final energy consumption in the European Union (EU) and 36% of energy-related greenhouse gas emissions [2]. It is essential to highlight that the average energy consumption in a household in developed countries is more than 10,000 kilowatt-hours per year, with more than 40% of this energy used in heating and cooling systems [3]. Buildings are, therefore, the largest energy consumers in Europe, with heating, cooling and domestic hot water accounting for 80% of the total energy demands [2]. In this context, improving the thermal properties of building envelopes is one of the growing needs in order to reduce energy consumption in the built environment.

With the aim of boosting the energy efficiency of buildings, the EU released specific legislative framework that includes the Energy Performance of Buildings Directive 2010/31/EU [4] and the Energy Efficiency Directive 2012/27/EU [2]. Such directives establish policies that will help achieve a highly energy-efficient and decarbonized building stock by 2050. Furthermore, it is expected that a stable environment for investment decisions will be created, allowing consumers and businesses to make more informed choices to save energy and money.

Furthermore, Directive No. 2002/91/EC [5] of the European Parliament and the Council of December 16 on the energy performance of buildings established several requirements. One of them is the obligation for all Member States to implement an energy certification system in buildings. The need to implement more concrete actions to enhance energy savings in buildings has given rise to a new concept in which buildings present almost zero energy needs (nZEB, "nearly zero-energy building") [6].

The European Commission adopted, in 2015, an ambitious Circular Economy Action Plan [7], which includes initiatives that stimulate a transition to a circular economy. Further, in 2020, the European Commission released a new Circular Economy Action Plan [8] aiming to increase competitiveness and foster sustainable economic growth, in addition to creating new jobs [9]. It established an action program that covers the entire cycle, from production and consumption to waste management and from the secondary raw materials market to a proposal for a legislative review on waste management [10].

On the other hand, the United Nations established the 2030 Agenda, which includes 17 Sustainable Development Goals [11]. The role of the construction sector, based on the concepts of circular economy, is fundamental for achieving these objectives, as it will allow more resilient buildings and more sustainable and innovative industries and cities.

Hence, the improvements in building materials and components have increasingly been targeted by the several players in the construction industry. The use of thermal insulation materials, for example, is proven to be an effective way to reduce heat losses in buildings by decreasing heat transfer through the building envelope [12]. Since some of the most common pathologies occurring on facades are due to poor thermal insulation, which causes a reduction in thermal comfort for users [13], and, in the recent years, very strict U-value criteria for building envelopes have been implemented by European countries [14], several studies have been carried out with particular interest in thermal mortars [15–18].

Thermal mortars have been a trend in the construction industry in recent years due to their ability to reduce heat transfer through the building envelope. This kind of mortar generally includes materials with low density and low thermal conductivity. Expanded polystyrene (EPS) and cork are examples of the most common lightweight aggregates to replace sand in thermal mortars [16,19,20]. Systems using aerogel have also been developed and studied, proving to be effective [21–23].

Regarding potential environmental impacts throughout the life cycle of mortars, most are associated with fossil depletion, mainly concerning the high consumption of fossil fuel in the mortar supply chain [24]. This fact highlights the urgency for the construction industry to change the current paradigm and to implement more environmentally responsible actions, with a focus on adopting a circular economy approach and ensuring a more sustainable sector.

The scientific community plays a fundamental role in directing the development of the construction sector towards sustainable solutions to face the challenges of energy consumption, climate change, resource depletion and waste generation. The number of scientific publications in this field is continually increasing, with an average annual growth rate of 21% [25]. This indicates that the circular economy and sustainability of the construction sector are areas that are receiving particular attention. The issue of waste production is also one of the highlights of the action plan for the circular economy, so it has been addressed by several studies [26–29] over the last few decades.

Studies on the incorporation of waste into mortar and concrete are, in turn, essential so that new sustainable solutions can be expanded to a larger and increasingly comprehensive scale, as these materials are widely used in construction. Optimizing the waste incorporation process on an industrial scale will allow the production of sustainable mortars in a cleaner production process compared to the traditional one [30].

Recycling, for example, not only minimizes the production of materials but also protects the environment by reducing carbon emissions. Better use of resources culminates not only in their conservation but also in improving the sanitary conditions of production sites. It is worth noting that since most of these wastes are hazardous materials, their disposal in open spaces should be avoided [31].

The incorporation of residues into coating mortars, whether thermal or not, has been the subject of study by several authors who have analysed their main physical and mechanical properties in the fresh and hardened states, as well as their durability, environmental footprint, and thermal and hygric performance [32–36]. However, the lack of a consolidated publication that compiles key information regarding the integration of waste into thermal mortars in a single document makes it challenging to access data in this research field. This topic requires thorough exploration, as the lack of standards and guidelines for thermal mortars incorporating waste becomes a limiting factor for laboratory studies and the consequent practical application of these materials. It is important to gather information from existing publications on this topic to establish a comprehensive database that facilitates access to these studies and their conclusions.

In this context, the main goal of the present work is to present a comprehensive literature review on the influence of incorporating waste into thermal mortars as an alternative to improve their thermal properties and reducing the consumption of primary materials in building construction. To achieve this primary objective, several secondary objectives were established: (i) a wide search for publications based on predefined keywords and selection of the studies of interest; (ii) scientometric data analysis of the selected publications; and (iii) a systematic literature review. It is intended with this work to identify the most common wastes incorporated into thermal mortars, the percentages and forms of incorporation referred in the literature, the properties that were mostly assessed and the main results highlighted by the authors. At the end of this work, it will be possible to identify the gaps in this area of the knowledge and discuss perspectives for future work.

2. Methodology

To achieve the objectives of this work, a four-step methodology was adopted. The first step includes the search for publications, the second is related to publication exclusion criteria and duplicate deletion, the third is the scientometric data analysis, and the fourth is the systematic literature review. Figure 1 presents a detailed diagram of the applied methodology.

The first phase of this methodology involves the search for publications to be analysed. This stage involves two main steps: selecting keywords to be applied in the chosen databases, namely Scopus and Web of Science, and gathering publications from other sources to complement the preliminary list. In the first case, the keyword combinations were chosen to cover the various terms used in the literature to refer to surface coating materials, such as "render", "plaster" and "mortar". The same happened for the terms that refer to thermal insulation properties, such as "thermal" and "insulation", and for the usually given names in the literature for waste materials, such as "waste", "residue", "by-product" or "Construction and Demolition Waste" (CDW).

Finally, the terms "energy efficiency", "sustainability" and "circular economy" were included in the search keywords, so that the correlation between these topics could be analysed. At this stage, 168 publications were found. Table 1 presents the keyword combinations applied in this review and the number of publications that were obtained.

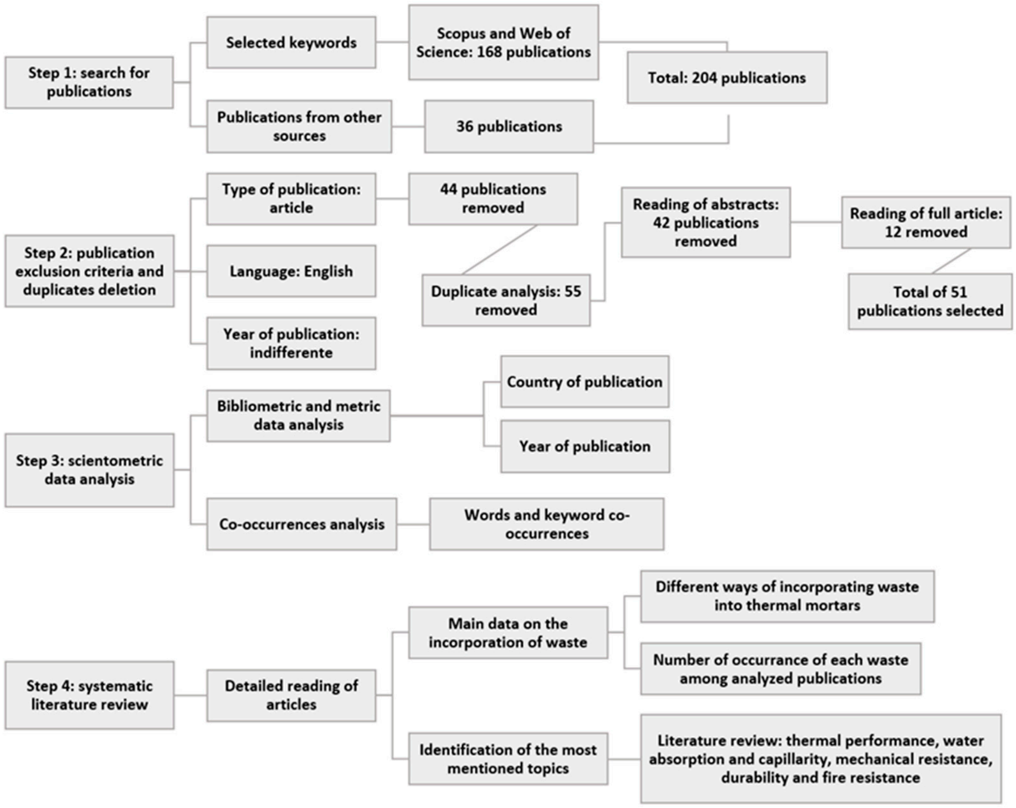

Figure 1. Four-step methodology.

Table 1. Keywords applied to search for publications in databases.

Group of Keywords	Number of Publications
"thermal mortar" OR "thermal render" OR "thermal plaster" OR "insulation mortar" OR "insulation render" OR "insulation plaster" AND "waste" OR "residue" OR "by-product" OR "CDW"	102
"thermal mortar" OR "thermal render" OR "thermal plaster" OR "insulation mortar" OR "insulation render" OR "insulation plaster" AND "waste" OR "residue" OR "by-product" OR "CDW" AND "energy efficiency"	29
"thermal mortar" OR "thermal render" OR "thermal plaster" OR "insulation mortar" OR "insulation render" OR "insulation plaster" AND "waste" OR "residue" OR "by-product" OR "CDW" AND "circular economy"	12
"thermal mortar" OR "thermal render" OR "thermal plaster" OR "insulation mortar" OR "insulation render" OR "insulation plaster" AND "waste" OR "residue" OR "by-product" OR "CDW" AND "sustainability"	25
Total of publications (Scopus + WoS)	168

Regarding publications obtained from other sources, they were selected from the bibliographic references of the 168 studies found in the databases, which were not automatically detected because they were linked to different keywords. The number of publications obtained from other sources was 36. Thus, the first stage brought together 204 publications.

In the second stage of the methodology, the first publication exclusion criteria were applied based on language, type and year of publications. Subsequently, publications that appeared more than once were also excluded. Only the studies published as articles and in the English language were accepted. The year of publication was considered irrelevant to assess the evolution of the number of publications over the years. Once this was done, 44 publications were removed. After analysing duplicates, another 55 publications were removed. Then, based on the topic of the publication, evaluated by reading the abstract or, in some cases, the complete document, another 54 publications were excluded because they did not effectively fit into the analysis of thermal mortars with the incorporation of wastes. Therefore, 51 publications were selected to be analysed in this review.

Considering only the 51 articles gathered for this review, the evolution of the number of publications over the years and the distribution of publications by origin countries were analysed to understand the authors' interest in addressing this topic and its evolution over the years to the present day, in addition to identifying which countries and regions have been most active in this field of research. Then, for all the publications collected through the databases, two co-occurrence analyses were carried out using VOSViewer: the co-occurrence of keywords defined by the authors and the co-occurrence of main words detected in the full text. This analysis was carried out through maps in which nodes and lines indicated the number of co-occurrences and interconnections between them, respectively. For better visualization, the map was divided by colours so that each colour indicated a cluster. The size of the nodes was proportional to the number of occurrences; therefore, the larger the node, the greater the event of the associated term. In this way, it is possible to understand which groups of words, expressions and possible trends are most associated with the topic under study [37,38].

After thoroughly reading the selected articles, it was possible to identify the four main topics covered by the authors that were chosen for a detailed review (thermal performance, water absorption and capillarity, mechanical resistance, and durability and fire resistance). For each topic, the main research results and findings, the most analysed properties, and the limitations of the studies under analysis were described. Finally, the conclusions of the systematic literature review were drawn, pointing the gaps in research as well as identifying future perspectives within the scope of the topic under study.

3. Scientometric Data Analysis

3.1. Evolution of the Number of Publications

Figure 2 shows the number of publications per year since 2012, the year of the oldest publication among the 51 that were selected, until June 2023, when the data collection for this literature review ended. Although there was no linear evolution in the number of publications, there was a growing trend over the years, except in 2019 and 2022, with 2021 being the year with the highest number of works published on this topic.

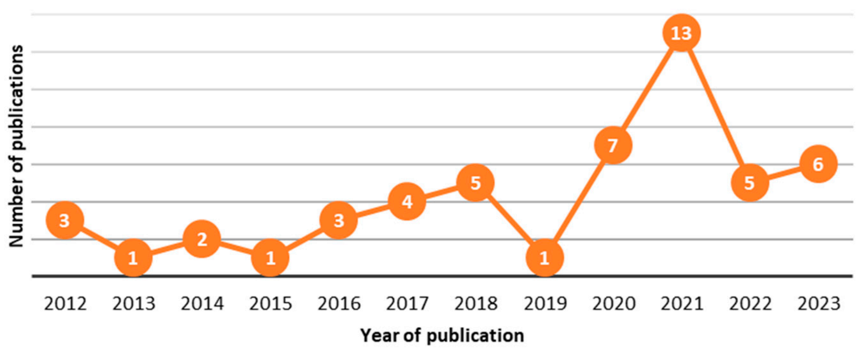

Figure 2. Number of publications per year.

Since the first international guidelines related to the sustainability of buildings and the construction industry, such as the Directive for the Energy Efficiency of Buildings, the Action Plan for the Circular Economy and the 2030 Agenda being released in 2012, 2015 and 2016, respectively, increasing interest from the scientific community on the properties of thermal mortars, as well as alternatives for waste disposal, was expected. This topic continues to gain prominence and interest, being the subject of new studies every year, contributing to a better understanding of this innovative topic.

3.2. Country of Origin of Publications

For this analysis, each publication was related to the origin country of the article's first author, to make a total of 16 countries. According to Figure 3, six countries presented three or more publications on this topic. Italy was the country with highest number of published studies (nine articles), followed by China, with seven publications. From Portugal and Turkey, six publications each were found, followed by Spain, with five, and Egypt, with three. Furthermore, five countries presented two publications each (Brazil, Canada, France, Sri Lanka and the United States of America), while in five countries (Chile, Czech Republic, Lithuania, South Korea and Thailand) only one publication each was found.

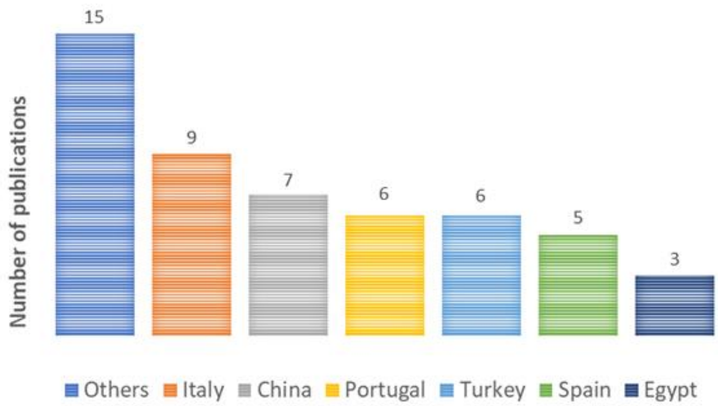

Figure 3. Number of publications by origin country of the first author.

Authors from European countries are predominant in the study of the incorporation of waste in thermal mortars because they are driven by the European criteria for energy efficiency and a circular economy, as well as the SDGs of the 2030 Agenda, seeing those mortars as a possible step forward [39,40]. In the case of China, the expansion in real estate investments over the last few years indicates that construction innovation is a prominent factor in meeting international criteria for energy efficiency and waste disposal [41].

3.3. Word and Keyword Co-Occurrences

Figure 4 presents the co-occurrence map of keywords defined by the authors of the publications. In this case, 1060 items were found and, for the analysis, keywords with a minimum of seven occurrences were considered, resulting in 60 keywords divided into five clusters. As expected, the three most cited keywords were "thermal insulation", "thermal conductivity" and "mortar" with 97, 81 and 74 occurrences and total link strength equal to 652, 538 and 474, respectively. It can be stated that most authors consider thermal properties when analysing mortars with the addition of waste.

According to Figure 4, cluster one is identified in red and comprises 17 keywords. This group brought together terms linked to materials and the mechanical behaviour of mortars, among which "cement" and "compressive strength" stand out as the most cited, with 45 occurrences each and total link strength equal to 292 and 279, respectively. Other terms found in cluster one were "gypsum", "lightweight aggregate", "mechanical performance", and "tensile strength", among others. Cluster two presents 17 items and is a green colour. This cluster grouped keywords related to energy efficiency and hygrothermal properties. The terms "thermal insulation" and "thermal conductivity" had the highest number of occurrences, equal to 97 and 81, and the highest total link strength, equal to 652 and 538, respectively. This group also included terms such as "energy efficiency", "water absorption", "moisture" and "hygrothermal performance".

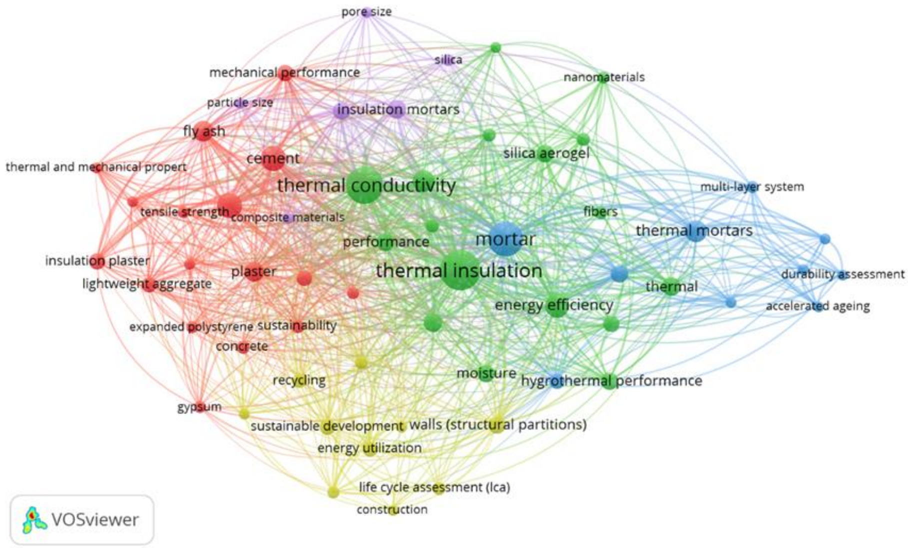

Figure 4. Author keyword co-occurrence map.

The third cluster has ten items presented in blue, of which "mortar" and "thermal mortars" were the most cited, with 74 and 30 occurrences and total link strength of 474 and 182, respectively. This cluster brought together terms related to the durability of mortars, such as "accelerated aging", "durability assessment", "degradation mechanism" and "climatic conditions". In yellow, cluster four grouped ten keywords that are related to construction and environmental aspects, such as "concrete", "recycling", "Life Cycle Assessment (LCA)", and "energy utilization", among others. In this group, the most cited keywords were "walls (structural partitions)" and "sustainable development" with occurrences equal to 19 and 15 and total link strength equal to 129 and 95, respectively.

Finally, group 5 presents in purple six items related to commonly used materials and their characteristics, namely "insulation mortars", "aggregates", "silica", "composite materials", "particle size" and "pore size". The first two are those with the highest occurrences, equal to 21 and 19, while the total link strength were equal to 132 and 153, respectively.

On the other hand, Figure 5 shows the co-occurrence map of individual words most used by authors throughout the full text of the publications, with a total of 3113 words found. For the analysis, words with a minimum occurrence of seven were considered, resulting in 62 words divided into three clusters. According to the analysis, the three words most cited by the authors throughout the full text were "compressive strength", "aggregate" and "wall", with occurrences equal to 40, 37 and 36, and total link strength equal to 234, 177 and 182, respectively.

These results suggest that the authors associate thermal mortars with walls, which was expected as this kind of mortar is mostly applied in the vertical elements of the building envelope. Furthermore, most authors incorporated waste materials to replace common aggregates. It is also worth highlighting that most authors took compressive strength into consideration when studying thermal mortars with waste to meet the minimum criteria defined in the standards for their use. This fact is understandable, since the introduction of low-density materials, such as waste, tends to cause a reduction in the mechanical resistance of mortars [42,43].

Regarding the division of the clusters, the first cluster had 22 items, presented in red. In this cluster, terms related to thermophysical and mechanical properties were grouped, namely "density", "porosity", "bulk density", "thermal property", "thermal resistance", "flexural strength", "mechanical resistance", and "bond strength", among others. The terms "compressive strength" and "aggregate" were the most cited.

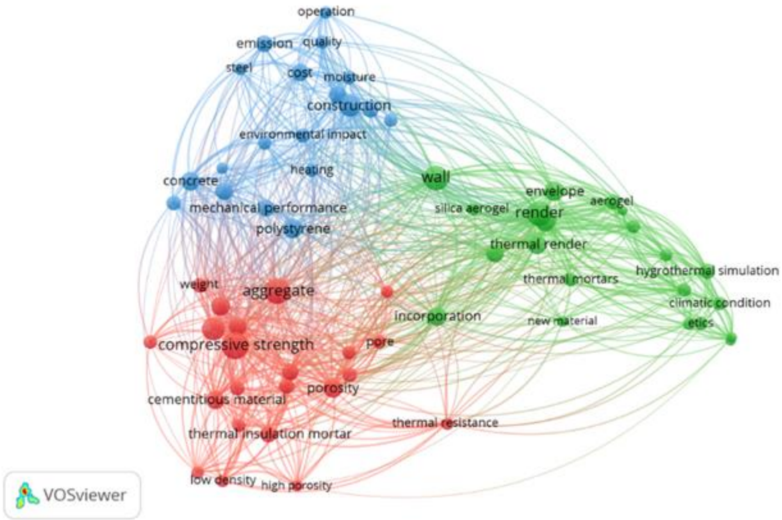

Figure 5. Individual words co-occurrence map.

Group two, in green, consisted of 21 items. The term "wall" was the most cited, followed by the word "render", with 34 occurrences and a total link strength of 191. In this cluster, terms referring to energy efficiency and durability were gathered. Words such as "energy efficiency", "envelope", "thermal render", "rendering", "multilayer system", "hygrothermal behaviour", "durability assessment", "aging cycle" and "climatic condition" can be highlighted.

The third cluster contained 19 items in blue. In this group, the most cited term was "construction", with an occurrence equal to 26 and total link strength of 138. The second most cited word was "polystyrene", with 22 occurrences and total link strength equal to 109. The items in this group included environmental aspects, in addition to some materials and terms related to the performance of mortars, which included "sustainability", "emission", "environmental impact", "EPS", "shrinkage", "heating" and "moisture".

In the clusters obtained in these two analyses, namely analysis of the co-occurrence of the authors' keywords and individual words in the full text, it was possible to verify the relationship between the topic under study and the keywords "energy efficiency" and "sustainability", which corroborated the selection of these two terms when doing the search for this work. The term "circular economy", also used in the search of publications, was not shown in any of the analyses, which indicates that this term is not widely used among authors.

4. Systematic Literature Review

4.1. Most Common Incorporated Wastes

All the wastes studied by the authors of the 51 selected publications were identified and then grouped according to their origin, whether mineral, vegetal, animal or synthetic (Table 2). In total, 41 wastes were identified, most of which had vegetal origin, covering 17 residues, followed by the synthetic ones, with 16 items, the mineral waste group, with 7 items, and finally, only 1 residue of animal origin was identified. The residue occurrence in the publications that were evaluated is also indicated in Table 2, in brackets. It is possible to state that fly ash was the most studied waste as a component of thermal mortars, with 12 occurrences. Then, expanded polystyrene (EPS) waste, rubber waste and mineral wool waste appeared, with nine, five and four events, respectively.

Considering the studies selected for this review (Table 2) and the type of mixture component for the wastes (as a replacement for sand, as a replacement for cement, as a replacement for lime binder, as a replacement for gypsum, and as an additive), 55% of the selected publications assessed the incorporation of waste in the total or partial replacement of conventional aggregates, such as river sand. On the other hand, several authors chose to replace the mortar binder totally or partially by a residue, with 23% of the studies incorporating the residue to replace cement, 6% lime and 2% gypsum. Furthermore, 14% of the studies tested the incorporation of residues into mortars as an additive, without completely or even partially removing any of the original components of the mortars under analysis.

Table 2. Waste incorporated in thermal mortars according to their origin, number of occurrences (in brackets) and type of mixture component ([a]: as a replacement for sand; [b]: as a replacement for cement; [c]: as a replacement for lime binder; [d]: as a replacement for gypsum; [e]: as an additive).

Item	Wastes	Ref.
1	**Mineral wastes:** fly ash [a,b,e] (12), mineral wool waste [a,c,e] (4), fibre glassa (2), recycled brass fibres [e] (1), mining residues [b] (1), expanded glass [a] (1), recycled pyroclastic aggregates [a] (1)	[28,29,34,39,41–56]
2	**Vegetal wastes:** coffee waste [a,b] (3), cork waste [a] (3), fallen leaves fibres [a,b] (3), hemp shives [a,c] (2), rice husk ash [a,b] (2), wood waste [a,b] (2), bagasse ash [b] (1), desiccated and smashed desiccated platanus acerifolia fruits [a] (1), chopped cane stalks [a] (1), almond/hazelnut/nut shells [a] (1), coconut shells [a] (1), bean and pea pods [a] (1), curauá fibres [e] (1), sunflower plant bark and pith [a] (1), recycled jute fibre [c] (1), thistle fibre [c] (1), olive stone [e] (1)	[16,28,35,36,40,45,57–66]
3	**Animal waste:** ground waste seashells[b] (1)	[67]
4	**Synthetic wastes:** EPS waste [a,b,e] (9), rubber waste [a,e] (5), silica fume [b,e] (3), paper sludge ash [a,b,e] (3), blast furnace slag [b,e] (2), recycled concrete aggregates [a] (2), recycled carbon black [a] (1), recycled roofing tile powder [d] (1), recycled from ceramic walls [e] (1), foamed plastic waste [a] (1), water-soaked cardboard [a] (1), waste polyethylene terephthalate (PET) particles [a] (1), pulverized glass fibre reinforced plastic (GFRP) [a] (1), silicate sawing sludge [a] (1), plastic cable waste [d] (1), opus signinum [c] (1)	[28,41–44,47,49,50,52,53,57,64,68–83]

The growing need to reduce the use of materials such as sand and cement in construction industry explains the majority of studies dedicated to analysing the incorporation of waste as substitute component. Most of the authors highlighted the two perspectives of the environmental gains: giving an alternative destination to the waste that would otherwise be discarded in landfills and reducing the consumption of raw materials in the construction sector.

4.2. Most Cited Topics

4.2.1. Thermal Performance

Thermal conductivity is a determining factor for classifying thermal mortars [84]. Due to this fact, all authors evaluated the thermal performance of mortars incorporating waste. Several publications incorporated fly ash into mortars, isolated or combined with another residue. In these studies, the addition of waste resulted in better thermal performance of the mortars. Li et al. [44] and Haibo [47] added fly ash and EPS waste to mortars simultaneously. The first author highlighted that as the content of EPS waste increased, the thermal conductivity of the sample decreased, more sharply when the EPS was in a low content and with less impact when it was in high content. Haibo's research corroborates these results since in this, the thermal conductivity of the mortars also decreased after the addition of waste. Haibo explains that the larger the content of waste, the greater the volume space occupied, which reduces the bulk density of the material, resulting in lower thermal conductivity. According to the author, to ensure a good performance of the mortar, the EPS particle size should be less than 2.5 mm.

In a study by Chen et al. [41], paper sludge ash and fly ash were added to mortars. The authors state that 8–20% of fly ash and 10–30% of paper sludge ash can effectively decrease the thermal conductivity and density of mortars. Blast furnace slag and silica fume were also studied with fly ash [49,50,52,53], resulting in more thermally efficient mortars. According to Li et al. [49], thermal conductivity is highly influenced by slag and, due to the smaller particles, slag and its hydration products perform the microaggregate and pozzolanic effects that hinder heat transfer and better reduce thermal conductivity.

The authors highlight that 20.73% fly ash and 21.49% blast furnace slag is the optimal mixture for thermal mortars, within an error of 1.52%. On the other hand, Wang et al. [50] propose as optimal ratio of 5:5:1 for fly ash, slag powder and silica fume to be incorporated in the mortar.

Rashad [52] obtained insulating plasters with low density and, consequently, low thermal conductivity (0.30–0.48 W/(m.K)) after adding silica fume and fly ash. He also stated that using gypsum as a binder material was better than cement for thermal insulation purposes. The reduction in thermal conductivity is justified by the author by the lower thermal conductivity of gypsum when compared to cement. These results corroborate another study by Rashad et al. [53], highlighting that replacing metakaolin with silica fume decreased thermal conductivity from 0.113 W/(m.K) to 0.095 W/(m.K).

The addition of fly ash separately has also been studied. A reduction in thermal conductivity was also achieved, either as a substitute for sand [46] or cement [34,48,51]. Bicer et al. [46] observed that as the grain size diameter decreased, ash density increased by 16.12%. Also, as the fly ash addition ratio increased by 10–90% in fly ash cement mixtures, thermal conductivity decreased by 14.47–24.52%. In another study, the incorporation of fly ash and tragacanth resin proved to reduce by 34.52% the original λ-value of the mortar, for the sample without resin, and by 42.03% for the samples with resin [48]. Borges et al. [51] stated that fly ash lowered thermal conductivity in mortar specimens, as expected, with the greatest decrease for 50% replacement of cement binder.

The incorporation of lower percentages of residues also proved to be relevant, such as in the study by La Scalia et al. [45], which added spent coffee grounds to the mortars. According to the authors, even adding only 5% spent coffee grounds leads to an important reduction in thermal conductivity and consequently to a greater insulating performance. In the study by Yildiz et al. [58], coffee wastes after microwave and ultrasound pretreatment were added to replace cement binder. Based on results for 10%, 20%, and 30% of waste, the authors concluded that ultrasound pre-treated coffee waste improves the thermal properties by reducing the λ-value of the insulation plaster. In addition, microwave coffee waste and ultrasound pre-treated coffee waste, compared to normal coffee wastes, provided gains of 19%, 30% and 33–50% in thermal resistance, respectively. Furthermore, the mortars presented better acoustic performance.

The thermal performance of mortars with EPS waste was considered satisfactory, with the thermal conductivity coefficient varying from 0.25 to 0.13 W/(m.K) in a study by Seputyte-Jucike et al. [70] and guaranteeing a decrease up to 0.09 W/(m.K) in a study by Koksal et al. [68]. The resin was once again used to enhance results in mortars with residues. Apricot resin was chosen by Bicer et al. [72] to be added at a content of 1% of the weight of the total cement and EPS was incorporated at ratios of 20%, 40%, 60% and 80% of the total volume in the mixtures. A strong correlation between thermal conductivity and density was found by the authors. In addition, when adding resin to the mixture, better results were obtained when compared to mixtures without resin.

Tittarelli et al. [69] conducted a comparison between mortars incorporating virgin EPS and EPS waste at the same volume content. Recycled EPS mortars proved to have lower thermal resistance than those manufactured with a virgin material, but this can be counteracted by increasing the percentage of EPS. The authors highlight that an economical saving of over 25% can be achieved using recycled EPS to obtain mortars with a specific thermal insulating capacity.

Some authors studied thermal mortars by adding EPS, paper sludge ash and waste insulation materials, recycled concrete aggregates and ceramic waste, and their tests resulted in mortars with better thermal performance [42,43,54,71,78]. These authors also state that the reduction in mortar density is strongly related to low thermal conductivity values [54].

Majumder et al. [28] compared the incorporation of wool fibres, hemp shives, recycled jute fibre, thistle fibre and opus signinum. Using recycled materials resulted in plasters with a thermal conductivity about 32% lower than traditional plasters using gypsum and/or lime. According to the authors, using natural fibres (sheep wool and thistle fibres) inside lime putty allowed for a decrease in thermal conductivity of up to 62%. Furthermore, through numerical simulation, it was possible to verify that adding those natural fibres improved the energy performance of the building envelope during the winter compared to traditional plaster. Finally, using recycled jute fibres in insulating panels shows promising results, with conductivity values always lower than 0.162 W/(m.K).

Some studies analysed the incorporation of rubber residues in thermal mortars to replace sand or as an additive, improving their thermal properties [73–77]. According to Kazmierczak et al. [76], the addition of crumb rubber leads to a reduction in thermal conductivity of up to 32% for a mortar with 6% of crumb rubber instead of river sand. As an additive for mortars, rubber particles were studied by Meshgin et al. [77]. The thermal conductivity measurements show that adding rubber particles both at a smaller and higher percentage resulted in lower thermal conductivity. According to the authors, the thermal conductivity of mortar depends not only on the volume fraction of the rubber particles but also on their average size.

Virgin cork has already been used in construction as a thermal insulation material for walls, but there are few studies on cork waste. Morgado et al. [16] and Panesar et al. [59] analysed the application of waste cork in mortars and concluded that the thermal conductivity results are satisfactory and guarantee an acceptable thermal performance of the mortars. Thermal conductivity values achieved a minimum of 0.0715 W/(m.K) for mortars with cork plugs, according to a study by Gennusa et al. [57]. In this same study, the authors evaluated the addition of more unusual residues, such as desiccated and smashed desiccated platanus acerifolia fruits, water-soaked cardboard, coffee parchment skin, which comes off during the roasting process, chopped cane stalks, almond/hazelnut/nut shells, coconut shells and bean and pea pods. The authors state that thermal conductivity is strictly influenced by the composition of the samples (considering the hydraulic lime content) and the final density reached by the samples after the drying process. The tests showed that thermal conductivity values reached a maximum of 0.1382 W/(m.K) for nutshells.

Other residues replacing sand were studied, such as straw and fallen leaf fibres [60], hemp shives [62], wood waste, waste polyethylene terephthalate (PET) and particles and pulverized glass fibre-reinforced plastic (GFRP) [64], sunflower plant bark and pith [65], recycled carbon black derived from scrapped off-the-road tires [79], expanded glass [39], recycled pyroclastic aggregates [29] and silicate sawing sludge [82]. It is noteworthy that a study conducted by Coppola et al. [81] with foamed plastic waste showed that the presence of plastic aggregates decreased mortar density up to 36% compared to a reference sample, for the maximum investigated natural sand volume replacement. In addition, the thermal conductivity decreased 10% for the 50% volume replacement.

In substitution for cement, several other studies can be highlighted [35,40,56,61]. Results found by Srikanth et al. [35] showed that adding 30% bagasse ash as a partial replacement for cement improved thermal performance by causing a 33% decrease in thermal conductivity. At the same time, the combination of bagasse ash and rice husk ashes (15% each) decreased thermal conductivity up to 31% compared to in conventional mortar. The research by Selvaranjan et al. [63] with rice husk ash instead of river sand presented values that confirmed those mentioned by Srikanth et al. [35]. The authors highlight that the rice husk ash can replace up to 30% of sand to produce a thermally enhanced wall plaster. Furthermore, in two identical prototype houses ash-based rice husk (i.e., 30% of rice husk ash) and conventional plasters were applied to experimentally evaluate their thermal performance, by measuring heat flux through the wall and internal and external wall surface temperatures. The average daily reduction in heat transfer across the wall with these mortars was about 26%. Results also show that rice husk ash mortars can reduce the energy that is required to maintain thermal comfort by about 9% than the conventional mortars.

Instead of gypsum binder, Durgun et al. [80] added recycled ceramic tile powder into mortars. According to the authors, the presence of recycled ceramic tile powder enhanced mass loss, decreasing thermal conductivity. In another study, Vidales-Barriguete et al. [83] added plastic cable waste to replace gypsum binder and the results showed that the thermal properties improved slightly with up to 60% of waste incorporation.

Some authors studied the incorporation of waste as an additive into mortars [36,55,66]. According to Barreca et al. [36], adding 70% of dry weight of olive stone allowed them to reduce the average thermal conductance of cement lime mortar by over 76% and its density around 30%. Furthermore, tests highlighted that the decrease in thermal conductance, related to the increase in the percentage of added olive stone, was greater than the decrease in density.

Figures 6–8 summarize the values of thermal conductivity obtained in studies assessing the thermal performance of mortars with fly ash, EPS waste and rubber waste, the most studied residues. Thermal conductivity values varied from 0.086 to 1.400 W/m.K for mortars with fly ash (Figure 6), from 0.071 to 1.200 W/m.K for mortars with EPS waste (Figure 7) and from 0.582 to 1.000 W/m.K for mortars with rubber waste (Figure 8). It can be stated that for the same percentage of waste; there was a considerable variation in the thermal conductivity measured by different authors. Also, the decrease in the value of the thermal conductivity with the increase in the percentage of waste, although observed in all studies, did not follow the same trend. That can be justified because not only is the percentage of waste relevant for the thermal behaviour, but also the dimensions of the waste, the composition of the mortar, the type of binder, the presence of additives and the combination of one or more wastes. Furthermore, the mortar may exhibit different behaviour when the waste is added to replace sand or binder or when used as an additive.

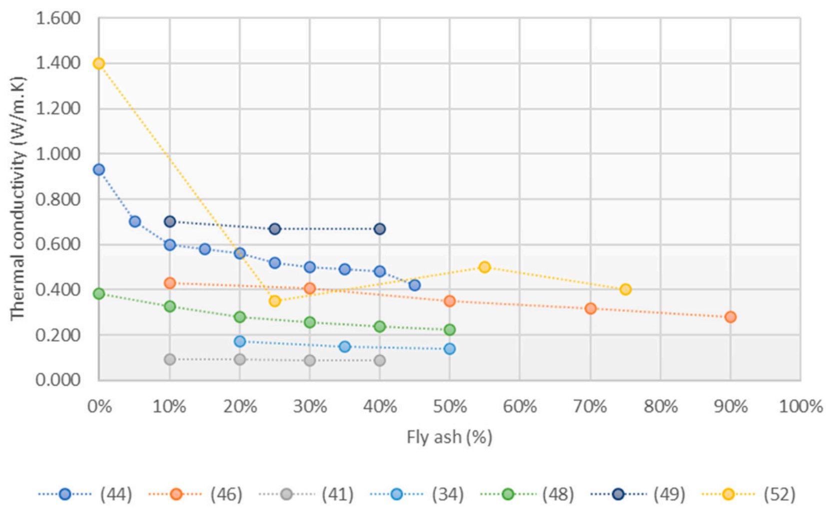

Figure 6. Thermal conductivity values for mortars with fly ash found in different studies.

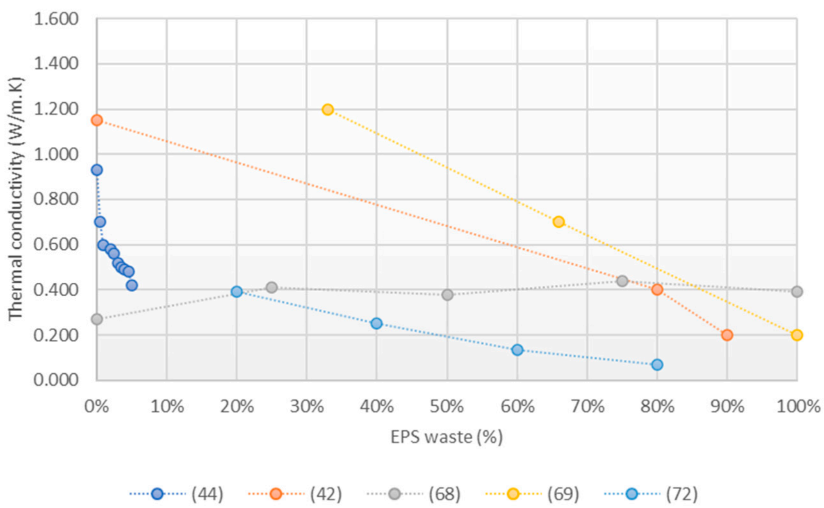

Figure 7. Thermal conductivity values for mortars with EPS waste found in different studies.

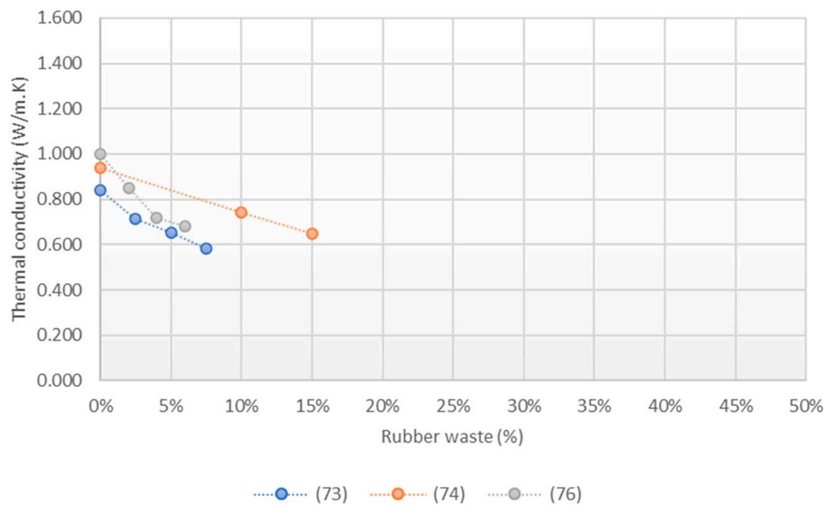

Figure 8. Thermal conductivity values for mortars with rubber waste found in different studies.

4.2.2. Water Absorption and Capillarity

Physical characteristics of residues, such as porosity, capillarity and water absorption, represent additional challenges in designing and processing thermal mortars with wastes [66]. These characteristics are crucial for construction materials as they represent one of the most important indicators of material durability [81]. Thus, several authors included water absorption and capillarity tests in their experimental campaigns.

Adding EPS waste and fly ash, in a study by Li et al. [44], resulted in mortars with a water absorption rate of 2.0% and a softening coefficient of 0.7%. The authors state that the polystyrene foam can guarantee a thermal mortar with excellent water tolerance and weather resistance. Other studies with EPS waste were also considered satisfactory in terms of water absorption and capillarity of the studied mortars [43,47,68,69]. Due to the good results obtained after incorporating EPS waste into mortars, Bicer et al. [46] expanded the study to evaluate the addition of waste to concrete. In all samples, water absorption rates were below 30%. For this reason and according to the authors, this type of concrete material could be used on exterior surfaces which are in direct contact with water.

Regarding porosity, Koksal et al. [68] evaluated mortars with EPS and vermiculite. According to their results, the porosity increased to almost 70% when the percentage of vermiculite and polystyrene increased. The authors also highlighted that there is a high correlation between porosity and unit weight, compressive strength, and thermal conductivity. In addition, cement particles tend to fill the gaps or porous structure of vermiculite due to the hydration process, while there is no such effect for polystyrene. Moreover, similarly to porosity, water absorption increases and mortars containing vermiculite absorb a high amount of water, up to 122.5%.

In a study by Coppola et al. [81], foamed plastic waste was added to mortars, which increased the water vapour permeability with the increasing of natural sand replacement, while capillary water absorption decreased. Coppola et al., stated that due to the pores' microstructure variation at higher lightweight aggregates incorporations, there is an increase in macropores, which positively influence thermal conductivity and water vapour permeability, reducing at the same time the capillary water absorption. The presence of macropores with the addition of residues such as wood, polyethylene terephthalate (PET) particles, and pulverized Glass Fibre-Reinforced Plastic (GFRP) instead of river sand, was also observed by Corinaldesi et al. [64]. The authors concluded that these mortars reduce both the resistance to water vapour diffusion and the capillarity.

Some studies analysed the water absorption and capillarity of mortars with fly ash [34,46,48,72]. La Scalia et al. [45] state that adding spent coffee grounds and fly ash instead of river sand increases water absorption while improving the thermal performance of the mortars. Bicer et al. [46] concluded that water suction remained below the critical values in samples with percentages of fly ash up to 30% instead of river sand. It was noted that the inner surface of mortars including fly ash have identical properties as the ordinary mortar such as breathing capability, nailing, boring, cutting, and sticking on the wall.

In another study by the same authors [48], fly ash was added to mortars to replace cement. When the fly ash percentage increased from 0% to 50%, the porosity of the samples increased by 18.91–28.62%. The authors highlighted that 1.5% resin added to the mixtures also had a great influence on the results. The study's findings show that 30% of fly ash in mortars enable their use in surfaces in contact with water without the risk of cracking, splitting or dispersing. Furthermore, the 40% and 50% fly ash additives should not be used in contact with water due to the increase of 30% in water absorption rates of the mortars.

On the other hand, Borges et al. [51] state that replacing cement with fly ash generally led to a decrease in the water absorption coefficient. The authors explain that fly ash acts as filler for the void space within the aggregate mixture, justifying the reduction in the capillary. It is worth mentioning that in this study, there was no addition of resin combined with fly ash. Studies with fly ash and silica fume [50,52,53] replacing cement resulted in an increase in the porosity of mortars, which may indicate that fly ash alone does not increase the porosity of mortars when used as cement substitute.

The addition of rubber waste to thermal mortars instead of river sand was analysed by Kazmierczak et al. [76]. According to the authors, crumb rubber mortars require a higher water content to achieve the same workability of the control mixture. The addition of crumb rubber decreases the bulk density and increase the mortar's water retention and air content. When rubber content increase, the capillary water absorption decreases due to the rubber ability to repel water and generate unconnected pores. Moreover, high levels of crumb rubber increase the void ratio and water absorption.

Jiang et al. [60] analysed the addition of straw and fallen leaves fibres instead of river sand in mortars. The authors explain that with the incorporation of three plant fibres from leaves, wheat straw and straw, the water absorption of the mortars increased by 15.84%, 5.47%, and 4.54%, respectively. In other studies, Pedroso et al. [40–61] added biomass fibres resulting from leaves after the pruning and cutting of the trees, instead of cement binder. The incorporation of aramid (0.50%), sisal (0.10%), and biomass (0.10%) fibres by total volume was compared. Both synthetic and natural fibres contributed to an important reduction in capillary water absorption of the mortars. In addition, a reduction in capillary connectivity and the changing of the pore structure of the thermal mortars can be highlighted.

According to Barreca et al. [36], the addition of olive stone in mortars causes a decrease in density but also an increase in water absorption. Barreca et al. highlight that it is necessary to combine olive stone mortars with a suitable waterproof coating to limit water absorption and the consequent increase in thermal conductivity. By replacing river sand by waste cork in thermal mortars, Panesar et al. [59] state that increasing the cork size up to 5 mm increases the total porosity of the mortars.

Expanded glass was used instead of river sand in thermal mortars by Záleská et al. [39]. After the tests, the use of lightweight aggregates in the composition of mortars resulted in their high porosity, low density, improved water vapour permeability and water absorption. Durgun et al. [80] added recycled ceramic roofing tile powder in thermal mortars instead of gypsum binder and concluded that the apparent porosity and water absorption of the mixtures increased. The authors state that this can be related to the pore structure of this type of waste. After adding recycled pyroclastic aggregates instead of river sand in mortars, Contrafatto et al. [29] state that only a mixture containing 0.1% of air entraining agent (AEA) and 1% of breathable resin, simultaneously, satisfied the requirements present in the standards [84] on mechanical strength, water absorption and thermal conductivity, being considered suitable for the use as lightweight insulating rendering mortar.

The values of the water absorption found for mortars with the most studied wastes, namely fly ash, EPS and rubber waste, are presented in Figure 9, and displayed values between 12% and 58.0%. For mortars with fly ash and rubber waste, there is a tendency for the water absorption to increase as the amount of incorporated waste increases. On the other hand, an increase in the percentage of EPS waste in the mortar can result in an increment [68] or reduction [72] in the water absorption values, which points to a great difficulty in comparing the values found in the literature.

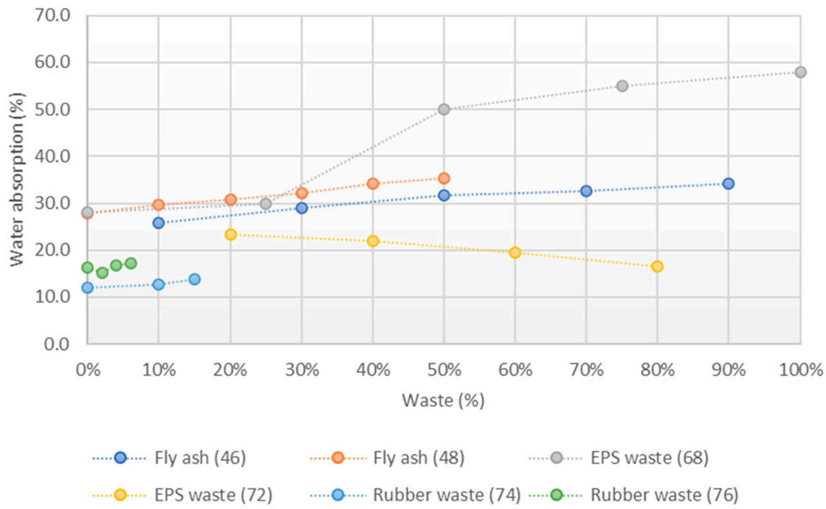

Figure 9. Water absorption values for mortars with wastes found in different studies.

4.2.3. Mechanical Resistance

One of most discussed topics by the authors was the mechanical resistance of thermal mortars incorporating waste. As expected, the mechanical performance of thermal mortars is a concern for the authors since the low density of this type of mortar tends to negatively influence the mechanical performance of thermal mortars [43–51]. Figures 10–12 present the values for the compressive strength obtained by different authors who studied the addition of Fly ash, EPS waste and rubber waste in thermal mortars. The values range from 1.0 to 57.0 MPa for samples with fly ash (Figure 10), from 0.7 to 57.0 MPa for samples with EPS waste (Figure 11) and from 2.9 to 42.0 MPa (Figure 12) for samples with rubber waste. It is noted that the increase in the percentage of waste incorporated in the mortar tends to reduce the compressive strength and, consequently, the mechanical performance of the mortars. Furthermore, for the same percentages of waste, there is a considerable variation in the values found. This fact highlights the difficulty in comparing the results of thermal mortars with wastes due to the complexity of the variables involved.

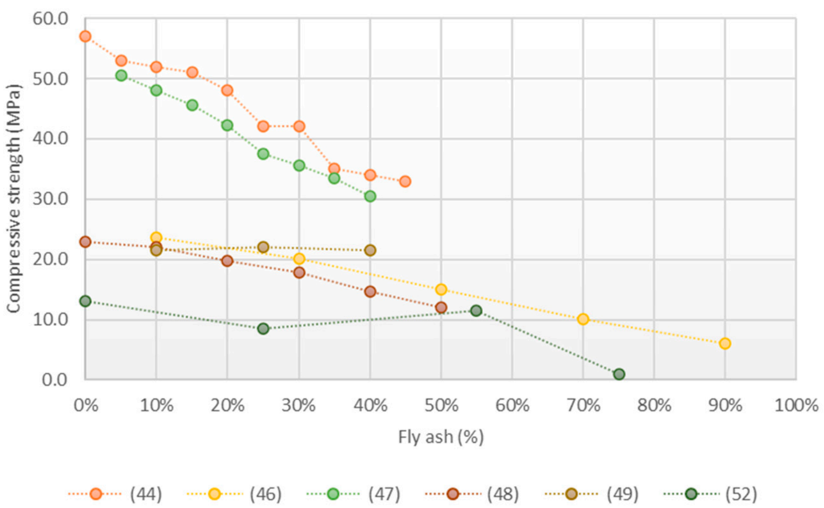

Figure 10. Compressive strength values for mortars with fly ash found in different studies.

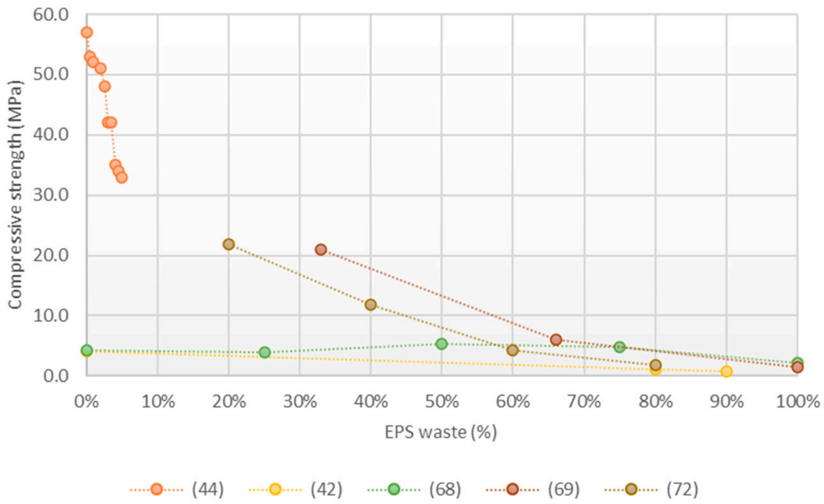

Figure 11. Compressive strength values for mortars with EPS waste found in different studies.

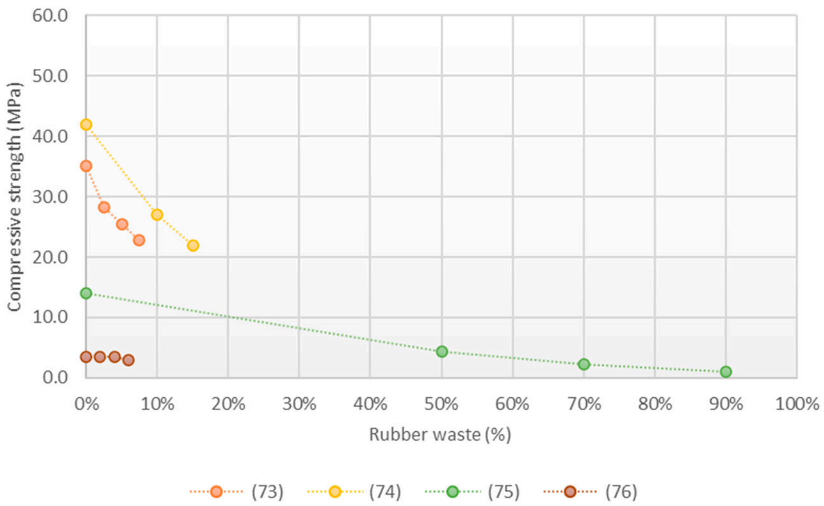

Figure 12. Compressive strength values for mortars with rubber waste found in different studies.

Li et al. [44] replaced river sand by EPS waste and cement binder by fly ash and assessed the compressive strength of cement mortars at 3 days, 7 days, 28 days, and 60 days, proving that it decreases as the content of polystyrene foam increases, at a range of 2.0–2.5% of waste. In addition, the flexural strength decreases with the increase in the content of coal ash and polystyrene foam. In a similar study, Haibo et al. [47] used the same waste, but instead of cement, lime and gypsum were used to stimulate the potential activity of fly ash and cement, thus making up for the loss of strength of the insulation mortar due to the addition of fly ash and modified EPS. The results show that replacing cement with 2–3% of EPS can significantly improve the mechanical properties and workability of thermal mortars.

In some studies, only the use of EPS waste was evaluated [68–70,72], such as in the research carried out by Tittarelli et al. [69]. The authors stated that replacing virgin EPS with recycled material improves the mechanical performance of the mortars without a significant variation in capillary water absorption and water vapour permeability. Bicer et al. [72] conducted their research to evaluate the use of EPS waste in concrete and concluded that those mixtures should not be used in columns and beams due to low compressive strength and elasticity modulus values of the samples. However, these concrete with low density can be applied as plaster and thermal insulation in floors, ceilings and wall, as they ensure both building load reduction and energy saving.

Paper sludge ash and fly ash were added to mortars by Chen et al. [41]. The authors state that although an excellent thermal performance was proved, the addition of fly ash and superfine slag also resulted in losses in the mechanical strength, particularly in early strength. Thus, the authors concluded that the addition content must be controlled within certain limits. In a similar study, Wang et al. [78] claim that the addition of paper sludge with a low wood fibre content (in the range of 2.5% to 7.5%) improved the toughness and softening coefficient of mortars. Additionally, an increase in wood fibre content to 15% improved the mechanical properties of mortars.

Ferrándiz-Mas et al. [71] studied mortars with EPS waste and paper sludge ash as a substitute of river sand and cement binder, respectively. For mortars containing 30% paper sludge ash, the compressive strengths were reduced by 88–96% with the addition of EPS, when compared to the control mortar. Furthermore, according to the same authors, mortars containing up to 20% paper sludge ash and either powder or ground EPS are suitable for type CS III rendering and plastering applications in the EU, mortars containing up to 30% paper sludge ash (with powdered EPS) and up to 20% paper sludge ash (with EPS ground) are appropriate for type CS II applications, and mortars containing 30% and 60% paper sludge ash (for ground EPS) and 40% and 50% paper sludge ash (powdered EPS) are suitable for CS I applications.

In a study with fly ash and blast furnace slag as additives [49], the results showed that both wastes have a positive effect on compressive strength. With the increase in fly ash and slag, the compressive strength of mortar increases first and then decreases gradually owing to the physical filler effect, being the maximum value obtained for mixtures with 20% fly ash and 25% slag. Li et al. [49] state that flexural strength is more controlled by the content of fly ash than blast furnace slag. According to the authors, the pozzolanic reaction between fly ash and cement lags cement hydration, decreasing mortars' flexural strength at early curing age with increasing fly ash content. Thus, the negative correlation between the contents of fly ash and flexural strength that was found is due to the "diluting action" of fly ash. The influence of fly ash in mechanical properties is due, according to the same authors, to its morphological and physical filling effects. On the other hand, blast furnace slag has an obvious influence on compressive strength and thermal conductivity due to its micro aggregate effect. Finally, the authors establish as optimal percentages for mortars 20.73% fly ash and 21.49% blast furnace slag.

Borges et al. [51] studied the addition of fly ash and insulating aggregates in mortars. The authors found that the increasing proportions of fly ash caused a reduction in strength (reductions of 4–24% for flexural strength and of 5–33% for compressive strength) with the highest reduction recorded for a 50% replacement. In addition, it also caused a drop in the dynamic modulus of elasticity. Furthermore, mortars with insulating aggregates proved to be less susceptible to cement replacement than sand mortars. Bicer et al. [46] state that as the addition of fly ash ratio increased 10–90% in mixtures as an alternative to river sand, and compressive strength values decreased by 1.25–9.4%, respectively. In another study by the same authors [48], in which cement binder was replaced by fly ash in a percentage growing from 0% to 50%, compressive strength decreased by 7.66–16.55%. Furthermore, compressive and tensile strengths values of the control samples (sample with 0% fly ash) and samples with 10% fly ash used as additives were, on average, the same. The authors proved that mixtures with approximately 20% fly ash can be used in loadbearing elements (including columns and beams), and the mixtures with 30–50% fly ash content can be used as non-loadbearing and cladding wall elements. Other studies with the addition of fly ash and silica fume resulted in suitable mechanical performance of mortars and good thermal insulation [50,52,53].

For non-structural elements, La Scalia et al. [45] stated that the addition of coffee waste and fly ash in thermal mortars led to suitable values of mechanical properties. In another study with coffee residues, Yildiz et al. [58] found that, in general, microwave and ultrasound pre-treated coffee waste additives improved the mechanical properties of mortars compared to raw coffee waste additives. The authors also highlight that pre-treatment of raw coffee waste led to an increase in 10% in compressive strength.

Mohamed et al. [73] studied the incorporation of micro rubber ash from recycled tires and lightweight fine aggregates to replace river sand in mortars. The compressive and tensile strength decreased when 5% micro rubber ash was used. For mixtures with 75% lightweight fine aggregates and 5% micro rubber ash, the compressive strength decreased by approximately 64% and 29%, respectively, when compared with the control specimens. In addition, the tensile strength decreased by approximately 57% and 19% when 75% lightweight fine aggregates and 5% micro rubber ash were used, respectively. Other studies with rubber waste resulted in a reduction in the mechanical performance of mortars as compressive and flexural strengths decreased [74–77]. To mitigate this effect, the study by Letelier et al. [74] combined crumb rubber and fine recycled concrete aggregates, obtaining a mortar that presented good mechanical performance, with a low decrease in mechanical properties, associated with an excellent thermal behaviour.

Passos et al. [42] studied the incorporation of EPS waste and insulation material waste, namely rock wool and fibre glass, to replace river sand in thermal mortars. The results point to a less mechanically resistant material, with lower modulus of elasticity, indicating greater deformability without rupture. In relation to flexural resistance, the performance of the mortars was also lower for the ones with residues, when compared to the reference mix. The fibre residues reinforced the mortar, explaining a 60% increase in tensile strength when compared to mixtures that only used EPS, supporting the results found in a similar study, in which the importance of combining more than one residue was highlighted, mainly if one of them is fibrous [43]. Furthermore, mortars in which sand was replaced by EPS presented lower adhesion resistance values, due to the lower intrinsic mechanical resistance of EPS. The authors highlight that rock and glass wool are mineral fibres that contribute to increasing the tensile strength of the composite and, in this way, also contribute to the adhesion resistance of the coating.

Studies on mortars with the addition of cork waste also showed a reduction in compressive and flexural strengths, despite the good thermal performance [16,59]. Similar results were obtained in studies with the incorporation of biomass fibres from leaves after the pruning and cutting of the trees [40,61], with wood ash and vegetable aggregates, namely sunflower plant bark and pith [65], with wood waste and polyethylene terephthalate waste (PET), with particles and pulverized glass fibre-reinforced plastic (GFRP) [64], with mining residues [56] and with recycled carbon black derived from scrapped off-the-road tires [79], and others residues [39,55,60,66,67,82].

On the other hand, mortars with compressive strengths complying with the standard values were found by Srikanth et al. [35]. In this study, bagasse ash and rice husk ashes were used to replace cement binder. For replacement percentages up to 30% for bagasse ash or 15% each for rice husk ash and bagasse ash, the authors found a positive effect in mortars' mechanical and thermal performance.

Studies on mechanical properties of mortars with waste replacing gypsum binder were also found. Durgun et al. [80] evaluated gypsum-based mortars containing recycled ceramic tile powder at ambient and high temperatures, pointing to a decrease in the bending and compressive strength, which can be caused by the increased water demand of the recycled ceramic tile powder in the mixtures. The study showed the degradation of the gypsum crystal structure and the aggregate–matrix interface. However, the residual strength values showed that the samples containing recycled ceramic tile powder had slightly better resistance to high temperatures. In another study, Vidales-Barriguete et al. [85] added plastic cable waste in gypsum-based mortars, which showed a good performance regarding cracking and impact resistance, when compared to the traditional ones. The authors justify this behaviour with the increase in the new mortar elasticity by approximately 50%.

4.2.4. Durability and Fire Resistance

Generally used as an external coating, thermal mortars play a fundamental role in construction durability as they are the first barrier to degradation agents [16]. In this sense, some authors have evaluated ageing effects and fire resistance. Thus, thermal mortars incorporating waste have been subjected to laboratory accelerated ageing tests to estimate their potential under long-term use under environmental conditions.

In the study carried out by Li et al. [44], a thermal mortar with EPS waste and fly ash incorporated to replace sand presented satisfactory results to acid-resistance, freeze–thaw resistance, and weathering resistance tests. The authors highlight that the compressive strength of the samples was about 50.8 MPa after 30 cycles of the acid resistance test, 50.2 MPa after 30 cycles of freeze–thaw resistance tests, and 49.6 MPa after 30 drying and wetting cycles. On the other hand, Passos et al. [42] state that after 18 wetting and drying cycles, mortars with EPS residues and waste insulation materials (rock wool, fibre glass) as a substitute of sand showed similar mass variation behaviour to that of the reference mortar, indicating potential to be used as external coatings. The specimens were also visually evaluated after each cycle and none showed any signs of deterioration, such as cracking and vesicle formation.

In another study, Coppola et al. [81] evaluated the durability of thermal mortars with foamed plastic waste. After 15 cycles of the sulphate attack test, the new mortars presented lower mass loss than the reference ones. The authors related the obtained results to the morphological modifications in the bulk porosity, assessed by mercury intrusion porosimetry tests, as the polymeric foamed aggregates led to changes in the pore microstructure, resulting in higher pore dimensions.

Morgado et al. [16] conducted tests of accelerated ageing tests in mortars with regranulated expanded cork, showing an increase in the mass of the specimens of 4% to 29% after hygrothermal and IR cycles. The same mortar was also subject to freeze–thaw cycles and a mass reduction of 3% to 15% was detected, which indicates degradation of the material. However, after the freeze–thaw cycles and hygrothermal and infrared cycles, a greater compressive strength was measured (14.29% and 6.78% higher than the control mortar, respectively). It is important to highlight that there was an increase in the thermal conductivity value after the hygrothermal and infrared cycles, while freeze–thaw cycles had no influence on this property.

Kazmierczak et al. [76] investigated mortars with crumb rubber, pointing to a higher durability than the reference mortar, as cracking reduced and tensile bond strength remained unchanged after thermal cycles. Furthermore, the behaviour of the mortars under fire was evaluated. According to the authors, with the incorporation of 6% of crumb rubber rather than natural aggregates, the mortars do not propagate flame and they are non-combustible. The authors concluded that mortars with 2% and 4% of crumb rubber content presented the best set of properties related to deformation capacity, thermal behaviour, and cracking, with tensile bond strength above the minimum required by the standards.

Kosiachevskyi et al. [62] studied the performance of mortars with hemp shives before and after accelerated ageing tests. Results show a slight increase in the porosity after the accelerated ageing tests, due to the cracking of the hemp particles/cementitious matrix interface, compensated by carbonation that fills of the pores with calcite. As for thermal conductivity, as it depends on the porosity, it also slightly increased.

Záleská et al. [39] evaluated the durability of mortars with expanded glass as substitute of river sand. They assessed salt crystallization and their effect on the mortar hygroscopicity. According to the research results, regardless of the binder type, all new mortars showed excellent resistance against salt crystallization, which is favourable for their application in the repair and renovation of salt-laden structures [84]. Yildiz et al. [58] carried out fire resistance tests on mortars with coffee wastes. The best fire resistance time was 95 min, with an incorporation percentage of microwave-pre-treated coffee waste of 20% and 30%.

Piña Ramírez et al. [54] tested the use of mineral wool from construction and demolition waste, such as rock wool, fibreglass and mixed mineral wool waste to replace river sand in thermal mortars. All samples were tested for direct fire testing and their mechanical and thermal properties before and after fire were compared. According to the authors, mortars that incorporate fibre residues have better thermal behaviour, with the addition of rock wool residue being the one with better performance after the fire test, reaching very low thermal conductivity values. Regarding mechanical performance, the surface hardness remains practically unchanged, but the flexural resistance worsens after the fire, although presenting better results than the reference mortar. The compressive strength values decreased after the fire due to the increase in porosity, with mortar with rock wool residue showing the greatest decrease, up to 45.41%. However, despite this decrease, the values remained in accordance with the requirements established in UNE-EN998-1 [84]. This research shows that cement mortars with mineral wool residues do not burn, so they do not add more load to the fire or release asphyxiating gases and fumes in the event of a fire. It also shows that they remain resistant to temperatures of up to 700 °C and have very low thermal conductivity; therefore, in addition to not collapsing, they would be able to protect other elements from combustible materials and, thus, prevent the spread of fire.

It must be noted that durability tests on thermal mortars with residues are of fundamental importance, but only a few studies have been dedicated to it. Fire resistance has not been the subject of much analysis and has been insufficiently evaluated, making it difficult to compare results for this type of mortar.

5. Synthesis and Discussion

Table 3 presents a synthesis of the 51 articles that were assessed. It is possible to state that the main objectives of the analysed studies are quite diverse. There is also a marked variety in terms of measured properties and types of incorporated waste, studied separately or in a combination of more than one.

Table 3. Synthesis of the 51 articles under the scope of this literature review, including waste incorporated into the thermal mortar and type of mixture component ([a]: as a replacement for sand; [b]: as a re-placement for cement; [c]: as a replacement for lime binder; [d]: as a replacement for gypsum; [e]: as an additive), objective of the study and measured properties.

Ref.	Waste	Objective of the Study	Measured Properties
[54]	Mineral wool from (CDW): rock wool [a], fibre glass [a] and mixed mineral wool waste [a]	Fire resistance of cement mortars with CDW	Shore D hardness, flexural and compressive strength, thermal conductivity and fire resistance test
[44]	EPS waste [a] and fly ash [e]	Weather resistance of thermal mortar with EPS waste and fly ash	Flexural and compressive strength, thermal conductivity, heat of hydration, weather resistance: acid-resistance and freeze–thaw cycles
[42]	EPS waste [a], insulation materials waste: rock wool [a], fibre glass [a]	Physical, mechanical, and thermal properties of thermal mortar for precast concrete wall	Density and capillarity coefficient, flexural, compressive and bond strength, water absorption, durability cycles: wetting and drying, thermal transmittance and thermal conductivity
[62]	Hemp shives [a]	Provide an original accelerated ageing test protocol and investigate the hygrothermal stresses on the morphology, chemical composition and properties of hemp mortar samples	Total porosity, thermal conductivity, moisture buffer value, water vapour permeability, accelerated ageing cycles: heat rain and heat–cold cycles
[56]	Mining residues [b]	Cost-efficiency analysis of mortars produced with mining residues	Density, capillarity absorption and drying, thermal conductivity, pore size distribution, flexural and compressive strength and cost-efficiency analysis

Table 3. *Cont.*

Ref.	Waste	Objective of the Study	Measured Properties
[68]	EPS waste [a]	Physical, mechanical and thermal properties of thermal mortars with EPS waste	Dry unit weight, apparent porosity, water absorption, flexural and compressive strength and thermal conductivity
[45]	Spent coffee grounds [a] and fly ash [a]	Technical, environmental, and economic performances of spent coffee as an aggregate in natural hydraulic lime and geopolymer-based mortars	Bulk density, water absorption, thermal conductivity, flexural and compressive strength
[73]	Micro rubber ash from recycled tires [a]	Physical, mechanical, and thermal performance of mortars with micro rubber	Flow ability, unit weight, drying shrinkage, compressive and tensile strength and thermal conductivity
[79]	Recycled carbon black derived from scrapped off-the-road tires [a]	Physical, mechanical, and thermal properties of mortars incorporating recycled carbon black	Void content and density, ultrasonic pulse velocity test, thermogravimetric analysis, thermal conductivity, volumetric heat capacity, thermal diffusivity and unconfined compressive strength
[35]	Bagasse ash [b] and rice husk ashes [b]	Mechanical, thermal, and environmental performance of mortar with agro-wastes (environmental and economic assessment)	Density, porosity, water absorption, testing of acid resistance, thermal conductivity, compressive strength
[16]	Regranulated Expanded Cork [a]	Assess the influence of incorporating different wastes as aggregates in thermal mortars	Compressive strength, ultra-sound velocity, young's modulus, thermal conductivity and accelerated ageing tests: hygrothermal, IR and freeze/thaw cycles
[39]	Expanded glass [a]	Structural, mechanical, hygric and thermal parameters of mortars with expanded glass	Bulk and specific density, total open porosity, water absorption, water vapour permeability, salt crystallization resistance, flexural and compressive strength, dynamic modulus of elasticity, thermal conductivity and volumetric heat capacity
[46]	Fly ash [a]	Impact of fly ash grain size on thermal and mechanical performance of mortars	Density, thermal conductivity, compressive tensile strength, elasticity module and water absorption
[41]	Paper sludge ash [a] and fly ash [a]	Effects of insulation aggregates on cement mortars	Compressive and flexural strength, thermal conductivity, bulk density and water absorption
[60]	Straw and fallen leaves fibres [a]	Physical and mechanical properties of thermal mortars with straw and fallen leaves fibres	Compressive and flexural strength, thermal conductivity and water absorption
[69]	EPS waste [a]	Comparison between mortars with virgin EPS and EPS waste	Compressive and flexural strength, dynamic modulus of elasticity, thermal conductivity, water absorption and water vapour permeability

Table 3. *Cont.*

Ref.	Waste	Objective of the Study	Measured Properties
[74]	Fine recycled concrete aggregates [a] and crumb rubber [a]	Physical and mechanical properties and durability of mortars with crumb rubber	Compressive and flexural strength, dry density, thermal conductivity, water-accessible porosity, water absorption by immersion and capillarity absorption
[80]	Recycled roofing tile powder [d]	Properties of gypsum-based mortars with recycled tile powder at ambient and high temperatures	Before and after exposure to the high temperatures: unit weights, mass losses, ultrasonic pulse velocities, bending strengths, compressive strength, volume changes and visual observation, apparent porosity, water absorption and thermal conductivity
[47]	EPS waste [b] and fly ash [b]	Physical, mechanical and thermal properties of mortars with fly ash and EPS waste	Bulk density, water retention, workability, bending and compressive strength and thermal conductivity
[43]	CDW: aggregates from recycled concrete [a] and ceramic walls [e]; insulation waste: EPS with graphite [e] and mineral wool [e]	Mechanical, thermal and physical properties of mortars with waste and its suitability for prefabricated materials (blocks and panels)	**Mortars:** compressive and flexural strength, shore C surface hardness, longitudinal modulus of elasticity, bulk density, water absorption by capillarity and thermal conductivity; **Panels:** resistance to bending; **Blocks:** suction or initial rate of water absorption by capillarity and compressive strength
[34]	Fly ash [b]	Optimization of thermal mortars focused on the fresh state properties	Fresh density, air content, water retention, capillary water absorption, compressive strength and thermal conductivity
[81]	Foamed plastic waste [a]	Hygrothermal and durability related properties of a cementitious mortar with foamed plastic waste	Density, capillarity water absorption, thermal conductivity, water vapour permeability, mercury intrusion porosimetry and durability: sulphate attack resistance and
[70]	EPS waste [a]	Thermo-physical and mechanical properties of thermal plaster with crushed expanded polystyrene package crumbs	Density, water vapour permeability, thermal conductivity and compressive strength
[48]	Fly ash [b]	Thermal properties of power plants fly ashes, cement and tragacanth composites in concrete or plaster	Water absorption, porosity, thermal conductivity, compressive and tensile strength
[57]	Desiccated and smashed desiccated platanus acerifolia fruits [a], triturated cork plugs [a], water-soaked cardboard [a], coffee parchment skin [a], chopped cane stalks [a], almond, hazelnut, and nut shells[a], coconut shells [a], bean and pea pods [a]	Thermal properties of new environmentally friendly materials with waste or vegetal products	Thermal conductivity
[66]	Curauá fibres [e]	Physical, chemical, and mechanical characterization of the curauá-reinforced cementitious composites	Uniaxial tensile testing, compressive strength, bulk density and thermal conductivity

Table 3. *Cont.*

Ref.	Waste	Objective of the Study	Measured Properties
[58]	Coffee wastes [b]	Physical, mechanical, thermal, and acoustic properties of thermal plasters with coffee waste	Compressive and bond strength, thermal conductivity, acoustic absorption, fire resistance, density and capillary water absorption
[78]	Paper sludge [e]	Adaptability of paper sludge with wood fibre into cement-based thermal mortar	Compressive strength, pressure-off ratio, density, water absorption and thermal conductivity
[71]	EPS waste [a] and paper sludge ash [b]	Thermo-mechanical performance of lightweight mortars containing expanded polystyrene and paper sludge ash	Thermal conductivity, workability, bulk density and compressive strength
[64]	Wood waste [a], waste polyethylene terephthalate (PET) particles [a] and pulverized glass fibre reinforced plastic (GFRP) [a]	Thermo-physical and mechanical characteristics of mortars with plastic and wood waste	Compressive and flexural strength, water vapour permeability, density, capillary water absorption and thermal conductivity
[75]	Rubber powder [a]	Thermo-mechanical properties and durability of mortars with rubber powder	Bond, flexural and compressive strength, drying shrinkage, permeability, thermal conductivity and resistance to penetration of aggressive chemicals
[65]	Bio-based: wood ash [b], vegetable aggregates (sunflower plant bark and pith) [a]	Thermo-physical properties of mortars and concrete made with bio-based materials	**Mortar:** bulk density, absolute density, water absorption, thermal conductivity; **Concrete:** flexural and compressive strength
[49]	Fly ash [e] and blast furnace slag [e]	Experimental and statistical analysis of the influences of flying ash and slag on the performance of mortars based on the response surface methodology	Fluidity, compressive and flexural strength, thermal conductivity, optimization design using the desirability approach of RSM
[50]	Fly ash [b], slag powder [b], silica fume [e]	Use of fly ash, slag and silica fume to produce alkali-activated cementitious composite mortar for walls	Compressive strength, dry density and thermal conductivity
[51]	Fly ash [b]	Physical and mechanical performance of cement-based coating mortars with different contents of supplementary cementitious material	Ultrasonic pulse velocity, flexural and compressive strengths, dynamic modulus of elasticity, bulk density, capillarity water absorption coefficient, open porosity and thermal conductivity
[29]	Recycled pyroclastic aggregates [a]	Mechanical and physical properties of mortars with recycled Etna volcanic aggregates	Flexural and compressive strength, density, water absorption, porosity and thermal conductivity
[52]	Fly ash [b] and silica fume [b]	Possibility of producing thermal plasters from common cementitious materials such as fly ash, metakaolin, and silica fume without employing any foaming agent or lightweight aggregate	Compressive strength, bulk density, total porosity, thermal conductivity and thermal resistance
[76]	Crumb rubber [a]	Fresh and hardened, thermal and fire properties and the durability of the composites using crumb rubber	Flexural and compressive strength, bulk density, dynamic modulus of elasticity, water absorption, thermal conductivity, fire resistance and ignitability test

Table 3. *Cont.*

Ref.	Waste	Objective of the Study	Measured Properties
[82]	Silicate sawing sludge [a]	Development of a new eco-product to find a correct recovery of silicate sawing sludge by means of waste management according to European criteria	Water absorption, specific density, flexural and compressive and bond strength, thermal conductivity, durability: freeze and thaw cycles and salt crystallisation cycle resistance
[83]	Plastic Cable Waste [d]	Analyse the physico-mechanical properties of gypsum boards including plastic waste aggregates from cable recycling	Young's modulus, shock–impact resistance, flexural strength, thermal conductivity and thermal comfort
[40]	Biomass fibres resulting from leaves after the pruning and cutting of the trees [b]	Employing fibres to mitigate some key properties decreased as a consequence of using aerogel in thermal renders	Compressive and flexural strengths, dynamic modulus of elasticity, adhesion test, superficial impact resistance, thermal conductivity, bulk density, capillary water absorption, drying index, water vapour permeability, and dynamic vapour sorption
[72]	EPS waste [a]	Use of EPS waste as aggregate in concrete with apricot resin-added cement	Density, thermal conductivity, porosity, water absorption, compressive strength and modulus of elasticity
[59]	Waste cork [a]	Impact of cork used as sand replacement on the plastic, mechanical, microstructural and thermal properties of mortar and concrete	Density, mercury intrusion porosimetry, rapid chloride permeability, thermal resistance, thermal conductivity and compressive strength
[63]	Rice husk ash [a]	Incorporation of rice husk ash on mortar for wall plastering to provide better thermal insulation, reduce the operational energy and enhance thermal comfort	Porosity, compressive strength, thermal conductivity, and environmental impact assessment
[55]	Recycled brass fibres [e]	Physical, thermal and mechanical properties of mortars reinforced with brass fibres	Density, porosity, ultrasonic pulse velocity, thermal conductivity, volumetric heat capacity, compressive and flexural strength
[28]	Wool fibres [c], hemp shives [c], recycled jute fibre [c], thistle fibre [c] and opus signinum [c]	Analysis for the thermal characterization of recycled materials for building insulation (numerical simulation)	Thermal conductivity
[61]	Biomass fibres resulting from leaves after the pruning and cutting of the trees [b]	Hygrothermal behaviour of an aerogel-based render (reference) with the same base formulation, replacing the powder with three different fibres	Hygrothermal numerical simulation
[53]	Fly ash [b] and silica fume [b]	Manufacturing an insulating binder free from Portland cement or foaming agent	Bulk density, thermal conductivity, total porosity, thermal resistance and compressive strength
[36]	Olive stone [e]	Original use of olive stone to improve thermal properties of cement lime mortar	Thermal conductivity, density and water absorption
[67]	Ground waste seashells [b]	Incorporation of waste seashells in a cement-based material for masonry and plastering	Water demand, setting time, compressive strength, drying shrinkage and thermal conductivity
[77]	Rubber particles [e]	Using rubber particles from recycled tires in Portland cement mortar	Compressive, flexural and bond strength (7 and 28 days of age), thermal conductivity and drying shrinkage

The thermal performance of mortars with waste is the property most studied, as it was expected since the increase in thermal resistance is essential in this type of mortar. The mechanical resistance and behaviour against water are also a concern highted by the work developed by most authors. It is a consensus among them that the gain in thermal resistance must be complemented by good mechanical and hygric performance. On the other hand, some authors committed to studying the durability and fire resistance of mortars with waste.

Most authors focused their efforts on laboratory tests with small-scale specimens. Only a few had a different approach, using numerical simulations to assess the performance and/or the effect of using the new mortars with waste. It is worth noting that the publications do not always clearly describe the practical purpose of studying the incorporation of waste into mortars, only describing the results found after performing laboratory tests using specimens of mortars with the incorporation of waste and comparing them with those found for the reference mortars (without waste). In most cases, the waste is incorporated as a component in the analysed mixtures by replacing some other component, namely cement, sand, lime or gypsum. Only few articles refer to using the residue in the mixture as an additive. This fact highlights the tight relation between this field of study and the sustainable approaches defined in the environmental guidelines, as most of the publications refer to the need for reducing the consumption of virgin raw materials.

Among the publications that were analysed, the percentages of waste incorporation varied considerably, even for the studies using the same kind of waste. According to the authors, the dimensions, shape, combined or isolated use, and the way the waste is incorporated into the mixture lead to this type of variation, making it difficult to standardize a percentage of incorporation. Furthermore, a wide range of laboratory procedures were used, which were not always deeply detailed in the publications, and required adaptations due to the unconventional behaviour of waste when in contact with the other components of the mixtures. The lack of standards for the characterization of mortars with waste explains the eventual need for the authors to create new procedures for laboratory tests or partially adapt the existing ones. It also must be highlighted that the authors did not always state clearly how the mixtures were prepared and how the measurements were performed, which can make it difficult for other researchers to make a good use of the results and to continue the research. Also, different reporting on the experimental procedure of each study raises difficulties in comparing results from different studies, a fact also pointed out by other authors [86]. So, it is fundamental to use standard tests and, when they cannot be fully applied, because they are not though for the incorporation of materials with characteristics that can be found in waste, the procedure should be described clearly and in detail to guarantee the intercomparability of results.

All the authors agree that there is a decrease in the thermal conductivity after adding the tested wastes. Furthermore, most of the authors attest that a strong relationship was found between the drop in thermal conductivity and the decrease in the density of the mortars, caused by the low density of the incorporated residues. Regarding water absorption, several authors have found that adding low-density waste to mortars results in the formation of macropores, which promotes greater water absorption. On the other hand, waste in filler dimensions can be beneficial as they seal the pores, resulting in less water absorption. The incorporation of waste results, in most studies, in a reduction in the compressive and flexural strengths. The percentage of waste, the combination of more than one type of waste, or using waste as additive can mitigate this decrease, allowing mortars to meet established standard criteria. Furthermore, several authors concluded that thermal mortars with residues can be used in non-structural applications.

When the durability of mortars was assessed, the authors stated that their performances were positive, with no relevant changes when compared to traditional mortars. The few studies regarding the fire behaviour of mortars with waste revealed that this kind of mortar restrains the propagation of fire and it is non-combustible, being able to protect other elements with combustible materials and, thus, preventing the spread of the flames.

Furthermore, some authors state that thermal mortars can achieve better results through the incorporation of waste combined with other materials, such as resins, air entrainers, and vermiculite, among others.

It can be stated that the publications found in the literature point to satisfactory results, with promising performances when compared with the reference mixtures. The main issue to be tackled when using waste in thermal mortars is the increased risk of nonfulfillment of the mechanical properties and durability specifications; however, authors have proved it to be possible to overcome the problem. Accurate mixture design and numerical simulation can be useful tools to that end and play a fundamental role to better evaluate the behaviour of these mortars. Therefore, it can be stated that the incorporation of waste into thermal mortars is an effective technique for helping achieve energy efficiency in buildings while alternatives are applied for the disposal of waste.

In terms of perspectives for the scalability of the application of thermal mortars with waste in the construction sector, its use as coatings in modular prefabricated wall systems manufactured on a large scale stands out. Furthermore, using these innovative materials as a base for construction elements, such as blocks, tiles, boards, and thermal insulation panels, can also be an alternative in the future. The application of numerical simulation is suggested to optimize the percentage of waste in the mixture, enhancing the hygrothermal and mechanical performance based on parametric analyses. Given the difficulty in evaluating the results of different experimental procedures found in the analysed studies, new standardized protocols for the experimental tests, adapted to the specificities of this mortars, must be developed and spread within the scientific community, to facilitate achieving the eventual correlation and comparability of future results, as already demonstrated in other studies [18,87].

Furthermore, new studies on thermal mortars with new waste and with waste already studied must be developed to enable the comparison of procedures and results, to evaluate the influence of the waste dimensions on the mechanical and thermal properties, verify the long-term performance of mortars through durability and fire resistance tests, carry out Life Cycle Assessment (LCA) to measure the possible environmental impacts caused by the manufacture and application of the mortars and, finally, analyse the costs and the availability of waste so that it is possible to consider the feasibility of applying thermal mortar with the incorporation of waste on an industrial scale, a very relevant factor for obtaining practical and feasible results, bringing this field of study closer to the reality of the productive sector.

Through this review, it is possible to state that the incorporation of waste into thermal mortars is a field of study of interest to the scientific community, a fact proven by the evolution of the number of studies over the years and their multiple approaches. Furthermore, it was possible to bring together the main publications identified in a single document, creating a database that can be a starting point for researchers who aim to investigate this area. Given the above, this work allows us to identify the benefits of incorporating waste into thermal mortars, analyses the gaps and discusses future perspectives within the scope of this topic.

6. Conclusions and Perspectives

According to the literature review presented in this work, regarding the incorporation of waste in thermal mortars, it can be highlighted that

- A total of 51 publications were found with relevant approaches to the study of thermal mortars with the incorporation of waste, in which 41 wastes, studied separately or combined, were identified.
- Fly ash, EPS waste, rubber waste and mineral wool waste were the residues that were more mentioned in the publications. Different ways of incorporating waste into thermal mortars were found. The use of waste as a substitute for sand was the subject of study in most publications (55%), followed by the addition of waste to replace cement (23%), as an additive (14%), to replace lime binder (6%) and gypsum (2%).

- The number of publications related to incorporating waste into thermal mortars has grown over the years. This increasing interest was expected due to international guidelines for improving energy efficiency of buildings and decreasing waste disposal.
- The most evaluated properties of the thermal mortars in the selected publications were thermal performance, water absorption, capillarity, mechanical resistance, durability and fire resistance. It is possible to state that, generally, there is a reduction in the thermal conductivity of mortars after the addition of waste. Furthermore, most authors attest that a strong relationship was found between the reduction in thermal conductivity and the low density of mortars, caused by the low density of the incorporated residual materials.
- Several authors have found that adding low-density waste to mortars results in the formation of macropores, which promotes greater water absorption. On the other hand, waste in filler dimensions can be beneficial as they fill the pores, resulting in less water absorption.
- Regarding the mechanical resistance of mortars, there is a tendency towards a reduction in compressive and flexural strengths after adding waste. The percentage of waste, the combination of more than one type of waste, or using waste as additives in mortars can be factors to the mitigation of this reduction, allowing mortars to meet established standard criteria. Furthermore, several authors concluded that thermal mortars with residues can be used in non-structural situations.
- In the studies involving the durability of mortars, the authors state that the performance of the samples is positive, with no significant changes when compared to traditional mortars. The few studies regarding the fire behaviour of mortars with waste revealed that mortars do not propagate fire and they are non-combustible, being able to protect other elements with combustible materials and, thus, preventing the spread of fire.
- The size and shape of the waste particles affect the properties of the thermal mortars as well as the addition of one waste or more types of waste in the mixture. An example of this is the use of fibrous waste to mitigate the decrease in the mechanical resistance of thermal mortars. Furthermore, some authors state that thermal mortars can achieve better results through the incorporation of waste combined with other materials, such as resins, air entrainers, and vermiculite, among others. Therefore, it can be stated that the incorporation of waste into thermal mortars is an effective technique for helping achieving energy efficiency in buildings while alternatives are applied for the disposal of waste and to continue the path towards a circular economy.
- It is important to highlight the need for new studies within the scope of thermal mortars incorporating waste so that results and trends can be confirmed, since 26 of the 41 wastes analysed were only tested in one study, making it difficult to compare the main conclusions. Furthermore, using thermal mortars with waste as a base for building elements, such as prefabricated wall systems, blocks, tiles, boards and thermal insulation panels, can be an alternative for future studies. The application of numerical simulation can be an interesting tool to optimize the percentage of waste and to assess hygrothermal and mechanical performance. Future studies must also be carried out to propose a standardized protocol for the experimental procedures to facilitate correlation and comparability of future results. As future perspectives on this topic, the relevance of implementing Life Cycle Analysis (LCA) and a deep evaluation of material durability, including fire resistance, stands out. Finally, studies on the production costs as well as on the perception of companies and customers regarding this innovative product in construction are also necessary.
- Through this review, it was possible to bring together the main publications on this topic in a single document, creating a database that can be a starting point for researchers who aim to investigate this area. Given the above, this work allowed identification of the benefits of incorporating waste into thermal mortars, analysed the gaps and discussed future perspectives within the scope of this topic.

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