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Review

The Challenge of Integrating Seismic and Energy Retrofitting of Buildings: An Opportunity for Sustainable Materials?

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Abstract: Recent earthquakes and escalating energy demands are exposing building stock deficiencies, particularly in terms of seismic resilience and energy efficiency. Many aged constructions do not fulfil current regulations both in terms of seismic and thermal design principles, thus requiring suitable retrofitting solutions. Integrated approaches for concurrent seismic and energy renovation have emerged as promising strategies in recent years, offering holistic solutions that optimize interventions and maximize benefits. While these combined methods hold significant potential for practical applications, there remain opportunities for further research to enhance their advantages. Furthermore, addressing climate concerns requires concentrated effort within the construction sector, where synergetic refurbishments can serve a dual purpose by reducing emissions and promoting the use of more sustainable materials. This study discusses strategies proposed in the literature for integrated retrofitting, considering their environmental impact, both in terms of energy performance and embodied carbon. The overview shows the innovation potential for the development of materials and systems combining acceptable performance with eco-friendly attributes. Yet, their application in integrated retrofitting systems, either as structural components or insulators, is still limited, underscoring the need for continued investigation and advancement. This paper concludes with recommendations to inspire further research and advancements in this critical field.

Keywords: integrated retrofit; seismic strengthening; eco-friendly materials; thermal insulation; sustainability

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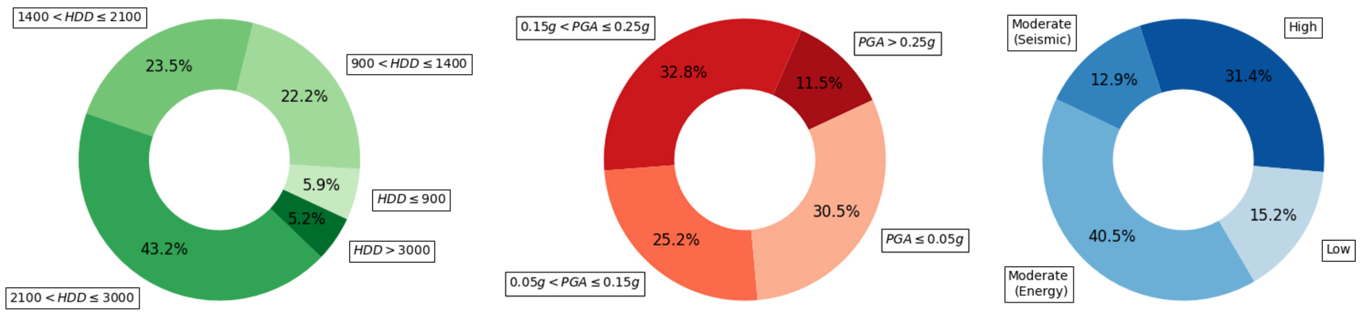
1. Introduction

Many existing buildings suffer from deficiencies related to substandard structural and thermal performance. Such inadequacies, coupled with the environmental impact of construction and use, constitute an open challenge for practitioners in the construction sector. Addressing these issues requires a multidisciplinary approach and involves the development of effective integrated retrofitting strategies combining structural and thermal upgrading [1]. While efforts within the academic community to tackle these challenges have been intensified, there are still several obstacles that hinder the widespread adoption of integrated retrofitting strategies [2] and the use of more sustainable materials [3] in practical applications. The integration of eco-friendly products and materials holds great potential to enhance the effectiveness and sustainability of integrated retrofitting strategies [4]. This paper aims to identify current proposals from the literature, assessing their benefits and shortcomings to stimulate further research and identify promising research directions.

In Europe, existing constructions are responsible for 40% of the total energy consumption and 36% of the total carbon emissions (with older buildings being the main contributors). They are also accountable for the depletion of about 50% of raw materials and 35% of the waste produced in Europe [5–7]. The highest percentage of energy use is due to the operational stage of buildings during their life cycle. Mostly composed of residential dwellings constructed between 1946 and 1980, the European building stock presents several deficiencies made further evident by the age of its constructions [7]. Indeed, it has been estimated that around 80% of European houses were built before 1990, thus they do not meet current requirements both in terms of seismic [8] and energy [9] performance. Studies considering the combined climatic needs (i.e., heating degree days HDDs and cooling degree days CDDs) and seismic hazard (i.e., peak ground acceleration PGA) for each European country have identified the regions that require an integrated retrofitting approach [10]. Countries with higher needs for combined seismic and energy renovation include Italy, Romania, Croatia, Greece and Bulgaria [7]. Following this prioritization approach and considering the Italian scenario, it has been estimated that in some regions, about 70–80% of residential dwellings need integrated retrofitting interventions. This finding further highlights the need for simultaneously addressing structural and thermal upgrading within the context of building renovation.

The potential benefits of combined retrofitting become apparent when considering the regulatory requirements and site conditions where the building stock is located. Commonly, energy and seismic demands can be expressed in terms of HDDs and PGA with a 10% probability of exceedance in 50 years. In Italy, for example, the aforementioned design parameters are specified in the DPR 412/1993 [11] and OPCM 3519/2006 [12] norms. In terms of energy efficiency measures for the Italian scenario, it can be estimated that around 72% of residential buildings are located in climatic zones with considerable energy demands (HDDs > 1400; see Figure 1a). At the same time, about 44% of dwellings are in seismic areas with medium to high levels of seismic hazard (PGA > 0.15 g; see Figure 1b). By combining such data and using the simplified analysis carried out in [7], it is possible to estimate that around one-third of the Italian residential stock potentially has a high need for integrated seismic and energy retrofitting (see Figure 1c). Analogously, about half of the residential buildings exhibit moderate demand for combined renovation, of which 13% with a prevalence for seismic strengthening and 40% for energy upgrading. Finally, the remaining part of the residential building stock presents less severe conditions either in terms of seismic or climatic requirements, thus having lower potential for integrated retrofitting.



(**a**) (**b**) (**c**)

Figure 1. Distribution of residential dwellings in Italian scenario based on seismic and climatic zonation to identify existing buildings potentially requiring: (**a**) energy renovation; (**b**) seismic strengthening; or (**c**) integrated retrofitting (data source from [7]).

The demolition and reconstruction of existing buildings seems to not be a viable solution to this issue, since this approach encompasses the highest amount of resource loss. On the other side, the partial recovery and renewal of the building stock offers a more attractive and sustainable alternative [13]. It should also be noted that the advantages of a new construction may in some cases be lower in terms of the environmental impact (e.g., operational energy demand) compared to an existing building properly retrofitted [14]. Moreover, such an approach cannot be adopted for heritage constructions, whose cultural value has to be preserved while, at the same time, it is necessary to improve their conditions.

Regarding this, some solutions have been proposed in the literature, also taking into account the sustainability of such retrofitting interventions [15].

Past experiences have demonstrated that piecemeal interventions very often fail to address the complex requirements for safer, more energy-efficient and sustainable existing building stock [16]. Even though this has been the most common approach for retrofitting and remains the most widespread practice in the construction sector, recent extreme events (e.g., the earthquakes in southern Europe such as L'Aquila 2009 [17], Emilia 2012 [18] and Central Italy 2016 [19]) have highlighted its limitations and disadvantages. Collapses after earthquakes or the inadequacy of non-integrated retrofitting interventions showed how greatly they can reduce the effectiveness of the refurbishment, in many cases not allowing for a suitable functionality of the building. Renovation applied to solve specific and episodic building vulnerabilities may solve single deficiencies, but, in most cases, existing constructions exhibit multiple problems related to energy, architectural and structural issues. Therefore, a synergetic and sustainable solution is required for an integrated renovation of the building stock, to make it more durable and resilient both for current comfort needs and against the risk of future seismic events.

The integration of renovation strategies is not only a necessity but also an opportunity to achieve cost-effective solutions while minimizing disruption and environmental impact. This innovative approach is even more urgent in light of the European Union's goals to face the climate crisis [20]. Preliminary studies indicate the economic benefits that can derive from the application of combined solutions compared to piecemeal interventions. These include reduced payback periods and optimized costs [21,22]. Indeed, an integrated strategy can reduce the cost of the intervention works and the economic losses due to building damages after seismic events. Moreover, the integration of structural retrofit with energy efficiency measures involves a financial return over the years due to lower expenses during building use [23]. Despite such advantages, a unique and effective retrofitting technique meeting multiple requirements presents several difficulties, especially for more ancient constructions [24,25].

In the context of the circular economy, it is crucial to consider the entire building service life since the design phase [26], and this is also applicable to interventions on existing structures. The construction sector has indeed a high environmental impact that needs to be reduced to achieve important goals such as the mitigation of global warming consequences [27]. Such objectives may be pursued both at the material level, using eco-friendly or end-of-waste products [28] and at the global building level, improving its performance and reducing its energy consumption [29]. It can thus be argued that integrated seismic and energy retrofitting solutions based on the use of sustainable construction components are the direction that practitioners and stakeholders should aim for.

Further studies should be made on the use of more sustainable materials within integrated renovation solutions. Despite the increasing attention given to the concept of integrated retrofitting, researchers have not yet extensively explored the potential of combining the utilization of eco-friendly materials with holistic intervention solutions. Such an approach requires detailed investigations to assess both the performance and the compatibility of sustainable materials with combined refurbishment. Even if the obstacles and challenges of building retrofitting and sustainability are relevant, the advantages and benefits of such approaches may justify the huge effort and be a key point for the construction sector towards its modernization.

2. Integrated Retrofitting Solutions

In the last few decades, building stock renovation has become a crucial concern in the pursuit of modern, sustainable societies. This endeavour extends beyond mere architectural and functional refurbishment, encompassing fundamental aspects such as the structural safety, energy performance and environmental impact of existing constructions. Recently, researchers have started to investigate this multifaceted topic, proposing innovative approaches to address its challenges [30]. However, a comprehensive and universally effective solution is missing due to the complexity of the topic, and a research gap still exists, requiring further research for the development of optimized strategies. Although several discrete techniques to separately improve the energy (e.g., the application of thermal insulators) [31] and structural (e.g., global and local interventions) [32] performance of buildings have been widely used in the past and constitute the basis of current retrofitting practices, research is increasingly shifting its focus to integrated strategies that synergistically address both issues.

An additional advantage of this integrated approach to building renovation lies in its potential for cost-effectiveness, particularly when combined seismic and energy retrofitting is used in areas of moderate-to-high seismicity [33]. This is because the reduction in the energy consumption for heating and cooling achieved by thermal retrofitting is coupled with significant cost benefits arising from the minimization of potential economic losses due to the catastrophic effects of earthquakes as a result of seismic upgrading [10]. Indicative costs due to several options for integrated retrofitting have been proposed in [34] and are considered in the following overview, even if they may considerably change depending on the specific country and site conditions.

2.1. Exoskeletons

A possible solution involves the addition of steel exoskeletons combining conjunction with thermal systems and new façade elements for aesthetic renovation [35]. This approach has been previously proposed and applied for structural retrofitting demonstrating notable efficiency in terms of seismic capacity improvement, even for complex and tall buildings [36]. Recent studies have aimed at exploiting the inherent advantages of this solution within an optimized unified system [37,38] (see Figure 2a). This work allowed for attaining notable performance targets with respect to the maximum displacement and seismic load capacity reached [35].

A considerable advantage of exoskeletons is their external application, since it minimizes occupancy disruption. However, such installations may be more suitable for outskirts rather than high-density urban areas where spatial constraints and zoning regulations limit their constructability. Indeed, exoskeletons entail considerable additional area requirements which may not always be feasible amidst urban complexes of existing structures. Furthermore, they necessitate a substantial quantity of material, increasing the costs and carbon footprint of the intervention. Nonetheless, this solution allows for considerable architectural freedom in designing new façades and offers a high level of adaptability and reparability thanks to the modularity of the steel structure. This modularity not only enhances architectural flexibility but also contributes to environmental sustainability [39]. From a seismic perspective, integrated retrofitting with exoskeletons can lead to substantial improvements, with lateral load capacity enhancements ranging from 50% to 100% depending on specific building conditions [34]. Studies have demonstrated that buildings retrofitted with exoskeletons suffer considerably less damage and exhibit a noticeable increase in dissipation and/or the maximum seismic load capacity, depending on the type of intervention applied (i.e., elastic or dissipative response) [35].

The application of exoskeletons has been primarily studied for the case of reinforced concrete (RC) frames. The adaptation of this technique for the retrofitting of masonry structures poses certain technical challenges and has reduced efficiency due to the relatively low ductility of such constructions. Thus, a detailed assessment of the actual conditions of the building is necessary to evaluate the feasibility of this intervention, particularly for cultural heritage buildings where the preservation of the existing façades and exterior architectural features is of paramount importance [15]. Consequently, specific retrofitting solutions presenting a higher level of compatibility with the existing elements should be adopted for listed constructions.

A further advancement in this strategy involves the development of responsive exoskeletons, which can partially solve the low ductility issue of structural elements in masonry constructions. This technique allows for the design of structures to be passive by adopting sacrificial elements or active by employing actuators and seismic energy dissipation devices. Responsive exoskeletons are meant to modify their seismic response according to earthquake intensity, optimizing both the dimensioning and structural behaviour of the system while mitigating the risk of brittle failure in fragile existing elements. To overcome the issues associated with the high base shear forces generated in non-dissipative structures with hinges at the base, the use of adaptive–responsive diagrids has been proposed [40]. In this way, a controlled soft-storey mechanism is forced, and the structure is conceived to change its boundary conditions at the base depending on the seismic action. For higher levels of horizontal loading, a fixed amount of sliding is allowed by the activation of special supports at the foundation level to reduce seismic stresses and increase the displacement capacity of the building. This strategy presents considerable advantages for stiff constructions such as masonry. Nevertheless, preliminary works must be carried out on the existing structure, which increase the cost and time of the intervention. Moreover, sophisticated design methods must be used to accurately predict the seismic response of the retrofitted building, and a high level of knowledge regarding the existing conditions of materials and structural elements is required.

(**a**) (**b**)

Figure 2. Integrated seismic and energy retrofit: (**a**) combination of structural, energy and architectural renovation using steel exoskeletons [37]; (**b**) visual representation of RC shell external structure for integrated refurbishment proposed in [41].

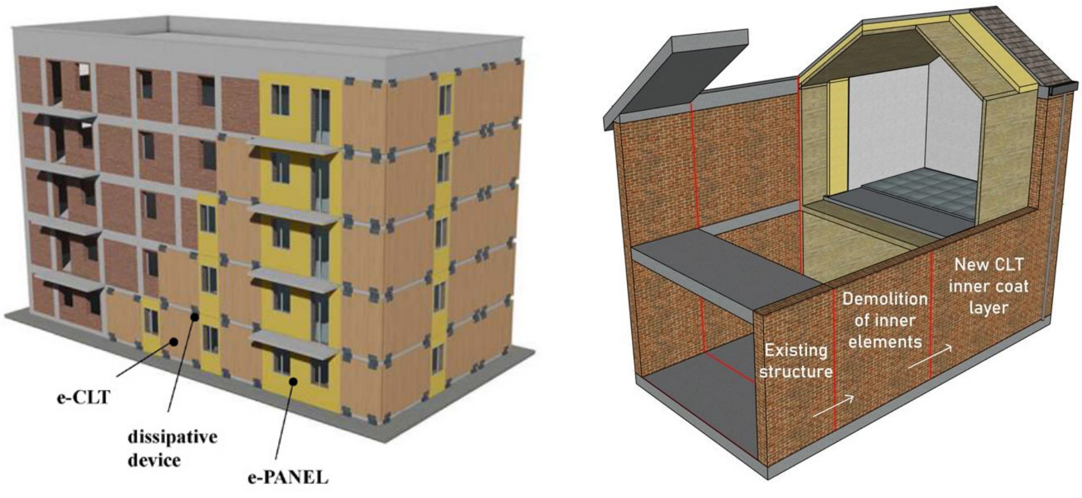
Regarding cost considerations, preliminary estimates for integrated retrofitting with exoskeletons may range between EUR 250 and 710 per m^2 of the building's floor area [34]. It should be noted that the need for new foundations to support the external structure can entail considerable additional costs compared to other renovation strategies and may pose technical challenges due to surrounding limitations.

While steel is the most commonly used material for exoskeletons due to its versatility and speed of assembly, proposals based on RC exoskeletons can be also found in the literature. For example, Pertile et al. [41] proposed a partially precast solution comprising insulation panels and steel rebars, with the RC inner layer cast on site using the thermal insulators as formwork. In this way, an external RC shell structure is formed (see Figure 2b). Albeit the increased stiffness of the new system results in somehow higher seismic demands, the retrofitting solution can at the same time drastically increase the horizontal load-bearing capacity of the existing structural elements and reduce their deformation under horizontal actions. Strengthening existing framed structures with RC exoskeletons has been shown to improve the seismic capacity by approximately 1.5 times in terms of the maximum base shear [42]. While offering advantages such as external intervention, adaptability to complex geometries and minimal disruption, RC exoskeletons may entail longer intervention times and reduced reversibility compared to steel counterparts.

2.2. Timber-Based Strategies

A promising and sustainable solution for integrated retrofit is offered by cross-laminated timber (CLT) panels [43]. The mechanical and thermal properties of this engineered wood product render it a reliable choice for such applications [44]. CLT is a prefabricated element that can be employed either internally or externally, requiring minimal time for intervention. While initial studies on this technology focused on applications for new constructions, promising results have been recently obtained from the use of CLT boards in structural renovation applications [45]. Proposals concerning their use for integrated retrofitting have highlighted that there is great potential to exploit the thermal properties of this product, alongside its mechanical characteristics.

In [46], an integrated retrofitting strategy was examined employing CLT boards for structural reinforcement together with insulating timber panels to improve the thermal performance of the original envelope (see Figure 3a). In terms of seismic capacity, CLT can limit the occurrence of brittle mechanisms in RC elements (e.g., short columns or soft storeys' failures), which are a typical failure in the presence of poorly detailed masonry infill walls [17], and enhance protection against the out-of-plane collapse of façades. The expected lateral load capacity improvement that can be achieved with timber-based panels ranges between 25% and 50%, depending on the effectiveness of the connection between the new elements and the structure as well as the initial condition of the building [34]. The potential drawbacks of this strategy may stem from the relatively low thermal performance of structural timber panels. The latter is often insufficient to meet the stringent requirements set in modern-day standards and ensure acceptable levels of indoor comfort. In this case, it may be necessary to consider thermal insulators specifically designed for this purpose, as proposed in [47], leading to an increased thickness of the retrofitted envelope. Moreover, special attention should be paid to the detailing of the connections between the CLT panels and the existing structure [44], as this typically turns out to be the weak point for the system.



(**a**) (**b**)

Figure 3. CLT panels for integrated retrofitting: (**a**) a conceptual representation of the solution proposed by Tardo and Margani [46]; (**b**) a schematization of work phases according to the "nested building" approach [48].

The cost evaluations for retrofitting solutions based on the use of timber panels range between EUR 350 and 500 per m^2 of the floor area [34]. While, in certain contexts, this solution may prove more economically favourable than steel exoskeletons, previous studies point towards a lower compatibility of CLT panels with incremental refurbishment and less potential for reparable interventions in comparison to alternative systems like steel exoskeletons [33].

The application of CLT panels for the internal retrofitting of constructions with listed envelopes has been examined in [48]. The solution proposed in this study involved the construction of a new internal CLT structure with enhanced seismic and thermal performance and has the advantage that it fully preserves the existing façade (see Figure 3b). Similar applications have been considered for the reuse of aged industrial buildings, facilitating the full renovation of deteriorated and abandoned constructions and providing them with new functions [49]. This method, which is termed "nested buildings", enables attaining performance levels comparable to new structures, both in terms of energy efficiency and seismic response. Nonetheless, considerations regarding the disadvantages of internal thermal insulation compared to external applications must be taken into account [50]. Furthermore, this intervention technique is quite intrusive since it requires the demolition of inner elements and slabs. This limits its applicability, particularly in the case of buildings whose internal finishing has a heritage value. For this reason, with respect to heritage constructions, "nested buildings" can find viable applications in historical city centres with masonry building aggregates, in which an external intervention is less feasible, and deep internal refurbishment is justifiable.

Other timber products different from CLT have been considered in the literature, such as oriented strand board (OSB) panels and laminated veneer lumber (LVL) [51,52]. Due to their lower costs and deadweight compared to CLT boards, such products may represent the most cost-effective strategy while maintaining satisfactory performance. However, research gaps pertaining to the thermal performance of OSB and LVL panels necessitate further investigation to assess the feasibility of their application for integrated renovation and provide a more detailed comparative analysis with CLT boards.

2.3. Composite Materials

In the last few decades, alongside conventional materials like steel, RC and timber, increasing attention has been paid to engineered composite materials [53]. Initially considered in mechanical and aerospace applications, the decreasing costs associated with the simplification of production processes and increased availability have enabled their extensive use in the construction sector, including building refurbishment [54]. A specific technique that is based on the use of an inorganic matrix, the textile-reinforced mortar (TRM) system, has been studied for applications on masonry envelopes and concrete elements, demonstrating promising performance in seismic strengthening and improved substrate compatibility compared to composites with organic matrixes (i.e., epoxy) [55].

The benefits brought by TRM systems in terms of seismic response have been experimentally validated for several configurations, allowing for the application of the retrofitting system either externally or internally, depending on the actual conditions of the specific building. It should be underlined that although external one-side applications offer the advantage of minimal occupancy disruption during the intervention, they may not provide a sufficient increase in terms of the seismic capacity. They may also induce buckling or out-of-plane phenomena which can nullify the benefits of the retrofit intervention [56].

Experimental investigations examining the performance of TRM systems combined with thermal insulators for integrated retrofitting (see Figure 4) [57] have verified that it is possible to improve both the response against horizontal actions and thermal efficiency. Notably, the application of this type of intervention on masonry walls can increase the lateral load capacity by 60% under in-plane actions and by 400% under out-of-plane actions, provided that suitable connections among the retrofitted elements are ensured [34]. In [58], the mechanical performance of several configuration schemes of a TRM-based integrated solution applied to a full-scale one-storey one-bay infilled RC frame has been assessed. The results obtained from the applications of two layers of TRM showed an increase of 45% in terms of the displacement capacity and 100% in the lateral resistance up to a 0.25% drift ratio compared to the unretrofitted frame.

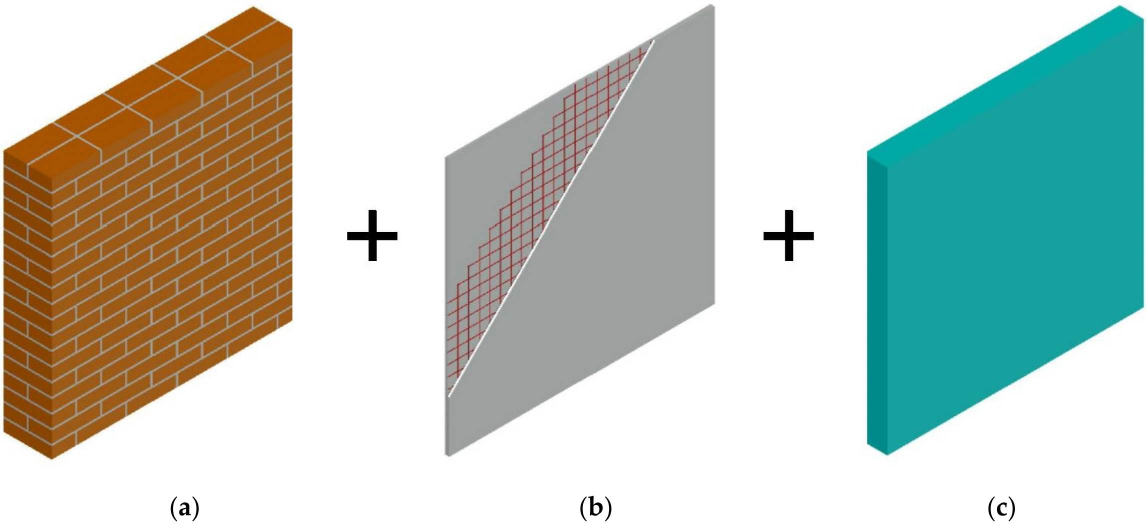


Figure 4. Conceptual scheme of integrated retrofit by means of composite materials: (**a**) existing envelope (brick masonry wall); (**b**) TRM system; and (**c**) thermal insulator (XPS).

Systematic investigations to assess the thermal performance of TRM systems incorporating insulators remain limited. Until now, proposals in the literature have mainly focused on commonly used insulation materials, such as Expanded Polystyrene (EPS). Even though conventional insulation products come at a reasonable cost and have proven thermal performance, they may entail a high environmental impact. Hence, embracing eco-friendly materials and solutions is imperative [59] in alignment with European and international objectives towards decarbonization and mitigating climate change consequences [6,20].

A different solution following prefabricated concepts has been proposed in [60] showing promising outputs. In this study, an integrated solution composed of a textile-reinforced concrete panel comprising an embedded capillary tube system has been applied to scaled RC infilled frames and masonry walls. The assessment of the RC frame's seismic capacity revealed a structural response similar to the strategy employing TRM and XPS panels, with an increase in the in-plane load resistance of 33% compared to the unreinforced structure. Concerning the thermal performance, the in situ characterization of the retrofitting solution showed that with this system, it was possible to maintain almost constant the indoor temperature at 20 °C, despite the reduction in the outdoor temperature.

From an economic standpoint, integrating TRM systems with thermal insulators proves highly competitive compared to other solutions. The estimated cost ranges between EUR 160 and 270 per m^2 of the envelope surface [34]. Cost estimations are influenced by the type of materials used and the existing conditions of the envelope; masonry substrates in poor condition require extensive repair before the reinforced plaster can be applied [54], and this may have a substantial impact on the overall cost.

As an alternative to the use of thermal insulation panels, energy performance may be enhanced using inorganic matrixes tailored to this purpose. Lime-based mortars, for instance, have been studied to combine mechanical and thermal functions in a single material, reducing the overall retrofitting system thickness and ensuring compatibility with masonry and ancient substrates [61]. A repair mortar including microencapsulated phase change materials (PCMs) has been studied in [62], showing the beneficial effects of PCMs both in terms of thermal properties (e.g., 65% reduction in thermal conductivity for the highest dosage compared to the reference mixture) and temperature regulating efficiency. Of course, developing mortars with adequately high thermal performance without compromising mechanical properties is a very complex task. In addition, the relatively low thickness of TRM layers (typically < 2 cm) practically precludes satisfying the energy code requirements with the use of a thermally enhanced mortar matrix alone.

Consequently, the use of thermal insulation remains the preferred option when meeting the thermal transmittance thresholds set in standards is a prerequisite.

The use of geopolymers has been considered as a means to overcome the significant reduction in mechanical performance generally caused by the modification of the mortar mix design required to achieve good thermal properties [63]. Geopolymers are inorganic aluminosilicates formed by alkaline activation to obtain a substitute for Portland cement (PC) and exhibit interesting properties, particularly in terms of thermal performance [64]. They are commonly produced using fly ash or metakaolin, thus contributing to reducing the environmental impact of the binder compared to PC, and their balanced mechanical and thermal properties make them a promising option for combined retrofitting. Despite advancements, certain challenges need to be addressed to enable the use of these materials on a large scale. Research studies observed reduced workability and short setting time, as well as a considerable sensitivity of the geopolymerization process and the generation of salts possibly detrimental for both humans and substrates [65]. Furthermore, the use of fly ashes for alkaline activation seems less convenient nowadays since a policy of the gradual closure of coal-fired power plants has been adopted in several European countries due to their high environmental impact, and therefore the availability of this by-product is expected to reduce [66]. Despite their balanced mechanical and thermal properties, geopolymers mortar matrixes have not reached adequately high levels of performance to allow for the complete substitution of thermal insulators. Recent studies investigated the performance of an integrated solution employing geopolymer-based TRM together with a thermal insulation system, showing advantages also in terms of structural response (e.g., out-of-plane capacity) thanks to the increased lever arm of the TRM layer position with respect to the substrate [67].

2.4. Alternative Strategies for RC Buildings

In addition to the aforementioned solutions, various strategies have been specifically proposed for applications in RC frame buildings. In [68], the substitution of the existing envelope made of infill masonry walls with autoclaved aerated concrete (AAC) blocks was considered, with the intervention being carried out externally. The use of AAC blocks with low thermal conductivity and deadweight enabled improving thermal performance and reducing the seismic inertia forces generated by the excitation of the infill elements. Another advantage of this solution lies in the reduced cost of the intervention, which can range between EUR 120 and 150 per m^2 of the envelope surface [34]. However, cost savings are offset by the high environmental impact resulting from the considerable amount of waste materials generated by the demolition of the existing elements. This is in contrast with the need for higher sustainability in the construction sector and the reduction in residues at a minimum to limit climate change consequences [69]. Additionally, limitations regarding the dynamic response of AAC structures and the achievable thermal and seismic enhancements restrict the benefits of their application for integrated retrofitting. The anticipated lateral load capacity increases by a range between 50% and 100% for in-plane and 300% and 400% for out-of-plane effects [34].

Following a similar concept, a composite sandwich panel formed of steel fibre-reinforced micro-concrete for structural reinforcement and a polystyrene inner layer for thermal performance enhancement was developed in [70]. With this system, which replaces the existing infill walls in RC frames, it is possible to greatly improve the seismic and energy responses of the original building, meeting code requirements. However, potential limitations of this method, as well as the previous one, stem from the need to partially demolish the old envelope and the complexity of realizing such interventions for building typologies other than RC frames.

Another proposed approach consists of a solution composed of steel omega profiles anchored to the RC elements of the existing frame to improve the out-of-plane capacity of the masonry infill [71]. At the same time, such a system supports 3D-printed thermoplastic panels developed to enhance the thermal performance of the existing envelope, as well as for architectural renovation. Concerning the seismic behaviour, this system can increase by almost 50% the out-of-plane capacity of the infill walls, while, for the thermal response, it is possible to satisfy the minimum requirements provided by the standards in terms of thermal transmittance, also resorting to incremental renovation by increasing the panel thickness. This modular solution combines the benefits of integrated retrofitting with those of prefabrication (e.g., following circular economy principles), minimizing the intrusiveness of the intervention and avoiding the need for complete wall replacement.

3. Materials for Integrated Retrofitting

In addition to the advantages of integrated seismic and energy retrofitting strategies, a further opportunity lies in the adoption of sustainable materials. Several eco-friendly solutions have been proposed in the literature, warranting greater attention and in-depth studies to assess the suitability of their practical application. These eco-friendly products can be incorporated into the retrofitting solution in different ways, including their integration into cementitious materials for the partial replacement of aggregates [72] and the development of innovative thermal insulators utilizing by-products or vegetal materials [73].

Traditionally, virgin river sand and natural stone serve as primary aggregates in concrete and mortar mixtures. However, the intensive exploitation of these natural resources has led over the years to their overutilization with the consequent risk of depletion, which is especially evident in several regions at the local level [74]. The impact of such phenomena is multifaceted, encompassing sustainability concerns alongside economic and social damages. Considering the environmental consequences of river sand mining, the process employed to obtain raw materials involves deforestation, the loss of biodiversity, soil erosion and air pollution, as well as a higher hydrologic risk [75]. To mitigate these issues, the utilization of alternative raw materials and the assessment of the environmental performance of resulting mixtures have been studied in the literature, often employing life cycle analysis (LCA) tools to compare them with traditional materials [76].

3.1. Sustainable Aggregates

3.1.1. Rice Husks

The incorporation of vegetal additives in mortars has been investigated by Quintaliani et al. [77], with emphasis on the experimental characterization of the thermal and acoustic properties of such mixtures. More specifically, the study considered lime-based mortars incorporating rice husk, spelled bran and Khorasan wheat chaff in different sizes, which allowed them to achieve good thermal and acoustic performance. The mixture including rice husk in ground form resulted in an M5 mortar with a thermal conductivity (λ) of 0.531 W/mK. The beneficial effect of rice husks (see Figure 5a) has been confirmed by other studies, which have also considered the influence on mechanical performance [78,79]. Marques et al. [79] considered a cement-based mortar containing rice husk, achieving a thermal conductivity of 0.355 W/mK and a compressive strength of 9.34 MPa. The high silica content of this raw material [80] renders it a promising solution for mitigating the drop in mechanical strength, which is mainly caused by the increased porosity and lower strength that it exhibits compared to conventional aggregates (i.e., sand). Moreover, rice husk is a renewable waste material with large availability in several countries, with limited disposal options besides landfills [81]. Therefore, its use in substituting virgin sand is not only a promising solution but also a significant opportunity. Furthermore, rice husk ash has been proposed as an alternative to fly ash in producing geopolymer mortars [81] yielding promising results but with limitations similar to those associated with geopolymer binders, as previously discussed.

(**a**) (**b**) (**c**) (**d**)

Figure 5. Sustainable aggregates (**a**) rice husks; (**b**) hemp hurds; (**c**) cork granulates; and (**d**) spent coffee grounds.

3.1.2. Hemp Hurds

Another option investigated in the literature involves the incorporation of hemp-based products into concrete and mortar mixes [82–84]. The components of the hemp plant mostly used for applications in the construction sector are the hurds of the plant (Figure 5b). The latter are obtained from industrial processing and exhibit some promising properties that have been studied by many authors [85]. These hemp-based products have already found several applications in the construction sector, including the manufacturing of sustainable bricks, primarily valued for their thermal functions [86]. Studies focusing on cementitious materials containing hemp aggregates report thermal conductivity values ranging from 0.06 to 0.18 W/mK [85]. However, the achieved mechanical performance still falls short of the requirements for structural applications, with compressive strength values generally being lower compared to mixtures containing other vegetal products such as rice husks (see Table 1).

Given the limitation in mechanical properties, the use of hemp-based mortars for integrated retrofitting appears restricted compared to other materials. Nevertheless, their employment in combination with other products may be viable to achieve the required balanced performance in terms of structural and thermal functions. Indeed, products incorporating hemp aggregates also showed other advantages deserving to be exploited, namely remarkable durability under accelerating aging tests [87].

3.1.3. Cork Granulates

Alternatively, the addition of cork granulates (see Figure 5c) may offer a viable solution to improve the thermal behaviour of mortars. The effects of the partial substitution of sand with cork in cement-based mixtures have been investigated in [88], showing a considerable decrease in the mechanical performance at 28 days. Indeed, the compressive strength of all the mixtures containing cork was <50% of the control mixture. However, it was possible to reduce thermal conductivity by approximately 30% with a 20% dosage of cork inclusion. In another study, Brás et al. [89] compared the inclusion of cork granulates with that of EPS in cement-based mortars, showing the beneficial effect of cork in terms of thermal conductivity (see Table 1). Moreover, mortar mixtures with cork grains exhibited superior mechanical properties compared to those containing EPS. It can thus be argued that the inclusion of cork in inorganic matrixes represents a promising option from a thermal performance standpoint, in addition to being a renewable resource. Exploring options beyond the use of cork granulates, some researchers studied the addition of cork powder in self-compacting concrete [90]. However, it is important to note that the natural process of cork creation from oak bark takes approximately nine years, and cork is primarily concentrated in a few areas of the world, with Portugal being the largest producer accounting for around 50% of total production [89]. In addition, cork waste from the manufacturing process has several applications, mainly in the incorporation of granulates in panels for insulation purposes. Moreover, there are still few studies in the literature concerning the durability of cork granulates included in mortar mixes [88], necessitating further research to properly assess the durability of mortars incorporating cork granulates and to identify suitable measures for protection against biological attacks (e.g., fungi) [91].

3.1.4. Coffee Grounds

Spent coffee grounds constitute another waste material that is considerably abundant and has been recently considered for similar applications (see Figure 5d). Coffee, being one of the most consumed beverages around the world, generates significant by-products during both its manufacture and consumption processes, necessitating proper disposal methods other than landfills [92]. Some researchers proposed to incorporate coffee grounds into clay bricks to increase their insulating properties while maintaining acceptable mechanical characteristics. In [93], it has been shown that low amounts of coffee grounds form open-cell porosity in the bricks, thus resulting in worse mechanical and thermal performances. On the contrary, higher quantities create mainly closed-cell porosity, improving the thermal behaviour and presenting suitable mechanical properties for optimal percentages of the coffee grounds' addition.

A further application of this waste product has been studied for the partial substitution of sand in mortar mixes, demonstrating the possible thermal insulation improvement produced by this addition [94]. It has been shown that the inclusion of coffee grounds involves an increase in water demand to achieve adequate workability, making necessary the addition of suitable plasticizers to avoid excessive reduction in the mechanical properties of the mortar. Despite this, the study highlighted the improvement in the material insulation performance (i.e., reduction in thermal conductivity) and the lower environmental impact associated with the use of this by-product instead of virgin sand. However, for high amounts of coffee grounds, the mechanical performance becomes very poor, which suggests limiting its percentage to 5% by volume according to La Scalia et al. [94]. In this study, a thermal conductivity of 0.46 W/mK and a compressive strength equal to 12.4 MPa were obtained for a natural hydraulic lime (NHL) mortar with 5% coffee grounds included. Compared to the reference mixture with no coffee addition, the corresponding parameters were reduced by 16% and 12% for the thermal conductivity and the compressive strength, respectively (see Table 1). This shows the considerable potential that such a product may have for application in mortar mixes.

The possible pre-processing of spent coffee grounds to improve the main properties of this product for its inclusion in concrete mixtures has been investigated in [95]. Pyrolyzing coffee grounds was applied to reduce the organic content of the material, which hinders the hydration process of the binder particles. The results demonstrated the beneficial effects of the thermal treatment in the compressive strength attained by the end-product. The mechanical performance of control mixtures improved with the inclusion of treated coffee grounds, depending on the pyrolysis temperature used. Conversely, the concrete mixtures containing untreated grounds exhibited a considerable reduction in performance with increased substitution dosages. Further analysis should be carried out to assess the effects of the pyrolysis process on thermal performance, which may justify the possible suitability of coffee grounds for integrated retrofitting.

Similar to cork granulates, durability concerns may arise with spent coffee grounds due to potential biological colonization in moist conditions, such as those present in fresh mortars. However, pre-processing to reduce the organic content may also enhance the durability performance of coffee-based mixtures, though this requires verification through future studies.

3.1.5. Other Types of Aggregates

A possible answer to reduce the high quantity of waste produced by the demolition of existing buildings is represented by the use of recycled concrete aggregates in mortar mixes [96]. On one hand, this enables reducing the amount of natural resources employed in the construction sector and, on the other, it is an opportunity to find a proper allocation to a by-product that would be otherwise disposed in landfills. Several researchers examined the mechanical performance of concrete and mortar mixtures incorporating such recycled aggregates [97–99]. Samiei et al. [97] considered an increasing substitution of fine natural aggregates with recycled concrete aggregates in cement and blended cement–lime mortars. This resulted in the worsening of mechanical performance for cement mortars, while for the blended mixtures, the increasing amount of recycling aggregates had a beneficial effect with an improvement in mechanical properties of up to 60% (see Table 1). This was attributed to the synergic action of lime hydraulicity and the filler effect of the recycled aggregate fine fraction, leading to a higher densification of the lime mortars. Similarly, Restuccia et al. [98] studied the addition of the fine fraction of coarse recycled aggregates, also called recycled sand. The research examined the effects of washing and sieving on the quality enhancement of recycled aggregates. The findings indicated that these processes can indeed lead to an improvement in aggregate quality.

In any case, studies concerning the incorporation of recycled concrete aggregates in mortar mixtures did not demonstrate beneficial effects in terms of thermal performance, as expected. Nonetheless, the positive consequence is its higher sustainability due to the utilization of a waste product.

Expanded perlite is a natural material that offers promise in improving the thermal properties of mortars. This is a volcanic stone that has a cellular structure presenting micro air voids and exhibits low thermal conductivity in the range of 0.04–0.06 W/mK [100]. Such values of thermal conductivity are much lower compared to other mineral stones, while the density of the loose material is between 80 and 150 kg/m^3 [101]. Given its low density, expanded perlite is used as a lightweight material in walls and roofs and has been considered for addition in mortars by some authors, yielding some promising results [100,102–104]. Govaerts et al. [105] proposed the use of a lime-based insulating render incorporating perlite for the thermal retrofit of heritage buildings and studied the hygrothermal performance of such a material. It was found that the insulating render with perlite causes lower shifts in temperature compared to the historic mortars but with an increased moisture level of the support, thus requiring special care in the design phase. Yu et al. [106] studied the pozzolanic effect of perlite powder on the compressive strength of concrete mixtures. They examined different mix designs and considered other mineral additives as well. Their results showed a significant pozzolanic effect by natural perlite powder, indicating that this material can be used as an active mineral admixture in cementitious mixtures. The outcomes of this investigation are limited to cement concrete; therefore, further studies are required to assess the effect of perlite on other types of mixtures, such as lime-based mortars. Even if it cannot be considered an actual sustainable product since it is a virgin stone, its use in mortar mixes instead of sand greatly improves the thermal performance and sound insulation of the mortar thanks to its light weight. However, it produces a decrease in mechanical properties, so requiring a proper balance according to the intended employment of the mortar (e.g., rendering or structural purposes); see Table 1.

Table 1. Lightweight and recycled aggregates for the improvement of mortar thermal performance: used binders with ranges of thermal conductivity and compressive strength at 28 days derived from studies in the literature.

Material	Main Binder	Thermal Conductivity [W/mK]	Compressive Strength [MPa]	Refs.
Rice husk	Cement/hydraulic lime	0.36–0.53	5.0–9.3	[77,79]
Hemp hurds	Lime	0.06–0.18	1.4–4.7 *	[85]
Cork granulates	Lime	0.10–0.80	0.4–1.0	[89]
Coffee grounds	Hydraulic lime	0.29–0.46	2.2–12.4	[94]
Expanded perlite	Cement + lime	0.12–0.91	2.9–7.8	[104]
Recycled concrete	Cement/lime	N/A	5.0–8.0	[97]
PCMs	Cement	0.59–1.07	14.4–37.0	[62]
PET waste	Cement/lime	0.09–0.27	1.9–21.4	[107]
EPS beads	Cement	0.14–0.25	4.0	[108]

* Cylindrical samples.

Recycled plastic has also emerged as a potential material for enhancing thermal performance in building components. The huge amount of yearly plastic production worldwide requires alternative options for its treatment given the massive environmental impact derived from its disposal in landfills. The reuse of plastic at the end of its life cycle will thus fall within circular economy principles towards more responsible waste management [109]. Moreover, the benefits in terms of sustainability that can be obtained from plastic recycling may be further increased if its employment in building components provides an enhancement of their thermal performance. The incorporation of polyethylene terephthalate (PET) waste is an interesting option in this field since it enables reducing the thermal conductivity of cementitious materials by employing a by-product [107,110]. In [107], the virgin aggregates of cement- and lime-based mortars containing silica fume were substituted by increasing dosages of plastic waste. The authors found that the inclusion of plastic produced a decrease in mechanical performance but could also reduce thermal conductivity up to 76% compared to the reference mixture. Analogously, in [108], a cement-based mortar containing EPS beads has been investigated showing considerable advantages in terms of thermal performance, which were also accompanied by a considerable reduction in the compressive strength with an 80% decrease compared to the reference mortar (see Table 1).

The values of thermal conductivity and compressive strength obtained from studies in the literature for some of the materials here considered are summarized in Table 1. It can be noticed that the two parameters are inversely correlated, and a proper balance is hard to find in the same material for applications in integrated retrofitting solutions. However, it can be observed that the development and characterization of mortars including new and eco-friendly materials is an appealing topic among researchers trying to provide an answer to such an increasing need towards a more sustainable and efficient construction sector.

3.2. Traditional vs. Alternative Thermal Insulators

3.2.1. Ordinary Thermal Insulators

As demonstrated previously, materials with dual functions, serving both structural and thermal roles, often struggle to meet the current energy performance requirements of buildings without compromising mechanical properties to an extent unsuitable for structural applications. For this reason, thermal insulators still seem a necessary option in the field of building retrofitting, even if appropriate choices can foster the advantages of their use in an integrated renovation.

Numerous solutions for thermal insulation have been proposed over the last few decades [101,111]. Nowadays, the most common products applied on new and existing buildings are represented by EPS and XPS (see Figure 6a), whose good thermal performance combined with the affordable price makes them an attractive option [112]. However, the environmental impact associated with their production and final disposal is an aspect that is gaining increasing importance in the choice of the products to apply (see Table 2), thus requiring a further assessment to consider more sustainable solutions [73,113]. Additionally, researchers tried to assess the possible contribution of ordinary insulation panels to the in-plane performance of masonry walls subjected to seismic loading [114]. It has been observed that the flexibility of the insulator prevents significant damage to the insulation product itself. Moreover, the in-plane stiffness and the shear capacity of the insulated masonry walls increased, the latter in the range of 50–65% according to the insulator used. This was explained by the contribution of the mortar layer used for the adhesion between the wall and the insulator. Despite the promising results achieved, further investigation is still required to properly validate such outputs.

(**a**) (**b**) (**c**)

Figure 6. Thermal insulators: (**a**) extruded polystyrene (XPS); (**b**) wood fibreboard; and (**c**) expanded cork panel.

Rock wool, an inorganic fibrous material available as filler or boards, remains a widely used traditional solution for thermal insulation [115]. Presenting a relatively low value of thermal conductivity (see Table 2), it is a versatile product that can be perforated, cut or adjusted at the building site without any loss of thermal resistance. Moreover, it generally involves lower environmental costs compared to polystyrene, even if the measures for its disposal at the end of life and its damaging health aspects need some considerations concerning its use in the future [116]. Some proposals have been carried out to study other uses and potentials of mineral wool waste, such as their inclusion into plaster matrixes [117], according to circular economy principles.

A commonly used insulation material exhibiting interesting performance from the thermal point of view is polyurethane, a product formed by the reaction between isocyanates and polyols, with the addition of expansion gas which fills the closed pores during the expansion process [111]. Manufactured as boards or as a foam, its low thermal conductivity, between 0.025 and 0.0.046 W/mK, compared to XPS or rock wool, makes it a good option in order to achieve a high thermal performance of building envelopes [118]. However, it should be considered that strong health hazards arise from this material when exposed to fire, since polyurethane releases hydrogen cyanide and carbon monoxide when burning, as well as other toxic products [119]. This is a strong limitation for the practical application of this material, which on the contrary would be safe in its normal use. Furthermore, an important issue arises from environmental concerns since, like polystyrene, it is formed by petroleum-based raw materials whose extraction, manufacturing and disposal at the end of life strongly contribute to pollution. Nonetheless, in the last few years, research works studied the incorporation of alternative products into polyurethane to reduce its environmental impact, such as by the use of eggshell waste [120].

3.2.2. Alternative Insulators

Although traditional options exhibit good performance with low values of thermal conductivity, most of them present high environmental impacts due to their production and/or final disposal. Indeed, the assessment of insulating materials should go beyond their thermal performance and consider their environmental sustainability [121]. For this reason, several products have been developed adopting recycled and/or waste products and are nowadays available on the market. Asdrubali et al. [73] reviewed the development of such "unconventional" sustainable building insulators, highlighting the environmental advantages of such products. The latter include the local availability of materials, the use of industrial by-products, limiting transportation and minimizing disposal impacts. Indeed, the use of locally available products can further reduce their environmental impact, as well as support the local economy [122].

An example is cellulose, a natural polysaccharide constituting paper and wood, from which it is possible to make thermal insulators. Similar to rock wool, it is possible to produce both fibre boards and filler materials. However, cellulose natural products either from virgin resources or recycled ones are used, thus fostering its competitivity against synthetic materials [123]. Some authors suggested that the environmental impact in terms of the greenhouse gas emission and embodied energy of insulation materials made of cellulose fibers is lower than traditional solutions, including rock wool [124]. However, this strongly depends on the materials used (e.g., resins) and the process employed for the fabrication of these panels, which can greatly affect their impact over the entire life cycle of the insulator [116]. As a matter of fact, it is possible to use wood residues from the sawmill industry and forest maintenance operations for the production of natural and eco-friendly insulators fostering the recycling of wood by-products and avoiding incineration at the end of their useful life. Insulators made of cellulose can be cut and perforated at the construction site without any loss of thermal resistance, thus allowing for a considerable versatility of this material. The main drawback of cellulose is its high sensitivity to environmental conditions, especially to temperature and moisture [125]. As for solid wood, the hygroscopic behaviour of cellulose causes significant dimensional changes both at the micro- and macro-structural levels. An increase in the moisture content from 0% vol. to 5% vol. may thus increase the thermal conductivity from 0.040 W/mK to 0.066 W/mK [111].

Wood fibreboard (see Figure 6b) is a type of engineered wood made of wood fibres of various densities, from low- to high-density fibreboards, which represent a promising product for thermal insulation purposes (see Table 2). Given the small size of cellulose fibres, it is possible to achieve good energy performance, improving the thermal properties obtained from solid wood or other structural timber products. Several authors have proposed solutions to enhance the thermal properties of wood fibreboards, adopting, for instance, ultra-low-density solutions [126], and more sustainable components have been suggested [127]. However, moisture sensibility and thus durability still remain great obstacles to the long-term efficiency of this product, also because current commercial solutions adopt environmentally harmful substances (e.g., paraffin, bitumen) [128], therefore requiring greener and bio-based additions to be developed and studied. As an alternative to employing a binder, the lignin of wood can be activated using aluminium sulphate, also acting as a pesticide and anti-moth agent [101]. In [116], the authors estimated that the substitution of conventional resins with natural products would reduce the equivalent emissions of CO_2 at 46% for fibreboards.

Another natural product is cork (see Figure 6c), whose granulates can be used either for filler material or to make thermal insulation boards with good durability performance [129]. Produced from the cork oak, it achieves remarkable thermal properties (see Table 2). Exhibiting an acceptable compressive strength, cork represents an excellent insulation material under compressive loads. It is also characterized by good acoustic properties for impact and airborne insulation, as well as sound absorption [130]. Natural or expanded cork agglomerates present low thermal diffusivity, providing higher thermal delays than other traditional insulators like XPS [131]. This implies a considerable improvement in the thermal performance of the building envelope, especially when used in constructions exposed to variable thermal conditions, such as in temperate climates. Cork boards are often inserted in external thermal insulation composite systems (ETICSs) in substitution of traditional and less sustainable products (e.g., EPS and XPS).

Simões et al. [129] studied the mechanical and thermal performance of uncoated cork expanded boards exposed to external environmental conditions and their trend over time. They found that medium-density cork boards are suitable for the uncoated external insulation of building façades, thanks to their good mechanical properties combined with satisfactory hygrothermal behaviour. Their reasonable durability was demonstrated given their resistance to long-term exposure to external conditions. Regarding short-term behaviour, Tadeu et al. [132] found numerically that moisture variations are limited to the outer surface layers of the expanded cork boards, while for high moisture content levels to be maintained internally, it is necessary to have considerable outer humidity levels for long periods. Despite their good durability, Barreca et al. [133] proposed a bio-based render for agglomerated cork insulating panels to protect them from damage and sun radiation.

Concerning the environmental impact of cork-based insulation boards, Silvestre et al. [134] applied a cradle-to-grave life cycle analysis (LCA) and analyzed the results per the life cycle stage. They found that cork boards have a low contribution to several impact categories when compared to other insulators, such as EPS (see Table 2). In particular, the production of cork products requires a lower consumption of fossil fuels, as well as a lower global warming potential over a 100-year period. However, it is necessary to consider the context where this material is employed since the production of cork is concentrated in few areas of the world (mainly Portugal and the Mediterranean area [135]), and its application in regions where this product is uncommon may involve much higher environmental impacts due to transportation.

Several other sustainable insulation solutions have been studied and proposed in the literature, many of which still require further research and development before being applied in practice. Overall, the increasing attention towards vegetal and natural products by researchers and stakeholders should be underlined. For instance, hemp fibres have been proposed for building insulators, given the good thermal conductivity that can be achieved for hemp-based products as well as their low environmental impact (see Table 2). Among several ecological aspects, hemp biodegradability is an important benefit that allows for a better end-of-life treatment of such products [136] but at the same time, may involve lower durability over time. Indeed, as typical for vegetal materials, protection against moisture uptake is required, as well as adequate measures against rodents, insects and fungi attacks.

Other applications imply the use of flax fibres, namely to produce insulation panels with satisfactory thermal performance (see Table 2). Moreover, thanks to the elasticity of its fibres, flax products can be used as acoustic and impact sound insulators [130]. The combination of flax and hemp results in a high-performance insulation material, with the best performing products achieving values of thermal conductivity equal to 0.033 W/mK [101]. Some authors proposed the use of rice husks for composite insulation boards, obtaining values of thermal conductivity ranging from 0.060 to 0.074 W/mK [137,138]. The mechanical, thermal and acoustic properties of such products have been studied considering several mixing ratios with other waste materials as well. Moreover, the addition of expanded cork granulates has been investigated, performing a multi-criteria analysis to select the most suitable composite formulation [139].

Finally, promising results have been obtained from the development of recycled synthetic materials or adopting industrial by-products, trying to reduce the use of virgin materials and the environmental impact due to disposal in landfills. Recycled plastic, such as PET, which is one of the most produced plastic products, has shown good thermal performance (thermal conductivity between 0.034 and 0.039 W/mK) [73], in combination with the reduction in energy consumption and global warming potential as demonstrated by LCA [140]. Other wastes such as recycled textile fibres, largely available and produced from manufacturing (e.g., cotton), have been proposed to face the urgent need for reduction in waste disposal in landfills and find a proper reuse for them with encouraging thermal performance [141] (thermal conductivity between 0.041 and 0.053 W/mK).

The typical ranges of thermal conductivity for some thermal insulators with their associated embodied energy are reported in Table 2. The latter is indeed a fundamental parameter for an overall assessment of a building insulator, which cannot be limited to its thermal performance. In addition, a graphical comparison of the embodied energy of traditional and less conventional thermal insulation materials is reported in Figure 7. As it can be seen, the embodied energy of some unconventional insulators is still comparable with that of more ordinary products (e.g., rock wool), which require more optimized processing to reduce their environmental impact. It should also be noted that the values of embodied energy obtained from studies in the literature refer to different LCA methodologies (i.e., cradle-to-gate or cradle-to-grave), which may alter the results and make the comparison unfair in some cases. These are here reported with the aim of providing an overview of the sustainability presented by each product, which may considerably differ according to the specific context and production process.

Table 2. Typical ranges of thermal conductivity for some traditional, natural-based and recycled insulation materials with their associated embodied energy.

Material	Thermal Conductivity [W/mK]	Embodied Energy [MJ/kg]	Refs.
Expanded polystyrene (EPS)	0.031–0.038	105.486 (CTGR)	[112,116]
Rock wool	0.033–0.040	26.393 (CTGR)	[115,116]
Wood fibres	0.038–0.050	25.0 (CTGA)	[113,142]
Cork	0.037–0.050	51.517 (CTGR)	[101,116]
Hemp	0.038–0.060	15.00 (CTGA)	[101,143]
Flax	0.038–0.075	39.50 (CTGA)	[101,136,144]
Waste paper + textile fibres (wP and T)	0.034–0.039	18.17 (CTGA)	[143]

CTGA stands for cradle-to-gate; CTGR stands for cradle-to-grave.

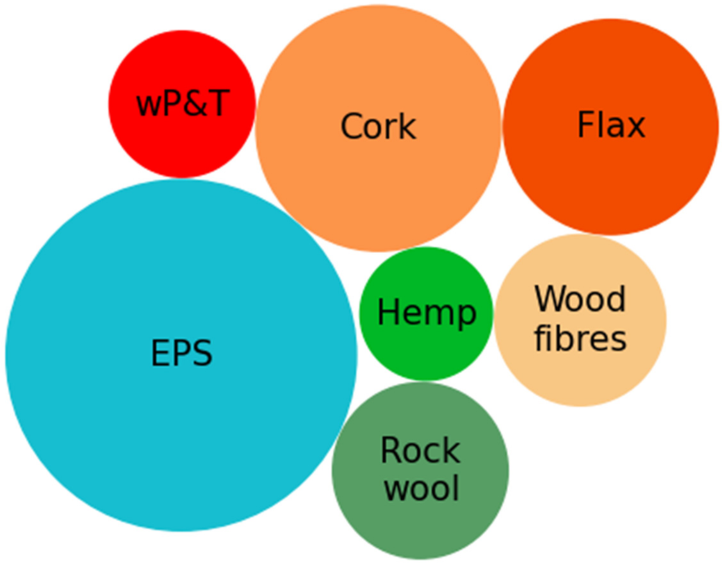


Figure 7. Embodied energy [MJ/kg] of traditional, natural-based and recycled thermal insulators (bubble chart representation).

Although many eco-friendly solutions have been proposed in the literature, an important limitation to the widespread application of eco-friendly insulators seems to be their slightly lower thermal performance compared to traditional synthetic materials and their durability, which needs further investigation. Moreover, some authors identified the main reason for this in a common inertia in the use of ordinary products, also justified by a more structured commercial network that allows for lower prices for traditional insulation materials [116]. It seems that a shift of the paradigm is necessary towards a gradual transition to more sustainable building products, also involving producers and the main stakeholders of the construction area. This, together with the increasing adoption of integrated seismic and energy retrofitting solutions, will be a key issue in the future of the building sector.

4. Final Remarks

This paper presents a comprehensive discussion of the main challenges and opportunities associated with the adoption of integrated retrofitting techniques and sustainable materials. It reviews the literature on materials and solutions for integrated seismic and energy renovation, showing various possibilities and ways of application. Compared to traditional piecemeal intervention approaches, combined techniques allow for the improvement in building performance both in terms of the structural capacity and thermal efficiency boosting the effectiveness and time of the intervention.

Considering the current vulnerabilities of the building stock, as well as standard requirements for seismic capacity upgrades and energy performance, integrated strategies seem to be the ideal option for building retrofitting. Many strategies have been proposed in the literature, demonstrating an increasing interest in the topic by researchers and stakeholders, aiming at applying such innovative techniques in practice. However, several obstacles remain, complicating the development of effective solutions in this field.

This paper explores proposals for integrated refurbishment and the employment of eco-friendly materials, such as mortar matrixes with enhanced properties, able to combine suitable mechanical and thermal responses. It is possible to achieve suitable performance at the building level in terms of structural and energy behaviour starting from its components, reducing at the same time the environmental impact of the retrofitting solution. However, the demanding requirements in terms of structural and thermal properties make the development of a material with combined and balanced performance complex, and such limitations still seem to require the employment of thermal insulators within an integrated renovation system. With such an innovative solution, it is possible to avoid the use of high-performing traditional products thanks to the contribution of the structural component to the energy function. For this reason, alternative options for the thermal insulation of buildings have been shown as well, allowing for the combination of the benefits of thermal refurbishment in terms of energy saving and comfort with a lower environmental impact.

The gradual substitution of traditional materials with more sustainable products will be a key aspect in the coming years for future gradual decarbonization within the construction sector. This paper pointed out the gaps that still exist concerning materials and solutions for integrated renovation, as well as the opportunities to promote further research and applications toward the development of efficient products and techniques presenting lower environmental costs. The future of the building sector cannot miss the chance to join such two aspects to meet the ambitious targets required by modern societies and international goals to face the climatic challenge.

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