Lecture Notes in Civil Engineering

Rossella Corrao · Tiziana Campisi · Simona Colajanni · Manfredi Saeli · Calogero Vinci *Editors*

Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering)

Colloqui.AT.e 2024 - Volume 2

Springer

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ISSN 2366-2557 ISSN 2366-2565 (electronic)
Lecture Notes in Civil Engineering
ISBN 978-3-031-71862-5 ISBN 978-3-031-71863-2 (eBook)
https://doi.org/10.1007/978-3-031-71863-2

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Contents

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Implementing Circular Economy Strategies for Applications in Construction: Optimizing Cellulose-Based Waste in Building Materials

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Abstract. Integrating wastes in construction and building materials represents a promising possibility to implement circular economy (CE) in construction. This approach, conceived to find a solution to the massive waste generation, is recognized for its sustainability and efficiency as it exploits unused materials as valuable resources for the production of novel building materials. In this context, special attention is given to cellulose fibres, used for their lightweight nature and mechanical strength that can be exploited to improve materials performance for applications in construction. This paper offers an overview on cellulose-based wastes use in construction, exploring characteristics and potential applications. As some relevant examples, cellulose fibres can serve as lightening elements in building blocks and reinforcement in cementitious composites. Moreover, cellulose fibres show a high-energy performance with reduced environmental impact compared to other insulating materials. Furthermore, that significantly contributes to the energy efficiency in buildings. In order to decrease reliance on virgin fibres, three types of cellulose-based wastes are discussed: olive stones (as agricultural waste), waste-paper (as municipal waste), and paper industry by-products (as industrial waste). The analysed residues, that integrate technological innovation and environmental awareness, outline a prospective scenario in which the development of novel construction materials is in line with the environmental standards, following the principles of the CE and energy efficiency strategies. This study is component of two PhD theses focusing on the reutilisation of wastes from various sectors in the field of building materials. More particularly, one of these is developed under the National Recovery and Resilience Plan (PNRR) and is aimed at investigating green solutions to improve the energy efficiency in buildings by valorising and reusing secondary raw materials.

Keywords: Circular economy · Building materials · Cellulose waste · Olive waste · Paper waste

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R. Corrao et al. (Eds.): Colloqui.AT.e 2024, LNCE 611, pp. 69–85, 2025.
https://doi.org/10.1007/978-3-031-71863-2_5

1 Introduction

The uncontrolled consumption of resources and the increasing energy demand significantly impact the environment, causing climate change and other disastrous consequences. The construction sector emerges as a key industry for the implementation of strategies to achieve global sustainable development goals, especially considering the growing challenges associated with climate change [1, 2]. It is widely acknowledged that the construction sector makes a substantial contribution to CO_2 emissions and energy consumption, while also generating a massive volume of diverse wastes annually. The management and disposal of such enormous waste raise significant concerns and consume considerable amounts of energy.

Furthermore, in the European context, approximately 75% of the existing building stock is energy inefficient. This fact indicates that a considerable amount of energy used in the operation of buildings is currently wasted inefficiently [3]. That can be minimised by improving existing buildings and looking for intelligent solutions and energy-efficient materials, systems and components [4]. In this scenario, energy efficiency in buildings is a key element to improve the energy performance of existing buildings and promote the construction of new low-energy buildings that can significantly contribute to the reduction of greenhouse gas emissions, which are the objectives of the recently revised 2018/844/EU—Energy Performance of Buildings Directive (EPBD) [5, 6]. These efforts are in line with the ambitious climate targets outlined by the European Green Deal, which aims to transform the continent into a climate-neutral area by 2050 [7]. In response to this challenge, energy regulations and standards are becoming increasingly stringent, with the aim of ensuring that buildings meet minimum energy efficiency requirements [8]. To make a proactive contribution, policies that facilitate the transition to near-zero energy buildings (NZEB) are indispensable. These buildings are characterised by a high energy efficiency, which can be achieved using renewable energy sources, low-energy technologies, and passive design approaches. The priority is to ensure high indoor environmental quality and to promote greater use of natural resources [9].

Currently, there is an increasing scientific and technological interest in adopting alternative sources for both the construction phase and the manufacture of building materials. The aim is to replace virgin and unrenewable materials with more sustainable solutions, and mitigate the environmental impact associated with building activities [1, 2]. In this context, the concept of Circular Economy (CE) emerges as an effective strategy to mitigate environmental impacts in construction. This approach focuses on the autonomous generation of resources through the functional and physical reconfiguration of wastes, favouring recovery at the end of the life cycle [10], as it will be further discussed in Sect. 2. Current research focuses not only on the development of durable structures but also on the implementation of processes and materials that could actively promote environmental sustainability and the conservation of natural resources [11].

This study aims to investigate the current status of applications of waste products as substitutes for natural fibres to promote CE practices. More particularly, cellulose-based wastes are investigated exploring the potential to develop building materials with good thermal properties for energy efficiency-focused interventions in buildings. The incorporation of wastes into building and construction materials is the central theme of two doctoral theses that are here mutually met. These researches investigate the reuse and integration of various types of wastes into novel building materials, aiming to improve CE principles and implement sustainability and energy efficiency in construction.

2 Circular Economy Implementation Strategies

The consistently increasing waste generation worldwide is a matter of significant concern and complexity globally. The more and more diffuse adoption of the CE model, aimed at conserving natural resources by reusing waste materials or by-products, is an integrated solution for a more sustainable waste management; moreover, that could facilitate the acquisition of new—often unused—sources of materials and energy.

The literature review highlights that the circular model is commonly advocated within the framework of the 3Rs, namely "reduce, reuse, recycle". In the context of the construction industry, the CE model can be implemented through various strategies, including "Design for Disassembly," "Design for Recycling", "Materiality", "Building Construction", "Building Operation", "Building Optimization", and "Building End of Life" [12]. When examining the connection between CE and the building sector from the perspective of materiality, essential considerations include reducing the production of construction waste, employing recycling methods for construction and demolition products, and conceptualizing buildings as material reserves [12–14]. Extending the concept to the wastes generated by other industries, not limited exclusively from the construction sector's, it is interesting to consider the inclusion of new resources and to assess the changes in value that can result from their integration within buildings. Three categories of actions have been identified in the literature based on the duration and type of the product transformation process [15]. These categories include:

a. short cycles, in which the product retains its function and its users (Refuse, Reduce, Resell/Reuse, Repair);
b. medium-long cycles, in which products are improved and manufacturers are re-engaged (Refurbish, Remanufacture, Repurpose);
c. long cycles, in which products lose their original function (Recycle, Recover, Remine).

Within that classification, the actions of "re-mine", "re-cycle", and "re-purpose" seem to correlate best with the reuse of wastes from other sectors in the production of building components (Fig. 1). The practice of re-mine focuses on the origin of materials, involving the use of resources destined for landfills. Recycling identifies physical and functional transformations of materials, characterized by the concepts of downcycling and upcycling. Re-purpose emphasizes the reuse of adapted components for a new function. The former describes the transformation of products into lower-quality materials with reduced functionality, while the latter refers to products transformed into materials with higher quality and greater functionality. In this context, the concept of cascading promotes the sequential or hierarchical use of materials [16]. This approach aims to maximise the use and efficiency of materials, minimising wastes dispersion, and contributing to environmental sustainability.

Various types of waste, such as municipal waste, industrial waste, and agricultural waste are incorporated into the manufacturing of standard concrete, lightweight concrete, aerated concrete, mortars, and lime/clay-based composites in the form of chips, fibres, or powders. These materials serve as lightweight aggregates or are integrated into the production of building blocks. They act as substitutes for or supplements to natural and artificial aggregates, resulting in a reduction in the density of the composites and an enhancement of their thermal characteristics.

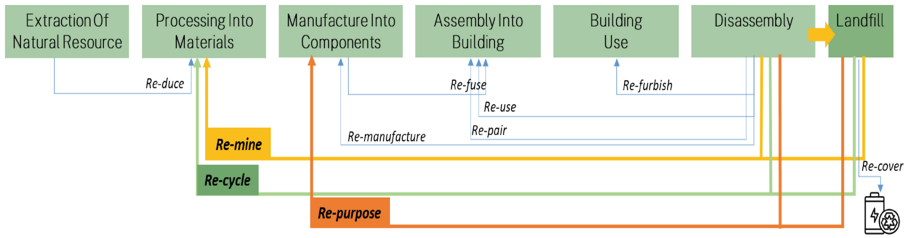

Fig. 1. Correlations between the 10R framework and the building process.© Authors *Sources* [15–17]

3 Materials and Methods

The initial part of this work briefly addresses the concept of the circular economy and its strategies within the construction sector. The subsequent section focuses on cellulose fibres and their properties, with particular interest to the material's thermal characteristics that could enhance the insulating capacity of the composite materials in which it is employed. The third part is dedicated to the examination of waste materials derived from cellulose, such as olive stones (from agricultural activities), paper (from municipal waste), and paper sludge (from industrial activities), to evaluate their appropriateness as substitutes for cellulose fibres in the production of building materials. The selection of these waste materials was guided by the aim of encompassing diverse waste categories, driven by the shared interest of two doctoral theses exploring the utilization of waste products in the development of building materials. Specifically, the analysis of olive stones aligns with UNIPA's research, supported by the National Project for Recovery and Resilience (PNRR), which investigates olive industry waste in southern Italy and the Mediterranean area to assess its potential reuse in the construction sector. Additionally, UNINA's research emphasizes the application of various waste materials in producing products applicable to different technical elements, thereby integrating the circular economy perspective into the construction sector. The analysed contributions consist of scientific articles, reports, and monographs obtained from official research databases such as ScienceDirect, Scopus, and Google Scholar setting the search by "title-abstract-keywords". The keywords used were "cellulose", "olive stones" and "paper", initially used individually and later in combination with "waste" to understand the main application fields. Then they were used with "building" and "construction" in order to evaluate the progress of scientific studies on the basis of publications dealing with the valorisation of waste in construction. The systematically organized data, presented in this article, focus on the density, mechanical strength, and thermal conductivity of the obtained products. This emphasis on such characteristics is crucial for validating the application of waste materials for dedicated applications in architecture and civil engineering in general.

4 The Integration of Wastes in Buildings: Applications

4.1 Cellulose Waste-Based Building Materials

Natural waste plays a significant role in effectively mitigating the environmental impact throughout their entire life cycle. The new approach to energy-efficient design also includes the development and use of natural and locally sourced building materials, including bio-based composites. The main objective is to minimise the overall impact of buildings, based on a life-cycle perspective [18].

Concerning this issue, the focus of this paper is cellulose-based products deriving from different types of waste to obtain sustainable, circular, and environmentally friendly building materials. This approach aims to reduce the dependence on non-renewable resources and the problem of long-term waste, favouring sustainable disposal practices. Cellulose is recognized for its thermal insulation properties, and its ability to confer lightness and strength to building materials makes it suitable for various applications in architecture and civil engineering [19]. From an economic perspective, cellulose can be a cost-effective solution for the manufacture of building components, contributing to the reduction of the production costs. This is attributed to its status as one of the most abundant materials in nature, coupled with its significant carbon storage potential. Indeed, cellulose, formed through the repetitive bonding of β-D-glucose as elucidated by Abdul Khalil et al. [19], constitutes the principal component of all plant fibres. It can be derived from agricultural waste as well as recycled paper and finds extensive applications in textiles, paper, building materials, and various industrial chemical derivatives [20, 21].

Cellulose fibres derived from agricultural wastes have been employed as a reinforcement material with low density and high mechanical properties [22, 23]. However, the most prevalent application is in the manufacture of thermal insulation products, garnering considerable attention due to its environmental sustainability, biocompatibility, compostability, low cost, and renewability. Cellulose-based insulation is currently available in the form of panels, where cellulose fibres are moulded with polyester or similar binders, or as loose fibres, applied manually or using specialised equipment, to attics, ceilings, or walls. The initial application of cellulose fibres as an insulation material dates back to 1919 in Canada, but it was not until the 1950s that commercial products were developed in the United States. The utilisation of wood pulp gained prominence in the 1970s, particularly due to the United States oil embargo [24]. Cellulose fiber insulation is distinguished by a lower value of embodied energy and environmental impact compared to conventional insulation materials. Its thermal conductivity (λ) is reported to be around 0.039 W/mK, a value very similar to that of cork and glass wool, both of which are about 0.040 W/mK, as well as to the value of recycled cotton, which is approximately 0.042 W/mK [25]. The reason of such low λ value lies in the microscopic structure of the cellulose-based products, which are characterised by several pores, some of which are interconnected, and others are not [26]. The observed conformation depends on the arrangement of the components combined with the cellulose.

4.2 Wastes from Agricultural Production: The Olive Stones

The first waste to be examined in this work is the olive stone (also called kernel), a by-product of the olive growing, as its potential thermal properties fit the research objectives of the NEST project, supported by the PNRR, which aims to examine the potential reuse of wastes from various industries in order to develop novel building materials with improved thermal performance. Currently, these by-products show several applications in various sectors already, but their suitability as efficient substitutes for cellulose fibres in the manufacture of building materials is being evaluated.

The global production of olive stones is estimated to range between 4.1 and 5 million tonnes per year globally [27]. In general, the production process involves four operational phases: cleaning and washing of the olives, crushing and grinding, extraction of the oil from the paste, and final refining. The solid, or semi-solid, by-product generated in olive oil production is called pomace, which is mainly composed of olive stones, pulp, and vegetation water [27]. More specifically, the olive stone is a material whose main constituents are cellulose, hemicellulose, and lignin, as well as fat and protein in smaller quantities, as shown in Table 1.

Table 1. Main constituents of the olive stone—© [28, 29]

Main Olive Stone compounds	Quantity [%]
Cellulose	31.9
Hemicellulose	21.9
Lignin	26.5
Lipids	5.53
Protein	3.20
Other sugars	0.48
Humidity	9.79

The stone constitutes the endocarp of the drupe, and its extraction occurs concomitantly with the residue during the oil extraction process. This may involve the direct elimination of the entire stone from the olive paste or arise from the dedusting procedure applied to spent pomace derived from olive pomace factories. Figure 2 shows the main processing phases involving the olive stones.

The average size and shape of the stone pieces mainly depend on the adopted extraction process, while the quantity varies from 25 to 40% of the weight of the pressed olives, depending on the used extraction technology [30].

Although in ancient Roman times, olive stones were used as a natural method to prevent the growth of weeds only [31], nowadays they show multiple applications. In fact, olive stones can be reused as additive and mixed with bitumen for road construction [32], or as a solid fuel and additive for animal feed or in the preparation of composite fertilisers [31]. However, the most popular use is as a biofuel in the form of pellets due to its high combustion power. In fact, several current studies focus on the development of improved methods to recover ligno-cellulosic materials in order to produce solid, liquid, or gaseous biofuels [29]. In addition to these applications, stone waste has been the subject of various research, exploring its integration into building and construction materials, with a focus on analysing its mechanical and thermal properties. This waste, indeed, possesses a rigid structure that can contribute to a better structural filling effect in many cementitious products [33].

Recent studies have explored the possibility of reusing olive wastes as partial replacement for some components in concrete and cement mortars. For instance, a study on the impact of substituting olive stones for clinker in concrete has revealed, after 365 days, a compressive strength of 50 MPa for mortars containing 10% waste, in contrast to the reference mortar which exhibited a compressive strength of 51.35 MPa. There was a small reduction of 2.6% in resistance, but a very satisfactory value was obtained considering the improved environmental drawbacks [34]. Uses of olive stone to produce biochar are reported in literature, evaluating also its impact on the properties of building materials, particularly cement-based composites [27, 33]. Furthermore, olive stones have been used as lighter aggregates to formulate self-compacting lightweight mortars with densities ranging between 1400 and 1900 kg/m3 [35]. Another study examined the mechanical performance of cement-based mortar by incorporating various proportions of olive solid waste aggregates as a partial substitute for natural sand. It was observed that after 28 days of curing, the mortar specimens with 5% waste showed a compressive resistance of 33 MPa, with a density reduction of 15.6% compared to the reference mortar. Moreover, that exhibited a thermal conductivity of 0.87 W/mK, representing a 21% decrease compared to the standard mortar [36].

Fig. 2. Diagram of the stages from which olive kernel is derived—© 2024, the authors.

Of particular interest, also as part of the doctoral research that is here partially presented, is the energy performance that olive stones could confer to building materials when used as aggregate. Indeed, one area of particular scientific interest concerns the use of olive stones to improve the thermal performance. In this context, a study reported that the addition of olive stone to cement mortar can significantly reduce the thermal conductivity of 76%, with 70% of the dry weight of olive stone, and a 30% reduction in density [30]. Mixing olive stone with clay has been also explored to increase the thermal insulating capacity of bricks [37, 38]. Other studies showed that the addition of olive stone to bituminous concrete mixtures improves peel strength, durability, and resistance to water and freeze-thaw [39]. Finally, the use of olive stone as reinforcement for the preparation of polypropylene-based composites has been investigated, generating an improvement in tensile and flexural modulus of up to 60% by weight of filler loading [40].

Continuous research and experimentation with waste from the olive oil industry show its significant potential to be integrated into innovative building materials and products while promoting circularity and sustainability in the industry of construction in a symbiotic way with other productive sectors.

4.3 Municipal Solid Waste: The Paper

Among cellulosic-derived municipal waste, paper offers interesting applications in buildings, as it is particularly advantageous due to the light weight. Paper and cardboard represent the second largest fraction of municipal waste on a national scale [41]. Considering the quantity of wastes produced annually, it is extremely interesting to evaluate the possibility of recycling these materials effectively in different products. Wastepaper is generally used as a lightweight, fibrous aggregate in novel cement-based composites aiming to reduce their density. Literature analysis reveals that the density of cement-based mortars with different compositions, including paper, is between 1450–2400 kg/m^3 [42, 43] compared with 2000–2400 kg/m^3 of the traditional cement-based mortars.

In the preparation of mixtures, wastepaper is often treated by pulping in water [42, 44]. Since paper shows a high absorption capacity, this prevents it from absorbing water from the pulp when mixed with the binder. Then the pulp is dried to reduce its moisture content [44]. Stevulova et al. [45] investigated the variation in density and strength for different mortar compositions having various water/binder ratios. Bulk densities varied between 1913 kg/m^3 and 2160 kg/m^3 and compressive strengths between 15.1 MPa and 32.7 MPa. It was observed that the amount of paper increase led to a gradual reduction in the density of the resulting compounds. However, there was a decrease in strengths and it was therefore necessary to avoid excessive quantities in order to preserve the overall mechanical strengths of the material. In mortar mixing tested by Hospodarova et al. [42], the inclusion of paper at a weight equivalent to 0.5% of the total weight of cement and sand was tested. This addition led to a reduction in the 28-day compressive strength from 41.15 MPa in the reference sample, to 30.34 MPa. The decrease was attributed to an elevated water/cement ratio compared to the reference sample. In mixtures consisting exclusively of paper and cement, the compressive strength ranged between 3.43 MPa and 6.43 MPa [46]. The fibrous structure of the paper imparts a porous configuration to the mixture, facilitating the efficient dissipation of absorbed energy and demonstrating ductile behaviour. That property suggested that the material could be well-suited for structural applications, particularly when considering that the resulting mortar achieved strengths comparable to those observed in conventional structural mortars [44, 47]. Furthermore, according to Lee et al., the use of newspaper residue in mortars as a cement substitute showed an increase in 28-day compressive strength ranging from 3.2% to 16.1% compared with the control sample [48].

The incorporation of recycled paper into the clay brick manufacturing process is used to generate pores and alveoli with the aim of reducing thermal conductivity. In fact, during the incineration of waste bricks, the organic content contributes to the formation of numerous pores, leading to a decrease in strength [49]. An analysis of samples composed of 9.1% wastepaper combined with clay, revealed a reduction in density, compared to the reference sample, from 1645 kg/m^3 to 1264.8 kg/m^3, and further to 1006.2 kg/m^3 in samples containing 50% paper [50]. Conversely, a decrease in compressive strength was observed from 51 MPa in the reference product to 33 MPa in the samples with 9.1% wastepaper [50]. Composites incorporating waste paper exhibit elevated water absorption levels in comparison to reference samples. That is explainable to the natural cellulose content within the waste paper itself. In fact, cellulose contains hydroxyl groups that facilitate the formation of hydrogen bonds with the water molecules, thereby increasing water absorption. This parameter must be kept under control and opportunely regulated as a high water absorption could lead to the formation of many voids with consequent loss of compactness, strength, and consequently reduced durability.

Analysing the thermal characteristics, the inclusion of cellulosic fibres in the matrix contributes to the formation of voids, leading to an increase in the thermal insulating properties of the material in parallel with the decrease in density. The thermal conductivity values of mortars investigated by Stevulova et al. vary between 1.86 and 2.30 W/mK [45], showing a reduction from reference values between 24% and 35%. Mixtures containing only cement and paper in various proportions achieved a thermal conductivity ranging between 0.0851 and 0.0978 W/mK [46]. Furthermore, in clay bricks, depending on the paper content, the thermal conductivity reached values between 0.39 to 0.5 W/mK [50] compared to that of traditional solid clay bricks, which range between 0.6 and 1 W/mK.

Experiments involving the use of other materials, mainly of organic nature, in the mixture can also be found in the literature. Wood-Crete, for example, is a material that incorporates waste-wood, wastepaper, and lime. The compressive strength of the developed material is very low, but the composites show good thermal conductivity ranging from 0.046 W/mK to 0.069 W/mK [51]. The addition of banana fibres treated with sodium hydroxide reduced the lignin and hemicellulose contents within the fibres, as well as caused their surface deparaffining. The surface modification allowed for greater cohesion between components, limited water absorption, and increased strength by taking advantage of the fibres' ability to stop splitting [52]. Finally, replacing 10% sand with sugar cane and paper led to an increase in compressive strength of the concrete block compared to the reference mix of 8.52% [53].

4.4 Wastes from Industrial Activities: Paper Mill Sludge

Paper mill sludge is a significant by-product of the papermaking industry, associated with considerable costs for its treatment and disposal, so it is interesting to evaluate its possible uses in other sectors, such as construction. The wastes are used both in wet form and as ash, not only as lightweight aggregates but also as a substitute for cement, exploiting their potential pozzolanic effect for strength development purposes.

In the literature, the study of environmentally and economically sustainable applications of deinking sludge, primary sludge and secondary sludge is highlighted. Deinking sludge results from deinking and bleaching processes [54, 55] and contains a mixture of organic materials as cellulose, inorganic materials as clay and calcium carbonate, and other components as fillers (ink particles, potentially containing heavy metals, and deinking additives, depending on their composition). Primary sludge results from process of water clarification, the inorganic component includes sand and calcium carbonate, while the organic component consists of bark, fibres and other wood waste [54–56]. Secondary sludge mainly consists of excess biomass generated during biological treatment. This sludge is mainly composed of organic material, namely cellulose and water [54, 55]. Before using such industrial by-products for the construction of building products, their composition should be carefully evaluated. The average composition of sludge is presented in Table 2. It is observed that it varies depending on the quality of paper produced and the production process; moreover, they could contain harmful substances, i.e. heavy metals, that if present in large quantities would limit the sludge use [57].

Table 2. Main constituents of the primary and secondary sludge—© [55]

Component	Primary sludge	Secondary sludge
Dry solid content [%]	48	32
Volatile solids [%]	33	48
TOC [%]	19	23
Copper [mg/kg DS]	238	71
Lead [mg/kg DS]	41	22
Cadmium [mg/kg DS]	<0.7	<0.7
Chromium [mg/kg DS]	24	17
Zinc [mg/kg DS]	141	135
Nickel [mg/kg DS]	6	8
Mercury [mg/kg DS]	0.1	0.09

Paper sludge has been used in concrete mix formulation as a replacement for fine sand; this leads to an increase in the water-cement ratio, as the waste shows significant water absorption, resulting in reduced strengths [58]. However, when the amount of added sludge is limited, acceptable compressive strength values can be obtained, allowing the mix to be used for the construction of masonry in concrete bricks and other non-structural elements.

The clay-based materials present in the sludge can be transformed into active metakaolin, acquiring pozzolanic activity [59, 60]. Calcining the sludge at 700 °C for 2 h resulted in a product with high pozzolanic activity. When incorporated as a 10% replacement for Portland cement, this product exhibited a 7 days' compressive strength 10% higher than that of the mixture composed of cement solely. Additionally, a reduction in setting time was observed, decreasing from 127.50 ± 5 min for the 100% cement mixture to 97.50 ± 5 min for the mixture containing calcined sludge [61]. Tests have been conducted to evaluate the use of a cement composed of lime mud generated through chemical treatments related to the kraft process, biological sludge, and fly ash from biomass burning [62]. These components were mixed to produce the clinker, subsequently combined with additional lime sludge and gypsum to formulate the binder. This binder was then mixed with sand and filler to produce the mortar, which, during the curing period, demonstrated a gradual rise in compressive strength, reaching approximately 13 MPa at 90 days.

Primary sludge is used to make bricks in combination with clay since, during firing, the calcite contained in the sludge participates as a reactive hydraulic component to consolidate the ceramic product. The strength values of the product differed depending on the initial characteristics and manufacturing processes of the blocks themselves. In general, the compressive strength is lower than the reference samples due to the increased number of pores introduced by the cellulose contained in the paper sludge. Considering bricks that are fired at 900/1000 °C, the addition of sludge (5%–10%–15%–20%) changed the compressive strength, which resulted between 14 MPa and 7.5 MPa compared to 20 MPa in the reference sample [57]. The addition of 20% sludge resulted in a density of approximately 1300 kg/m^3, which is lower than the density of solid clay bricks (1600–2000 kg/m^3) but comparable to that of hollow bricks (1000 and 1400 kg/m^3). Introducing paper wastewater sludge in addition to 6% of the clay weight resulted in a strength decrease that remained around 20 MPa [49]. The presence of sludge inside clay bricks decreased their conductivity; for the 9% rejection with respect to clay weight, a conductivity of 0.182 W/mK was reported [49]. That value can be compared to the conductivity of solid clay bricks, which generally varies between 0.5 and 1 W/mK.

Applications of primary sludges for the production of mortars in combination with cement and other binders are relatively rare. De Azevedo et al. explored the potential use of primary sludge in the production of mortars that included cement, lime, and sand. During testing, sludge was added in different proportions, and the optimal composition was identified by replacing 5% of lime. In that configuration, the compound achieved a compressive strength of 2.69 MPa after 28 days [63]. Other experimental applications included the use of calcareous sludge and biomass from Kraft paper production with respective functions as filler and as a substitute for metakaolin in the production of geopolymer mortars for structural use [64]. The study showed that the addition of the sludge retarded the setting time, increased the density of the mixtures and, consequently, their compressive strength. In fact, the compressive strength value of the reference mix after 28 days was 21.66 ± 0.03 MPa while the addition of 10 wt% limestone sludge caused a 30 wt% increase in strength to 28.11 ± 1.29 MPa [64].

Primary mud has been employed in the production of fiber cement [56], replacing virgin wood fibres. The composition, incorporating inorganic solids like sand, contributed to the development of density and strength in the sheets. The water content within the specimens can be reduced either by drying the sludges and initial pulp [49] or by subjecting them to treatments such as pressing alternated with sun drying to prevent irregularities on the brick's surface [65]. In some instances, within cement-based compounds, there was an anomalous decrease in the percentage of water absorption as the sludge content in the mixture increased [44, 63]. That phenomenon could be attributed to the tubular shape of the cellulose fibres, fostering improved adhesion between the paper pulp and cement pulp in the mortar mix, consequently reducing the pore size. Indeed, internal pores become saturated with air and water during cement hydration, thus diminishing their capacity to absorb and ascend through capillary action [44].

5 Discussion and Future Studies

The presented studies show that the use of cellulosic wastes such as the discussed olive stone, paper, and paper mill sludge, is in full conformity with the principles of remine, recycle, and repurpose. Hence, this practice emerges as a potential strategy to successfully implement CE. The combined use of such wastes with different binders is mainly associated with a decrease in product density, attributable to the significant porosity introduced. The decrease in density leads to a subsequent decrease in structural resistance but, simultaneously, results in low thermal conductivity. To preserve the lightness of the materials, without compromising the final mechanical resistances, the addition of wastes might be limited—with a reduced environmental implementation—or explore additional components beyond those analysed, as indicated in some reported papers that would require additional investigation. However, the data available in the scientific literature indicate a considerable variability in the tested mixes. Therefore, the two doctoral research projects, here presented, are aimed at facing, and experimenting, with new compositions of the mentioned materials to stabilise and enhance the property values.

For the first doctoral research, it is observed that the use of olive stones in building materials is a sustainable solution, solving the problem of disposal and contributing to the development of materials with acceptable mechanical properties, and good insulation properties. However, there are challenges, including high water absorption and the potential for decay in humid environments, unless the latter is proactively inhibited through the addition of substances such as sodium silicate. This addition improves durability and strength over time, providing protection against fungi and parasites. On the other side, it could decrease the green effort on sustainability. Furthermore, it could be a solution to combine the use of olive pits with waterproof coatings and test solutions to ensure consistent performance over time. In addition to considering the technical aspects, the economic aspect must also be analysed, assessing if the use of such wastes in building materials is actually cost effective. This additional aspect requires detailed evaluations of the associated costs and benefits, contributing to an informed decision on the actual value for money of integrating olive stones into construction processes. In any case, the addition of such waste into novel building and construction materials would improve the sustainability of the sector in light of the CE approach, despite any speculation on possible financial benefits. Further studies will be conducted on the manufacture of novel mortars and concretes reusing olive wastes (pomace, olive stones, and vegetation water) mainly intended for the implementation of the thermal performance of building, as envisaged by the current EU and Italian regulations.

From the second doctoral research, paper and sludge products typically show high moisture content and are frequently dried before being incorporated into mixtures. The additional treatment, if implemented on an industrial scale, could have a significant impact. Therefore, as part of the research, there are plans to supplement existing data in the literature with life cycle analyses of some of the mentioned products, considering various production methods. These treatments could be substituted by incorporating additional hydrophobic components in the compounds or implementing surface sealing treatments that do not compromise environmental impact. The analysis demonstrated that paper and sludge are employed in the production of bricks and building blocks to reduce loads on the structure. To minimize construction time and costs, the research may explore the experimentation with modules produced via 3D printing and assembled dry, along with an evaluation of the reduction in impacts associated with the construction process. Additionally, opportunities for utilising sludge with pozzolanic action have been identified, although the potential presence of heavy metals in the sludge necessitates careful assessment. Purification treatments for the products should be also considered, and impact analyses conducted to assess their practical applicability.

6 Conclusions

This double-clutch study focused on the application of wastes materials in the construction sector, as an approach derived from the CE and delineated through the various frameworks in the literature. This approach, originally designed to promote sustainable production processes and reduce resource consumption, has found application in various sectors, including construction. The new paradigm in materials production, geared towards producing efficient and eco-friendly solutions, embraces the development and use of natural and local building materials, including bio-based composites.

Thanks to its biocompatibility and degradability characteristics, cellulose emerges as a promising application option. Cellulose fibres are already being investigated for their use as a reinforcing component in many binding materials and as insulation in various forms. Three categories of cellulose-based waste with potential use in the construction sector have been here identified and discussed: olive stones, wastepaper, and by-products of the paper industry. The investigation and development of renewable composite materials can open up new perspectives in the field of green building, contributing to more sustainable solutions to environmental challenges and promoting ecosystem-friendly building practices.

However, it is crucial to turn attention to proper waste management by exploring new technologies aiming to increase greener production processes and improve the properties of cellulose-based materials. The main challenges for the future are improving the durability and the mechanical performance of these composites, without impacting with production costs, and promoting environmentally friendly technologies. These advances are essential to address the growing environmental concerns and drive the global industry in a more environmentally conscious direction.

Acknowledgements. A. Calà and M. Saeli would like to acknowledge the Project "Network 4 Energy Sustainable Transition—NEST", Spoke 8: Final use optimization, sustainability \& resilience in energy supply chain, Project code PE0000021, Concession Decree No. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP UNIPA B73C22001280006, Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3—Call for tender No. 341 of 15.03.2022 of Ministero dell'Università e della Ricerca (MUR); funded by the European Union—NextGenerationEU.

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