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Review

From Field to Building: Harnessing Bio-Based Building Materials for a Circular Bioeconomy

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Abstract: The transition from a linear to circular economy is driving a growing emphasis on utilizing bio-based materials for bioenergy and construction purposes. This literature review seeks to offer a thorough bibliometric and critical analysis of bio-based building materials, particularly those that incorporate agricultural residues. A selection of pertinent articles was analyzed using text-mining techniques, revealing a substantial increase in research output on this topic, from 74 publications in 2000 to 1238 in 2023. Key areas such as sustainability, sources of bio-based materials, building applications, design and analysis, material properties, and processes have been extensively examined. The cluster "Sustainability" was the most frequently discussed topic, comprising 28.85% of the content, closely followed by "Building Materials and Techniques" at 28.07%. Given the critical role of life cycle assessment (LCA) in sustainability, an additional analysis was conducted focusing on existing research addressing this subject. The findings of this study are aimed at advancing the incorporation of waste-derived bio-based materials into a circular economy framework, thereby supporting the broader objectives of sustainability and resource efficiency.

Keywords: agricultural by-products; bio-based materials; building; circular economy

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1. Introduction

The construction sector is a major contributor to environmental degradation, global warming, and climate change, leading to the growing interest in new resources, green building materials [1], environmental sustainability, and energy efficiency, together commonly called 'Green Building' [2]. Enhancing building sustainability and energy efficiency involves increasing thermal efficiency, reducing energy consumption and CO_2 emissions, and employing unconventional eco-friendly materials, recyclables, and renewables with a low environmental footprint. Several recent studies are, thus, focused on new resources and sustainable materials that could be integrated into the building process [3,4]. Substituting traditional construction materials, e.g., concrete, steel, and plastic components, with unconventional eco-friendly materials could significantly reduce air and water pollution, environmental impacts, CO_2 emissions, and waste solid production via modern energy-saving techniques [5–7]. Eco-building materials could be obtained through the reconversion of wastes, in accordance with the Circular Economy Action Plan (CEAP) objectives [8]. In recent years, there has been a significant research focus worldwide on the valorization of agricultural wastes (AWs), including animal, food process, and crops wastes [9–11].

Several studies have focused on new eco-friendly building components to significantly reduce CO_2 emissions, environmental pollution, and waste production [12,13], with their low environmental impact and unique features of thermal performance, ductility, and mechanical strength forming the basis of this growing research trend. Based on these observations, in recent years, the valorization of agricultural waste has become an important step toward environmental protection, energy saving, and sustainable development [14–16]. The use of organic waste could also become a passive technique that guarantees a more sustainable architecture as well as favoring a lower energy impact [17,18].

An AW-based material is essentially a building component comprising a matrix reinforced by some distinct constituent materials, generally reinforcement fibers or aggregates, to improve its mechanical and physical performances [19–21].

Bio-based materials produced through agricultural practices can be classified into two main categories: those derived from animals, and, to a lesser extent, those derived from plants. Among them, natural fibers, suitable for replacing synthetic fibers as reinforcement within bio-composite materials, are of great importance [22].

1.1. Plant Bio-Based Building Materials

Materials such as hemp, flax, mycelium, lignin-based fibers, wood waste, sunflower, cork, corn cob, coconut, rice husk, timber, and bamboo particles can be combined with inorganic substances like lime and cement to create bio-based construction materials. There is research indicating that these materials typically enhance thermal insulation and sound absorption due to their high porosity. Bio-wastes also contribute to improved indoor comfort by enhancing hygrothermal conditions, and generally have a strong capacity for moisture buffering, which helps regulate indoor humidity [2,23,24]. Additionally, many bio-wastes exhibit strong mechanical properties, contributing to greater stiffness and strength, and often show high resistance to fractures [25–27].

Several studies have investigated the use of natural fibers as a reinforcement for composite materials instead of synthetic ones (e.g., glass fiber, polymeric fibers) [28]. Asdrubali et al. and Xia et al. demonstrated that, thanks to cotton's low thermal conductivity, wooden boards incorporating cotton stem as a fiber reinforcement have good thermal behavior [29,30]. D'Alessandro et al. assessed the thermal and acoustic behaviors of straw bale walls, finding good thermal performance [31]; their experimental trial results showed a thermal conductivity between 0.050 W/mK and 0.060 W/mK, below the maximum recommended by AFNOR (Association Française de Normalisation) for thermal insulation, i.e., 0.065 W/mK. Measurements carried out in situ showed that the thermal behavior of straw balls walls, due to the high diffusivity and low thermal inertia, were satisfactory in winter but not summer conditions. On the contrary, the acoustic behavior, due to the low density, exhibited a worse performance. Collet and Pretot analyzed the thermal properties of hemp concrete by mixing hemp and hydraulic lime, demonstrating that thermal performance varied according to formulation, density, and water content. Nunes et al. studied the properties of cement particle panels produced by using banana fibers [32,33], observing that increasing the banana fiber content from 0 to 75% caused an increase in bulk density, from 1754 kg/m^3 to 1995 kg/m^3, and a decrease in thermal conductivity, from 0.233 W/mK to 0.279 W/mK.

1.2. Animal Bio-Based Building Materials

In contrast to the lignocellulosic structure of plants, animal bio-based materials, whether fibrous or non-fibrous, have a protein-based structure primarily comprising keratin, along with other components such as fibroin, collagen, chitosan, and lipids [34].

The main animal bio-based materials are sheep wool, camel wool, goat wool, chicken feather (barbs), chicken feather (barbules), chicken feather (pulverized), pig hair, horns, and cheese industry by-products. Sheep wool has long been used in the construction industry for its thermal and acoustic insulating properties, and many studies have focused on repurposing this livestock waste for building applications [35,36].

In the construction sector, wool is primarily utilized as a thermal and acoustic insulator [36] and as a reinforcing fiber in bio-composites to enhance mechanical properties such as ductility and shrinkage resistance [37].

Araya et al.'s experimental study [38] focused on processing and analyzing pig hair, a by-product of the food industry, by examining its morphology, physical, and mechanical properties to assess its potential effectiveness as a natural fiber reinforcement in mortar mixes.

The findings of their research indicate that the impact strength can be enhanced by up to five times compared to plain mortar. Additionally, the compressive and flexural strengths, bulk density, porosity, and dynamic modulus of elasticity of the fiber-reinforced mortar containing the specified pig-hair content are not significantly altered.

Oliveira et al.'s review explored the latest developments and research in the use of animal-based waste materials for sound insulation [39], comparing the performance results of biomaterial derived from sheep wool, camel wool, goat wool, chicken feather (barbs), chicken feather (barbules), and chicken feather (quills pulverized).

1.3. Main Uses of AW in Building Sector

1.3.1. Bio-Aggregates in Concrete, Earth Bricks, and Composite Soil

Agricultural waste-derived bio-based materials can enhance the mechanical properties of concrete. Furthermore, previous research has highlighted the economic benefits of incorporating these wastes into concrete production. Various studies have evaluated the effectiveness of different agricultural residues, such as sugar cane straw ash and rice husk ash (RHA), as partial replacements for traditional materials like blast furnace slag and Portland cement [40,41]. The findings indicate that these residues can be environmentally friendly fillers, improve concrete's compressive strength, and reduce the global warming potential. The performance of concrete mixtures using agricultural by products like oil palm ash and fly ash has also been assessed, showing promising results in terms of durability and strength [42,43]. Khalil et al.'s review investigated the use of bamboo fiber-reinforced composites, identifying several studies that have compared the properties of bamboo fiber-based bio-composites with those of glass fiber-based composites. The researchers found that bamboo fibers can replace up to 25 wt.% of glass fibers without diminishing the mechanical properties of glass fiber-based composites [44].

The average values of compressive and flexural strength of unfired earth bricks incorporating waste materials are reported in Table 1.

Table 1. Mechanical behavior of raw earth adobes incorporating agricultural wastes.

Waste Used	Compressive Strength [MPa]	Flexural Strength [MPa]	References
Sheep wool	3.14	0.88	[45]
Millet	6.5	0.17	[46]
Rice Husk ash	3.4	_	[40]
Bagasse	3	_	[47]
Banana fibers	5.92	0.95	[22]
Straw	4.64	2.03	[48]

1.3.2. Bio-Aggregates as Insulation Materials

Research into natural fiber wastes has revealed their potential as sustainable insulation alternatives, offering benefits such as low cost, minimal energy use, and high biodegradability. Studies have compared these bio-based insulations with conventional materials like expanded polystyrene, finding favorable results in terms of performance and environmental impact. The development of bio-insulation materials continues to advance, with research focusing on improving their properties and applications [29,49]. Giroudon et al. studied the possibility of using lavender straw to produce composite material [50], while Cintura et al.'s review investigated the possibility of using vegetal agro-industrial residues for building products, focusing on their thermal insulation properties [51]. The use of agricultural wastes like cork and olive stone in mortar mixes has demonstrated significant benefits. For instance, incorporating olive stone into cement lime mortar reduced its thermal conductivity and density, providing enhanced insulation properties [23,52,53]

Muñoz Velasco et al. considered the use of coffee grounds as aggregates to produce fired bricks, showing that the use of this organic waste improved thermal performance (thermal conductivity decreased from 0.73 W/mK to 0.38 W/mK) [54].

Liuzzi et al. demonstrated that incorporating waste fibers from olive pruning, ranging from 4% to 12% by total weight, enhanced the thermal insulation properties of clay-based plasters. Their findings revealed that increasing the fiber content resulted in a decrease in density, from 1669 kg/m^3 to 1409 kg/m^3, a reduction in thermal conductivity, from 0.593 W/mK to 0.428 W/mK, and an increase in porosity [23]. Nunes et al. investigated the properties of cement particle panels incorporating banana stems [32], finding that increasing the banana fiber content from 0% to 75% resulted in a rise in bulk density, from 1754 kg/m^3 to 1995 kg/m^3, and an increase in thermal conductivity, from 0.233 W/mK to 0.279 W/mK.

Asdrubali et al. conducted a comparative analysis of sustainable building insulation materials, e.g., reeds, bagasse, cattail, corn cob, cotton stalks, and date palm, focusing specifically on their thermal properties, including thermal conductivity, specific heat, and density [29].

These findings suggest that agricultural wastes can effectively replace conventional materials in mortar, improving thermal performance and sustainability. Overall, the integration of agricultural wastes into construction materials offers a promising route toward more sustainable building practices.

Table 2 summarizes the thermal conductivity of the most common insulation materials. The acoustic performance values of a selection of animal bio-based materials are illustrated in Table 3.

The aim of this study is to offer a bibliometric and critical analysis of bio-based building materials, specifically focusing on composite materials that incorporate agricultural and food residues.

Table 2. Thermal behaviors of organic and inorganic insulation materials (adapted from Hung Anh et al. [55], Journal of Building Engineering, 2021).

Biomaterial	Category	Density [kg/m^3]	Thermal Conductivity [W/(mK)]
Glass wool	Inorganic	13–100	0.03–0.045
Rock wool	Inorganic	30–180	0.033–0.045
Calcium silicate	Inorganic	115–300	0.045–0.065
Cellular glass	Inorganic	115–220	0.04–0.06
Vermiculite	Inorganic	70–160	0.046–0.07
Ceramic	Inorganic	120–560	0.03–0.07
XPS	Inorganic	32–40	0.032–0.037
EPS	Inorganic	15–35	0.031- 0.040
Cork	Inorganic	110–170	0.037–0.050
Melamine foam	Inorganic	8–11	0.035
Phenolic foam	Inorganic	40–160	0.022–0.04
Polyethylene Foam	Inorganic	25–45	0.033
Fiberglass	Inorganic	24–112	0.033–0.04
Sheep wool	Organic	25–30	0.04–0.045
Cotton	Organic	20–60	0.035–0.06
Kenaf	Organic	40	0.038
Cellulose fibers	Organic	30–80	0.04–0.045
Jute	Organic	35–100	0.038–0.055
Pineapple leaves	Organic	210	0.035
Rice straw	Organic	154–168	0.046–0.056
Hemp	Organic	20–68	0.04–0.05
Bagasse	Organic	70–350	0.046–0.055
Coconut	Organic	70–125	0.04–0.05
Flax	Organic	20–80	0.03–0.045

Table 3. Acoustic characteristics of animal bio-based materials and inorganic materials.

		Frequency [Hz]	SAA	e [mm]	ρ [kg/m^3]	References
Animal bio-based material	Duck feathers	1000	0.30–0.54	11.5	70–80	[56]
	Chicken Feathers	650–1600	0.99	25–75	48	[57]
	Goose down fibers	800–6300	0.33–0.95	30.0	1140.0	[58]
	Sheep wool	500–2000	0.77	60	18–23	[59]
	Wool hot-pressed board	800–3150	0.60	24.0	249.5	[60]
	Wool mat	100–3150	0.78	50.0	100.0	[61]
	Camel wool	1000	0.97	50.0	-	[62]
	Goat fiber	2000	0.94	50	-	[62]
Inorganic	Glass wool	500	1	50	-	[29]
	Rock wool	500	0.9	50	-	[29]
	EPS	500	0.5	50	-	[63]

In this research, a bibliometric analysis was carried out on indexed manuscripts using an advanced SCOPUS database search performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow diagram, adapted herein for our research and considering an interval time range from 2000 to 2023 [64]. In detail, the structure of this review is as follows: (i) describe the temporal trends in publications over the years; (ii) identify in which field the research has been mostly focused; and (iii) evaluate the most important links among topics. The final objective of this work is to identify research gaps to address future research developments.

2. Materials and Methods

2.1. Article Selection

This exploration focused on "bio-based materials" for building purposes. Articles were initially selected from SCOPUS using specific search terms relating to building materials, food and agricultural waste, and plant-based aggregates. Filters were applied to narrow the fields to environmental science, engineering, materials science, and related disciplines, resulting in the selection of over 9500 manuscripts published between 2000 and 2023. Only 10% of these were reviews, while the remaining 90% were original articles. All relevant data, including titles, keywords, and abstracts, were downloaded for analysis, and the search queries used to perform our study are reported in Table 4.

Table 4. Search scripts for extracting relevant research works.

Step	Search Query	Number of Manuscripts
Initial research	*(TITLE-ABS-KEY (building AND material*) OR TITLE-ABS-KEY (construction AND material*) OR TITLE-ABS-KEY (building AND component*) AND TITLE-ABS-KEY (food AND waste) OR TITLE-ABS-KEY (agr* AND waste) OR TITLE-ABS-KEY (plant AND based) OR TITLE-ABS-KEY (vegetal AND aggregate*) OR TITLE-ABS-KEY (food AND residues) OR TITLE-ABS-KEY (forestry AND residues) OR TITLE-ABS-KEY (agr* AND by-product) OR TITLE-ABS-KEY (bio-based) OR TITLE-ABS-KEY (agricult*) OR TITLE-ABS-KEY (rural) OR TITLE-ABS-KEY (livestock) OR TITLE-ABS-KEY(husbandry))*	22,135
* Subject area filter application	*(TITLE-ABS-KEY (building AND material*) OR TITLE-ABS-KEY (construction AND material*) OR TITLE-ABS-KEY (building AND component*) AND TITLE-ABS-KEY (food AND waste) OR TITLE-ABS-KEY (agr* AND waste) OR TITLE-ABS-KEY (plant AND based) OR TITLE-ABS-KEY (vegetal AND aggregate*) OR TITLE-ABS-KEY (food AND residues) OR TITLE-ABS-KEY (forestry AND residues) OR TITLE-ABS-KEY (agr* AND by-product) OR TITLE-ABS-KEY (bio-based) OR TITLE-ABS-KEY (agricult*) OR TITLE-ABS-KEY (rural) OR TITLE-ABS-KEY (livestock) OR TITLE-ABS-KEY (husbandry))*	9562

* Subject area limited to environmental science, engineering, materials science, social sciences, agricultural and biological sciences, chemical engineering, and earth and planetary science.

2.2. Article Elaboration

The text extracted was saved as a .txt file. The words shown in the titles, abstracts, and keywords were then assessed using a text mining process tool through the elaboration of the data via dedicated software platforms, i.e., Python version 3.12.6 (a high-level programming language), Microsoft Excel version 16.77 and Gephi version 0.10 (Gephi® Consortium, Compiegne, France; open-source software for network analysis), for graphical representations of the results. By performing a statistical analysis of indices obtained via the text mining process, significant and high-quality information useful for text interpretation was achieved.

The process began with tokenization, wherein irrelevant elements like punctuation, websites, numbers, and symbols were removed. The resulting word list was refined by eliminating low-frequency words and connectors, converting all text to lowercase, and standardizing terms with multiple spellings. The tokenization was performed using Python version 3.12.6, a versatile programming language ideal for scripting and data analysis, which allowed us to identify the most frequent terms for each year.

The final list of the 100 most significant words was exported to Excel version 16.77 for further analysis. Using the Gephi software version 0.10, these results were processed into a graphical representation in which vectors illustrate connections between words, and nodes represent the words themselves. Figure 1 includes a flowchart of this review, depicting the conceptual analysis based on an adaptation of the PRISMA flow diagram.

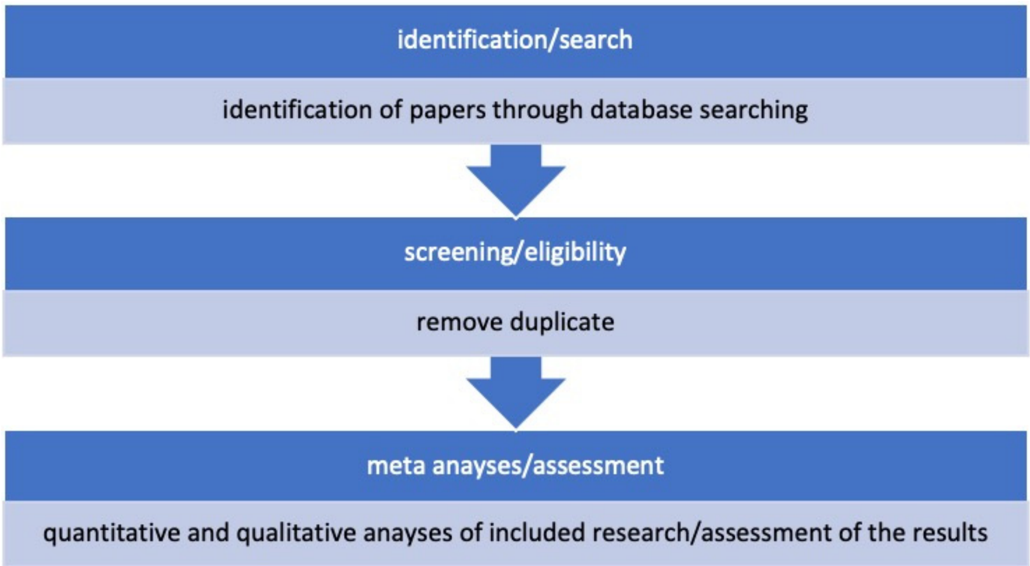

Figure 1. Research flow diagram.

2.3. Cluster Definition

A cluster analysis was conducted by grouping words with similar meanings into clusters, thus facilitating a multidisciplinary analysis by identifying key connections across different fields. Four clusters were selected to sufficiently cover the research scope while avoiding over-classification. The identified clusters are "Sustainability" (environmental and socio-economic concerns), "Bioresources" (types and sources of agricultural waste or products used for building materials), "Building Materials and Techniques" (energy and thermal performance analysis), and "Process and Methods" (design processes used to create building components).

Each of the 100 most relevant terms identified was assigned to the most appropriate cluster. Subsequently, a sub-cluster classification was performed to provide a more detailed analysis of the reviewed manuscripts, and the composition of the clusters is detailed in Table 5.

Table 5. Cluster composition.

Cluster	Lemmas
SUSTAINABILITY	environment—sustainable—waste—rural—urban—impact—field—emissions—social—land—traditional—recycling—economic—alternative—cost—community—life cycle carbon—green—climate—forest—health—change—global—human—wastes—ecological—farmers—impacts society—air landscape city—nature—solar—challenges—climate—change—risk—local—water—soil
BIORESOURCES	fly ash—organic—product—sand—concrete—cement—composite—bricks—component—plant—agricultural—natural—wood—food—bio-based—resources—biomass—composite—ash—fibers—utilization
BUILDING MATERIALS AND TECHNIQUES	building—construction—analysis—properties—energy—performance—characteristics—assessment—structure—structures—test—quality—parameters—strength—structural—thermal—efficiency—building materials—technologies—evaluation—engineering—housing—number—compressive strength—levels—resistance—wall—heat—construction materials—case study—behavior—power—tests—mechanical properties—temperature
PROCESS AND METHODS	production—system—development—model—design process—data—method—components—addition—industry—samples—processes—industrial—produced—information—strategies—treatment—activities—concentrations—density acid—elements—storage—techniques practices—complex—novel—integrated—composition—surface—management—application—effective—rate—technology

3. Results and Discussions

3.1. Analysis of the Trends

Firstly, the publication trend over the temporal range considered in this study was evaluated, and Figure 2 shows the results: From 2000 to 2015, there was a slight growth in publications, and from 2016 to 2023, the increment accelerated rapidly. Between 2000 and 2015, the number of manuscripts published per year varied from 74 to 362, and between 2016 and 2023, it increased from an initial total of 440 to 1242.

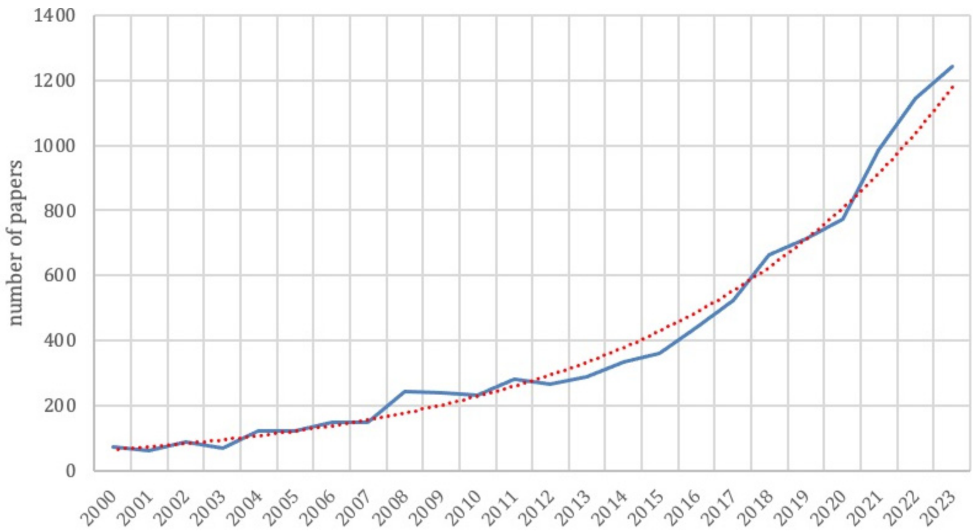

Figure 2. Manuscripts published per year (blue line) over the period 2000–2023, the red line is showing the trend curve.

The considerable growth in publications is due to the global increase in publications, but also to the augmented interest of scholars on these topics. Furthermore, the exponential growth in publications since 2015 seems to be influenced by the Circular Economy Action Plan (CEAP), adopted by the European Commission and approved in 2015, promoting actions to improve Europe’s transition from a linear economy toward a circular one, in accordance with the main global policies of environmental sustainability.

Subsequently, the top five contributing countries in the field of this review were identified, and the results are presented in Figure 3. The United States was the leading contributor with 1394 publications, accounting for 14% of the total. China followed with 13% of the total, while India contributed 7%, the UK 6.8%, and Italy 6.3% (610 publications). Together, these contributing countries produced over 49% of all publications on the subject across all continents.

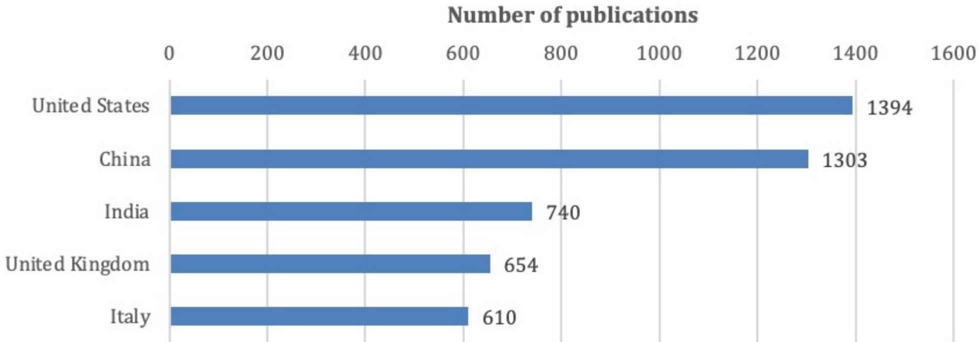

Figure 3. Top five countries contributors over the period 2000–2023.

3.2. Research on Most Recurrent Terms

Using .txt and .csv files, the trends of the 12 most significant thematic word occurrences over the 24-year period observed were assessed, and the obtained results are shown in Figure 4 and Table 2. The top 12 most frequent thematic words are biomass, compressive strength, concrete, recycling, waste management, agricultural waste, bio-based material, circular economy, insulation, life cycle assessment, mortar, sustainability, and agricultural waste.

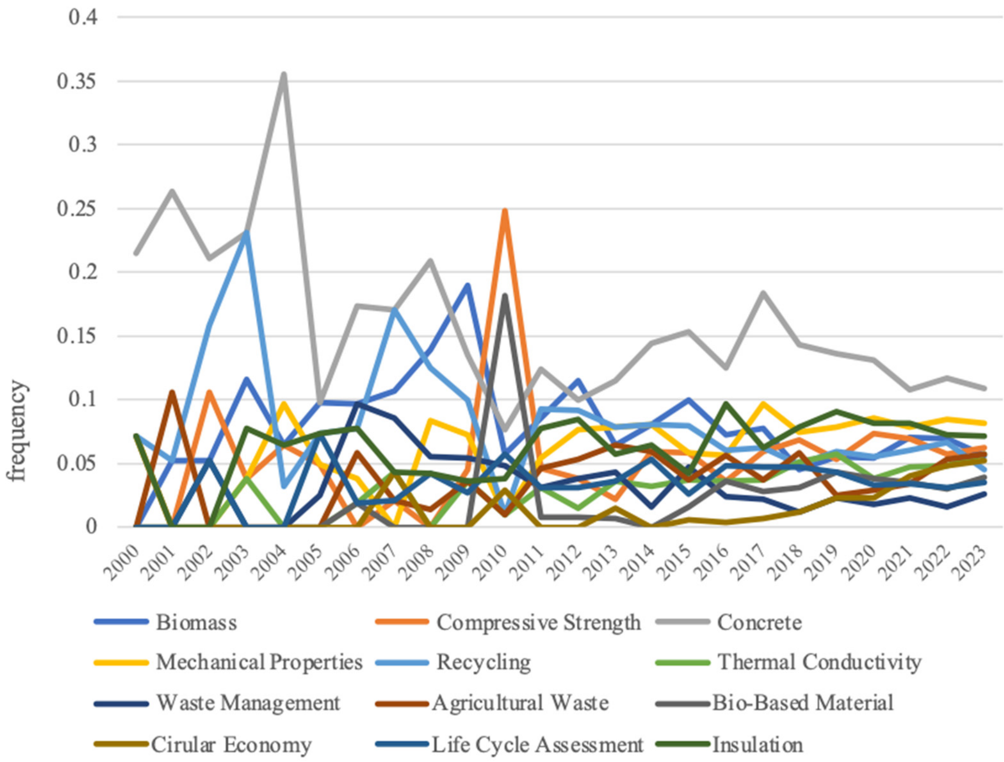

Figure 4. Trends of the 12 thematic words over the period 2000–2023.

3.3. Cluster Analysis

In the analysis, the top 100 words, derived from a tokenization process of the most frequently used terms, were categorized into one of four conceptual clusters. The cluster sizes were then determined by calculating the total weight of the terms within each cluster. The most significant prevalence was detected in the "Sustainability" cluster (28.85%), followed by "Building Materials and Techniques" with 28.07%, "Process and Methods" with 23.79%, and "Bioresources" with 19.29%. However, during the observed time range, the four clusters were well balanced. Figure 5 illustrates the cluster composition results, showing that the area of the pie chart is proportional to the percentage of words included in the cluster.

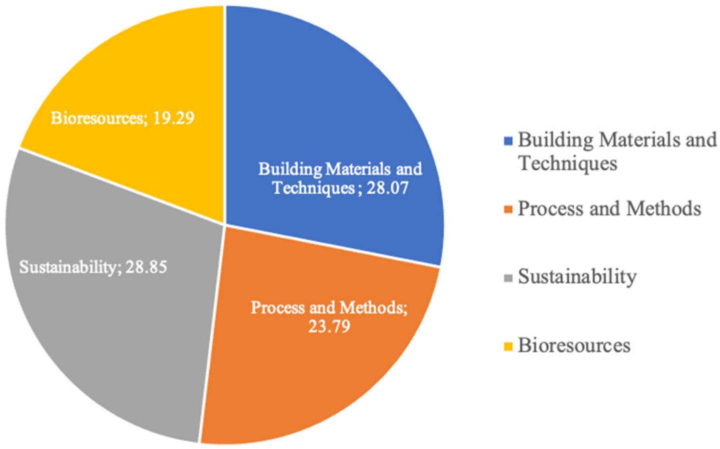

Figure 5. Cluster size: percentage of topics included in the four clusters over the period 2000–2023.

The next phase considered the trends of the four clusters over the years, as shown in Figure 6. These trends were assessed over four six-year periods (2000–2005; 2006–2011; 2012–2017; 2018–2023). For the principal cluster, representing the subject "Sustainability", a decrease was observed in the first three periods, and a slight increase in the last one. The second cluster, "Building Materials and Techniques", exhibited constant growth for all four periods, reaching a frequency of 29.14% in the last period, thus exceeding the "Sustainability" frequency of 28.96%. The cluster "Process and Methods" exhibited a slight decrease for the first three periods and a constant trend during the 2012–2017 and 2018–2023 periods. The smaller cluster concerning the theme of "Bioresources" registered a constant tendency from the period 2000–2005 to 2006–2011, a peak in frequency during the third period (reaching 21.45%), and a slight decrease in the final period.

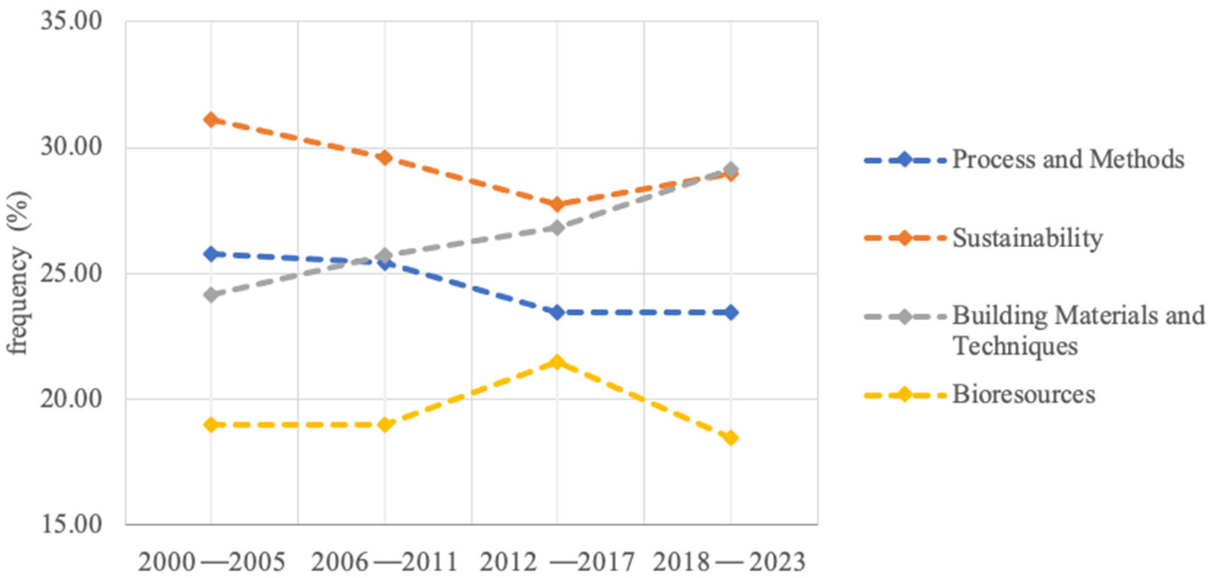

Figure 6. Trends of the four clusters over the period 2000–2023.

Subsequently, the trends of the top five words inside each of the four clusters have been evaluated. Additionally, in this case, the trends were observed over the four six-year periods (2000–2005; 2006–2011; 2012–2017; 2018–2023), and Figure 7 shows the results of this analysis. The five most used words within the cluster Sustainability were environmental, land, rural, waste, and water; for Process and Methods, they were process, management, method, component, and production.

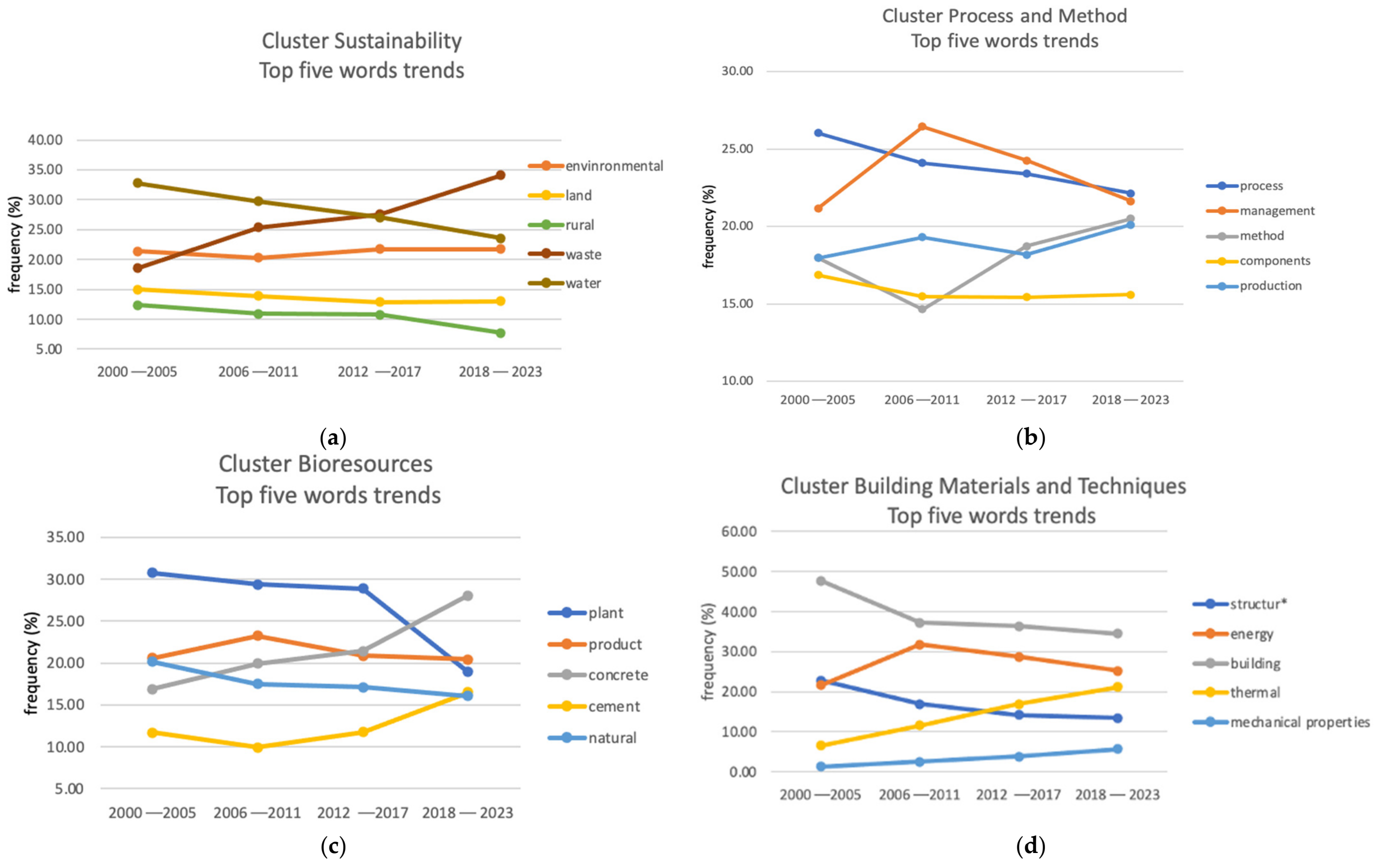

Figure 7. Trends of the top five terms detected within each cluster: sustainability (**a**), process and methods (**b**), bioresources (**c**) and building materials and techniques (**d**). Structur* represents the possible words: structure, structural and structures.

The top five words within the cluster Building Materials and Techniques were building, energy, mechanical properties, structural, and energy. Within the cluster Bioresources, the five most used words are plant, concrete, product, cement, and natural. This preliminary analysis of cluster compositions gives the first results concerning the trends of the research topic of interest over the period observed.

3.4. Sub-Cluster Analysis

To gain a more detailed understanding of the identified research, the four main clusters were subdivided into 13 sub-clusters to more accurately classify heterogeneous terms.

Sustainability was divided into "Environment" (44.48%), "Social" (25.23%), "Economic" (20.41%), and "Climate" (9.88%), covering ecological, social, economic, and climate-related aspects.

The sub-cluster "Environment" concerns all terms regarding ecological aspects, i.e., sustainability, impact, pollution, landscape, land, water, air, soil, forest, nature, field, and green. "Social" includes all social aspects of sustainability, such as rural, urban, social, local, traditional, community, health, human, city, farmers, and society. The sub-cluster "Economic" encloses all terms regarding economic aspects, such as waste, recycling, economic, cost, life cycle, and carbon. The last sustainability sub-cluster is "Climate", consisting of all terms regarding climate aspects: emissions, climate, global, solar, and climate change. The sub-cluster divisions of "Sustainability" are inspired by the three pillars of sustainability: environmental, social, and economic [65].

Building Materials and Techniques was split into "Properties", "Engineering", and "Energy Efficiency", focusing on technical characteristics, construction methods, and energy performance. Process and Methods was categorized into "Application", "Design/Analysis", and "Production", addressing building component fields, design processes, and production methods. Bioresources was divided into "Source/Origin", "Constituent", and "Building Component", covering raw material sources, material composition, and building components.

Figure 8 illustrates these sub-clusters, wherein the size of each reflects the proportion of terms within them.

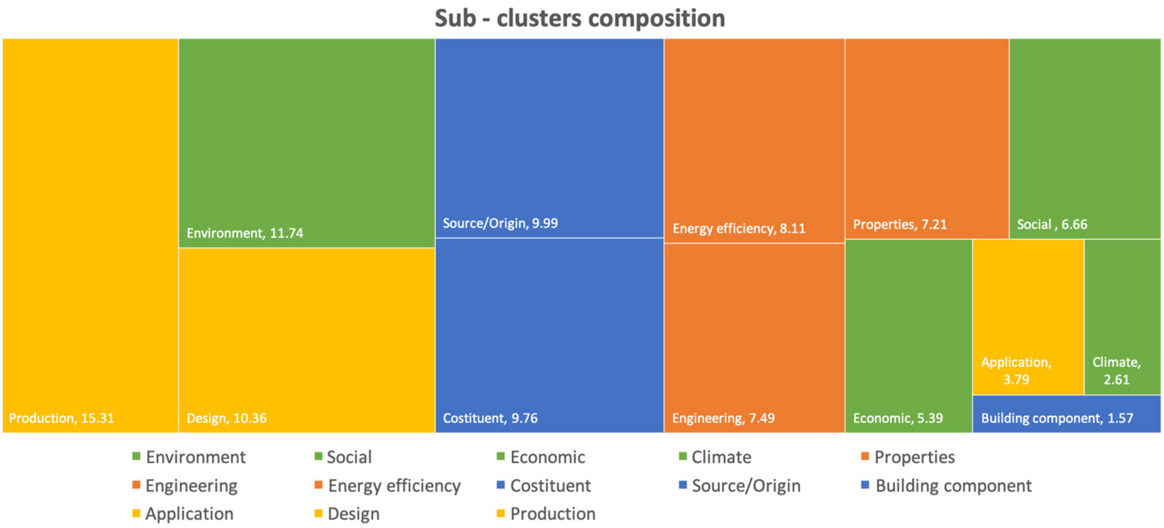

Figure 8. Outline of the 13 sub-clusters identified.

Within each cluster, the relative significance of each sub-cluster was evaluated over the 24-year period observed. Figure 9 shows the word occurrences relating to sub-clusters over the four six-year periods, and by analyzing these data, the sub-clusters concerning Sustainability show comparable behavior among all the four six-year periods investigated. Environment emerged above the other sub-clusters with an average frequency of 38.31%; Social registered an average frequency of 34.98%; Economic, 19.65%; and finally, Climate, 7.06%.

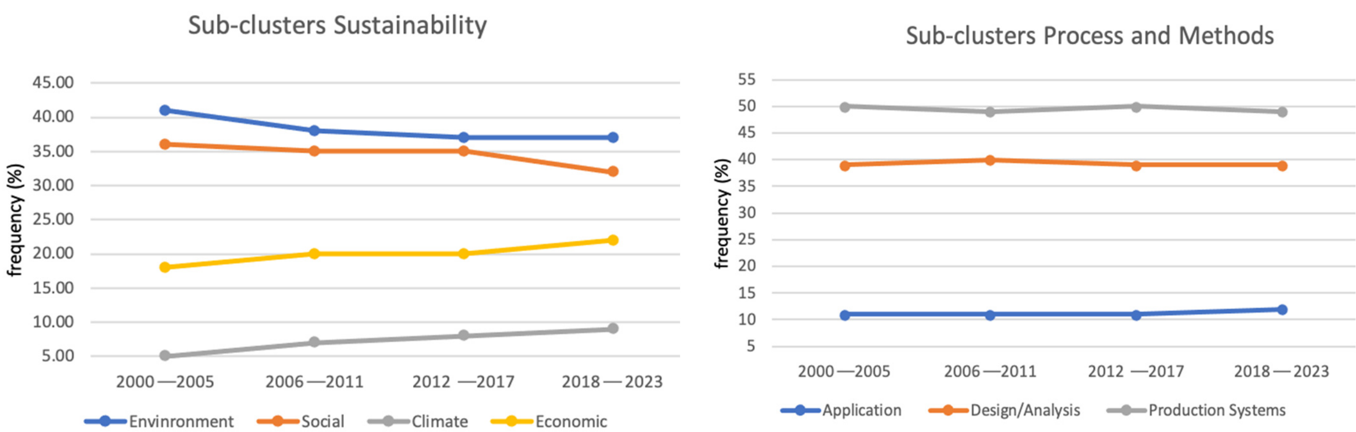

Figure 9. *Cont.*

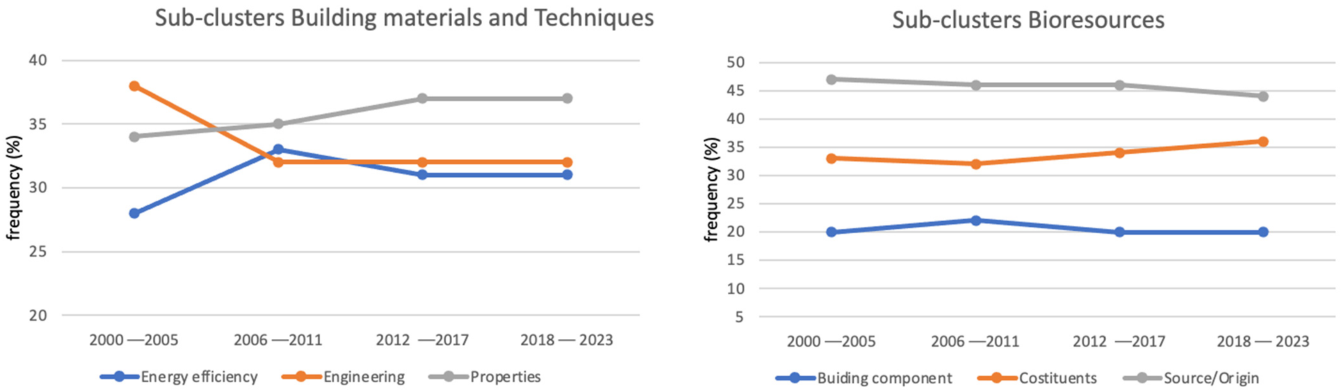

Figure 9. Trends of the 13 sub-clusters over the period 2000–2023.

Within the cluster Building Materials and Techniques, between the first and second observed periods (from 2000–2005 to 2006–2011), Engineering registered a rapid decrease; in the same interval, Energy Efficiency exhibited a straight increase, and Properties a constant behavior.

From 2011 to 2017, the sub-clusters exhibited a constant tendency, with little change in the last period. Furthermore, the sub-clusters of Sustainability exhibited a more equilibrate composition, which demonstrated a comparable level of research interest in all the three sub-clusters concerning the subject. Specifically, Properties had an average frequency of 35.50%; Engineering, 32.96%; and Energy Efficiency, 31.55%.

By considering the trends and composition of sub-clusters within Process and Methods, a constant trend is observed during all the analyzed periods; the sub-cluster composition is 49.41% for Production, 38.76% for Design/Analysis, and 11.83% for Application. In the Bioresources cluster, the trends observed were comparable for all the three sub-clusters; upon analyzing the sub-cluster composition, it emerged that the theme concerning the Source/Origin of bio-composites is the most interesting for scholars, with an average frequency of 45.27%, followed by Constituents with 34.39%, and Building Component with 20.42%.

3.5. Interrelationships between Terms

The highest number of relationships was found between “Building Materials and Techniques” and “Process and Methods” with 8486 occurrences, followed by “Sustainability” and “Building Materials and Techniques” with 7771 interconnections. “Sustainability” and “Process and Methods” had 7725 links, while “Bioresources” and “Building Materials and Techniques” exhibited 7106 relationships. There were 7047 occurrences between “Bioresources” and “Process and Methods” and 6474 links between “Bioresources” and “Sustainability”. Figure 10 illustrates these relationships, with different colors representing the various clusters and edge thickness indicating the number of connections. Key interconnections include terms related to “Sustainability” and “Building Materials and Techniques” (e.g., sustainable–building, recycling–concrete) and “Bioresources” and “Process and Methods” (e.g., plant–design, material–composites). Strong correlations also exist between “Sustainability” and “Bioresources” (e.g., rural–bio-based, soil–material).

Temporal analyses of research trends registered a considerable growth during the 24-year period observed, with an increase of about 1241% in publications (Figure 2).

Specifically, the research interest in the subject of our review, i.e., bio-based materials for building applications, reached a peak after the 2015. This sudden growth was influenced by the Circular Economy Action Plan (CEAP), adopted by the European Commission in 2015 [8].

The trends of the most recurrent and significative words were analyzed before their cluster classification (Figure 4). These raw data were important in implementing the subsequent analyses and classification to determine the four cluster subject areas. Except for an initial misaligned behavior at the end of the range, the 12 thematic words exhibited a comparable frequency, indicating that scholars focused on multiple aspects of the topic, with no prevalence of some over others (Figure 4).

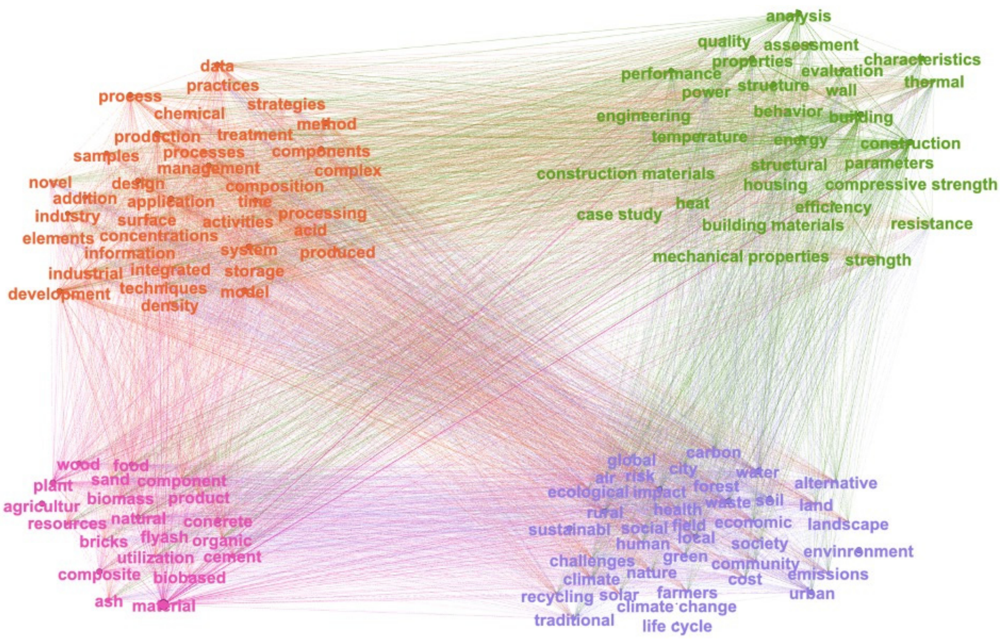

Figure 10. Overview of the words grouped into clusters. Different colors represent different clusters. Edges express the co-occurrence of topics. The thickness and darker color of the edges indicate a higher number of connections.

To analyze the evolution of research themes over a 24-year period, the data were divided into four six-year intervals: 2000–2005, 2006–2011, 2012–2017, and 2018–2023. The analysis revealed four balanced clusters: Sustainability, Building Materials and Techniques, Bioresources, and Process and Methods.

Key Findings:

- Sustainability: This was the most studied cluster, but it showed a decline in research focus from 2017. From 2012, both the Sustainability and Building Materials and Techniques clusters grew, with Building Materials and Techniques surpassing Sustainability in the most recent period (29.14% vs. 28.96%).
- Building Materials and Techniques: This cluster saw a significant increase in research interest, highlighting a growing focus on material properties, design processes, and techniques.
- Bioresources: This cluster had the lowest frequency (19.29%). The focus therein was more on the sources of bio-based materials than their applications in building components, indicating a gap in the research on practical applications.
- Process and Methods: Topics here remained consistent over time. The most frequently discussed sub-clusters were Production Systems (49.1%) and Design/Analysis (38.6%), with fewer studies on Application (11.83%), pointing to a gap between research and practical implementation.
- Word Frequency Trends: In the Sustainability cluster, the word “waste” exhibited a significant increase, reflecting a growing focus on waste valorization. Other words, like “environmental” and “water”, showed varied trends. In the Building Materials and Techniques cluster, energy efficiency gained prominence from 2000–2005 to 2006–2011.
- Sub-cluster Insights: Within the Sustainability cluster, the focus was on environmental, social, and economic aspects, with less attention to climate issues. The Building Materials and Techniques cluster saw an increased interest in energy efficiency, while the Process and Methods cluster remained stable, with a noticeable gap in the application of bio-based materials.

The use of natural wastes in bio-based building materials presents advantages and disadvantages, as specified in Table 6.

Table 6. Advantages and disadvantages of bio-based building materials.

Pros	Cons
Energy Efficiency: Bio-based building materials often contribute to energy efficiency in buildings by providing good thermal insulation and reducing heating and cooling needs.	*Development Stage:* Many natural-based materials are still in the prototype phase and require further development to address critical issues such as fire safety and moisture resistance.
Fire and Mold Resistance: Many natural fibers, such as hemp and flax, offer inherent resistance to fire and mold, enhancing building safety and durability.	*Certification Standards:* To be widely accepted in the construction industry, these materials must meet established certification standards, which can be a lengthy and costly process.
Lightweight Properties: These materials are generally lighter than traditional construction materials, which can reduce structural load and construction costs.	*Durability and Sustainability Concerns:* There are ongoing concerns about the long-term durability and true sustainability of these materials, as well as their performance under various environmental conditions.
Climate Regulation: They help regulate indoor climate and humidity, improving overall indoor air quality and comfort.	*Resource-Intensive Pre-Manufacturing:* The pre-manufacturing phase, including cleaning and preparing raw materials, can be resource-intensive and expensive.
CO_2 Capture: Bio-based materials can capture and store CO_2 from the atmosphere during their growth phase, potentially offsetting greenhouse gas emissions.	*Environmental Impact of Production:* The environmental impact of production processes needs to be minimized. Efforts could include reducing the use of additives or exploring alternative production methods, such as using seawater for washing wool.
Non-Toxicity: Unlike petrochemical-based products, bio-based materials are free from toxic chemicals, thus reducing health risks associated with indoor air pollution.	*Variability in Properties:* The properties of natural fiber-based materials can vary significantly depending on factors such as chemical composition, plant type, production methods, and environmental conditions like location, climate, and harvesting or dairying techniques.
Recyclability and Biodegradability: At the end of their lifecycle, these materials can be recycled or biodegraded, thus supporting a zero-waste economy.	
Longevity: Many natural materials are durable and can last for centuries, contributing to the sustainability of the built environment.	

Overall, using agricultural wastes supports the development of sustainable and eco-friendly construction materials enhancing the physical, mechanical, and thermal properties of the bio-derived materials.

Utilizing biomass for construction can be a feasible strategy, if it is properly regulated and considers the rising demand for biomaterials in construction and other high-demand fields. Future research needs to address land use dynamics, which pose significant challenges when evaluating new land uses such as biomass production and deforestation mitigation. These challenges highlight the importance of a circular bioeconomy approach, where waste from various biomass uses (agricultural, energy, and industrial) is recycled into raw materials for producing different types of bio-concretes, based on local availability.

Future research should prioritize extensive laboratory testing to thoroughly evaluate the properties of the proposed materials. This includes assessing their mechanical, thermal, and acoustic performance, as well as their durability, fire resistance, moisture tolerance, and environmental impact. Additionally, long-term studies are needed to explore the materials' behavior under real-world conditions, including their lifecycle performance, degradation over time, and interaction with other construction elements. Understanding these aspects will help validate the materials' suitability for various construction applications and inform necessary improvements or optimizations.

4. Life Cycle Assessments (LCAs) and Environmental Issues

Due to the high importance of life cycle assessments in sustainability, a further analysis has been performed by considering research addressing this topic.

A life cycle assessment is a comprehensive tool used to analyze and evaluate the costs and environmental impacts associated with a product, system, or service throughout its entire life cycle, from "cradle to grave" [66].

An LCA tracks all stages of a product's life cycle, from raw material extraction to manufacturing, usage, recycling, and final disposal, aiming to identify and quantify its impacts at each phase. The assessment evaluates the environmental, cost, and benefit aspects across the entire life cycle, offering a systematic framework to assess inputs, outputs, and environmental impacts of materials and energy throughout a product or service's life span.

Bilec et al. described a tailored approach for assessing the environmental impact of the construction sector, based on two primary methods for conducting an LCA: the Process Method, and the Input–Output (I/O) Method [67]. The Process Method represents a life cycle assessment as a process flow diagram and sets a specific point where the flow between processes and emissions becomes negligible, marking the end of the process. On the other hand, the I/O Method addresses the issue from an operational standpoint by using a matrix that accounts for the impact of each stage of the life cycle on the overall life cycle of a product or service.

In this review, almost 7% of the analyzed manuscripts, i.e., 631 studies, focused on issues relating to a life cycle assessment (LCA) and included LCA among their keywords. LCA is employed to evaluate the environmental performance of circular bio-based building solutions at the material scale in 417, at the component scale in 196, and at the building scale in 20 studies.

Rivas-Aybar et al. [68] used ISO 14040:2006 [69] guidelines to assess the carbon footprint (CF) of hemp-based building materials in Western Australia, considering local variations. For 1 m^2 of hemp-based board, the CF was estimated at -2.302 kg CO_2 eq. The main emission sources were electricity from the public grid for binder production (26%) and urea production (14%). Electricity from the public grid during the post-farm stage accounted for 45% of total emissions. Replacing this electricity with solar power reduced the CF by 164%, highlighting that hemp-based boards have lower embodied GHG emissions compared to traditional materials like gypsum plasterboards.

Füchsl et al.'s review highlighted that the most extensively studied renewable insulation materials are cork, cellulose, and hemp. Specifically, hemp, binders, and additives are the main causes of environmental impacts [70].

Ardente et al. performed a life cycle assessment of kenaf fiber insulation boards, adhering to ISO 14040 standards [69], covering all stages from production to disposal and evaluating the board's environmental and energy benefits in a typical residential setting. The study compared different insulating materials, identified key environmental impact sources, and highlighted areas with the greatest potential for improvement. The results reveal that the Global Energy Requirements (GER) amount to 59.37 MJPrim/f.u., where the functional unit (fu) is equal to the mass (kg) of insulating board with a thermal resistance R of 1 (m^2 K/W). Specifically, incorporating polyester fibers as a filler in the kenaf fiber insulation board led to substantial energy use, accounting for approximately 35% of the GER. Notably, around 38% of the total energy consumption comes from renewable sources, such as biomass. The results concerning energy and environmental comparisons of some conventional and unconventional insulation materials are reported in Table 7 [71].

Van der Lugt et al. focused on the potential of bamboo as a building material. Bamboo culms were environmentally and financially assessed and compared to traditional building materials, e.g., steel, concrete, and timber. From the study results, the authors affirmed that bamboo is a very sustainable building material and can be compared to more commonly used materials. From a sustainability point of view, bamboo culm is 20 times more favorable than its alternatives. The authors found that the environmental load (in mPt) of 1 kg of bamboo culm is composed of 99.4 for transportation, 3.2 for processing, and 1.6 for preservation [72].

Table 7. Energy and environmental comparison of conventional and unconventional insulation materials.

	Sheep Wool	Hemp	Flax	Cork	Mineral Wool	Glass Fiber	EPS	References
NRE * [MJ/kg]	12.3	-	4.4	-	17	43	95	[29]
GWP ** [kgCO_2eq]	−0.3	2.4	0.0	1.1	1.2	2.1	2.3	[29,70]
Primary Energy consumption [MJ/kg]	15	1.30	35	10	23	38	110	[29,70]
Total wastes [kg]	-	-	0.122	-	0.054	6.6	-	[70]

* NRE = non-renewable energy, ** GWP = global warming potential

In conclusion, by reviewing the research analysis, it transpires that, despite a substantial body of literature on life cycle assessments, significant gaps remain in the methodologies employed, which can be categorized into several key areas:

Standardization and Consistency: One of the primary issues is the lack of standardized methodologies across different studies. While an LCA is a well-established framework, variations in how different studies define boundaries, select impact categories, and interpret results can lead to inconsistencies. This lack of uniformity makes it challenging to compare results across studies and hinders the development of universally applicable conclusions.

Data Quality and Availability: The reliability of LCA outcomes heavily depends on the quality and availability of data, with studies often relying on outdated or incomplete datasets, which can affect the accuracy of the results. Furthermore, data availability can vary significantly between regions and industries, leading to gaps in the assessment of certain products or processes.

Impact Assessment Methodologies: The methodologies used for an impact assessment in an LCA are continually evolving. However, there is still a lack of consensus on which methods are the most appropriate for different types of products and impacts. For example, assessing environmental impacts such as resource depletion or social impacts may lack robust methodologies, leading to potential inaccuracies in the assessment.

Temporal and Spatial Considerations: LCAs often present challenges related to temporal and spatial variability, in that the environmental impacts of products and processes can change over time and vary by location. Many LCA studies do not adequately account for these factors, which can lead to misleading results. Addressing these considerations is, therefore, crucial for developing more accurate and relevant assessments.

Integration of Emerging Technologies and Practices: As new technologies and practices emerge, LCA methodologies need to adapt to incorporate these changes. For instance, advancements in renewable energy or circular economy practices may not yet be fully integrated into traditional LCA approaches. Keeping methodologies up to date with the latest technological developments is essential for ensuring their relevance and accuracy.

Addressing these gaps involves the ongoing research and refinement of LCA methodologies, which includes enhancing data quality, standardizing practices, incorporating emerging technologies, and broadening the scope of impact assessments. By addressing these challenges, LCAs can provide more accurate and comprehensive insights into the environmental and social performance of products and processes, ultimately supporting more informed decision making and sustainable development.

5. Conclusions

In this review, through the analysis of scientific publications focusing on bio-based building materials and published in the last 24 years, it was possible to draw a tendency line and detect the gaps existing in the literature. Furthermore, this analysis constitutes an efficient tool for setting the direction of future research. This study aimed to describe the trends of the most relevant research topics over the observed period and to contribute by developing a useful tool for future studies. The correlations between the most relevant terms were assessed by highlighting their occurrences within scientific articles. Furthermore, research gaps within this subject have also been identified, which will serve as a useful guide for future research and development. Aspects such as sustainability, the source of bio-based materials, building applications, design/analysis, properties, and process and methods have been deeply investigated and evaluated. This study's findings should be used for improving the reconversion of waste as bio-based materials for building purposes.

Generally, natural wastes offer promising benefits for sustainable construction, and addressing their current limitations and improving their overall environmental impact are essential for broader adoption and effectiveness.

Overall, the research has shifted from broad sustainability themes to a more detailed investigation of building materials and techniques, with growing attention to their efficiency and performance [73]. However, there are still gaps in the practical application of bio-based materials and integration into building components.

Future development of the research in this field will be oriented toward developing laboratory-scale applications into practical ones by integrating bio-based materials derived from agricultural wastes into rural building construction. This will contribute to the sustainability of rural infrastructure by utilizing locally available resources and reducing environmental impacts.

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References

1. Li, Y.; Rong, Y.; Ahmad, U.M.; Wang, X.; Zuo, J.; Mao, G. A Comprehensive Review on Green Buildings Research: Bibliometric Analysis during 1998–2018. *Environ. Sci. Pollut. Res.* **2021**, *28*, 46196–46214. [CrossRef] [PubMed]
2. Ghaffarianhoseini, A.; Dahlan, N.D.; Berardi, U.; Ghaffarianhoseini, A.; Makaremi, N.; Ghaffarianhoseini, M. Sustainable Energy Performances of Green Buildings: A Review of Current Theories, Implementations and Challenges. *Renew. Sustain. Energy Rev.* **2013**, *25*, 1–17. [CrossRef]
3. Turco, C.; Paula Junior, A.C.; Teixeira, E.R.; Mateus, R. Optimisation of Compressed Earth Blocks (CEBs) Using Natural Origin Materials: A Systematic Literature Review. *Constr. Build. Mater.* **2021**, *309*, 125140. [CrossRef]
4. Velasco, P.M.; Ortiz, M.P.M.; Giró, M.A.M.; Melia, D.M.; Rehbein, J.H. Development of Sustainable Fired Clay Bricks by Adding Kindling from Vine Shoot: Study of Thermal and Mechanical Properties. *Appl. Clay Sci.* **2015**, *107*, 156–164. [CrossRef]
5. Volf, M.; Diviš, J.; Havlík, F. Thermal, Moisture and Biological Behaviour of Natural Insulating Materials. In *Energy Procedia*; Elsevier Ltd.: Amsterdam, The Netherlands, 2015; Volume 78, pp. 1599–1604.
6. Ingrao, C.; Lo Giudice, A.; Bacenetti, J.; Tricase, C.; Dotelli, G.; Fiala, M.; Siracusa, V.; Mbohwa, C. Energy and Environmental Assessment of Industrial Hemp for Building Applications: A Review. *Renew. Sustain. Energy Rev.* **2015**, *51*, 29–42. [CrossRef]
7. Abdou, N.; EL Mghouchi, Y.; Hamdaoui, S.; EL Asri, N.; Mouqallid, M. Multi-Objective Optimization of Passive Energy Efficiency Measures for Net-Zero Energy Building in Morocco. *Build. Environ.* **2021**, *204*, 108141. [CrossRef]
8. European Commission. *European Commission Circular Economy Action Plan*; European Commission: Brussels, Belgium, 2020; Volume 28. [CrossRef]
9. Obi, F.; Ugwuishiwu, B.; Nwakaire, J. Agricultural Waste Concept, Generation, Utilization and Management. *Niger. J. Technol.* **2016**, *25*, 957–964. [CrossRef]

10. Kizinievič, O.; Kizinievič, V.; Pundiene, I.; Molotokas, D. Eco-Friendly Fired Clay Brick Manufactured with Agricultural Solid Waste. *Arch. Civ. Mech. Eng.* **2018**, *18*, 1156–1165. [CrossRef]
11. González-Sánchez, C.; Martínez-Aguirre, A.; Pérez-García, B.; Martínez-Urreaga, J.; De La Orden, M.U.; Fonseca-Valero, C. Use of Residual Agricultural Plastics and Cellulose Fibers for Obtaining Sustainable Eco-Composites Prevents Waste Generation. *J. Clean. Prod.* **2014**, *83*, 228–237. [CrossRef]
12. Brojan, L.; Petric, A.; Clouston, P.L. A Comparative Study of Brick and Straw Bale Wall Systems from Environmental, Economical and Energy Perspectives. *ARPN J. Eng. Appl. Sci.* **2013**, *8*, 920–926.
13. Hill, C.; Norton, A.; Dibdiakova, J. A Comparison of the Environmental Impacts of Different Categories of Insulation Materials. *Energy Build.* **2018**, *162*, 12–20. [CrossRef]
14. Obi, F.O.; Ugwuishiwu, B.O.; Nwakaire, J.N.; El-Haggar, S.M. Agri Wastes. *Niger. J. Technol.* **2016**, *35*, 223–260.
15. Velasco, P.M.; Ortiz, M.P.M.; Giro, M.A.M.; Castelló, M.C.J.; Velasco, L.M. Development of Better Insulation Bricks by Adding Mushroom Compost Wastes. *Energy Build.* **2014**, *80*, 17–22. [CrossRef]
16. Vatani Oskouei, A.; Afzali, M.; Madadipour, M. Experimental Investigation on Mud Bricks Reinforced with Natural Additives under Compressive and Tensile Tests. *Constr. Build. Mater.* **2017**, *142*, 137–147. [CrossRef]
17. Ionescu, G.-L. Passive House. *J. Appl. Eng. Sci.* **2017**, *7*, 23–27. [CrossRef]
18. Vox, G.; Schettini, E.; Science, E.; Campiotti, C.A.; Viola, C.; Unit, A.; Anguillarese, V.; Alonzo, G.; Blanco, I.; Mugnozza, G.S. Building Climate Control by Means of Passive Systems. In Proceedings of the AgEng2014: International Conference of Agricultural Engineering, Zurich, Switzerland, 6–10 July 2014.
19. Binici, H.; Aksogan, O.; Demirhan, C. Mechanical, Thermal and Acoustical Characterizations of an Insulation Composite Made of Bio-Based Materials. *Sustain. Cities Soc.* **2016**, *20*, 17–26. [CrossRef]
20. Bouguerra, A.; Ledhem, A.; Barquin, F.; Dheilly, R.M.; Queneudec, M. Effect of Microstructure on the Mechanical and Thermal. *Cem. Concr. Res.* **1998**, *28*, 1179–1190. [CrossRef]
21. Shahzad, A. A Study in Physical and Mechanical Properties of Hemp Fibres. *Adv. Mater. Sci. Eng.* **2013**, *2013*, 325085. [CrossRef]
22. Dungani, R.; Karina, M.; Subyakto; Sulaeman, A.; Hermawan, D.; Hadiyane, A. Agricultural Waste Fibers towards Sustainability and Advanced Utilization: A Review. *Asian J. Plant Sci.* **2016**, *15*, 42–55. [CrossRef]
23. Liuzzi, S.; Rubino, C.; Martellotta, F.; Stefanizzi, P.; Casavola, C.; Pappalettera, G. Characterization of Biomass-Based Materials for Building Applications: The Case of Straw and Olive Tree Waste. *Ind. Crops Prod.* **2020**, *147*, 112229. [CrossRef]
24. Sanjay, M.R.; Madhu, P.; Jawaid, M.; Senthamaraikannan, P.; Senthil, S.; Pradeep, S. Characterization and Properties of Natural Fiber Polymer Composites: A Comprehensive Review. *J. Clean. Prod.* **2018**, *172*, 566–581. [CrossRef]
25. Perrot, A.; Rangeard, D.; Menasria, F.; Guihéneuf, S. Strategies for Optimizing the Mechanical Strengths of Raw Earth-Based Mortars. *Constr. Build. Mater.* **2018**, *167*, 496–504. [CrossRef]
26. Das, O.; Kim, N.K.; Sarmah, A.K.; Bhattacharyya, D. Development of Waste Based Biochar/Wool Hybrid Biocomposites: Flammability Characteristics and Mechanical Properties. *J. Clean. Prod.* **2017**, *144*, 79–89. [CrossRef]
27. Saba, N.; Paridah, M.T.; Jawaid, M. Mechanical Properties of Kenaf Fibre Reinforced Polymer Composite: A Review. *Constr. Build. Mater.* **2015**, *76*, 87–96. [CrossRef]
28. Sood, M.; Dwivedi, G. Effect of Fiber Treatment on Flexural Properties of Natural Fiber Reinforced Composites: A Review. *Egypt. J. Pet.* **2018**, *27*, 775–783. [CrossRef]
29. Asdrubali, F.; D'Alessandro, F.; Schiavoni, S. A Review of Unconventional Sustainable Building Insulation Materials. *Sustain. Mater. Technol.* **2015**, *4*, 1–17. [CrossRef]
30. Xia, Z.; Yao, C.; Zhou, J.; Ye, W.; Xu, W. Comparative Study of Cotton, Ramie and Wool Fiber Bundles' Thermal and Dynamic Mechanical Thermal Properties. *Text. Res. J.* **2016**, *86*, 856–867. [CrossRef]
31. D'Alessandro, F.; Bianchi, F.; Baldinelli, G.; Rotili, A.; Schiavoni, S. Straw Bale Constructions: Laboratory, in Field and Numerical Assessment of Energy and Environmental Performance. *J. Build. Eng.* **2017**, *11*, 56–68. [CrossRef]
32. Nunes, L.; Cintura, E.; Parracha, J.L.; Fernandes, B.; Silva, V.; Faria, P. Cement-Bonded Particleboards with Banana Pseudostem Waste: Physical Performance and Bio-Susceptibility. *Infrastructures* **2021**, *6*, 86. [CrossRef]
33. Collet, F.; Prétot, S.; Pretot, S. Thermal Conductivity of Hemp Concretes: Variation with Formulation, Density and Water Content. *Constr. Build. Mater.* **2014**, *65*, 612–619. [CrossRef]
34. McGregor, B.A. Physical, Chemical, and Tensile Properties of Cashmere, Mohair, Alpaca, and Other Rare Animal Fibers. In *Handbook of Properties of Textile and Technical Fibres, 2nd, ed.*; The Textile Institute Book Series; Bunsell, A.R., Ed.; Woodhead Publishing: Cambridge, UK, 2018; pp. 105–136. ISBN 978-0-08-101272-7.
35. Dénes, O.; Florea, I.; Manea, D.L. Utilization of Sheep Wool as a Building Material. *Procedia Manuf.* **2019**, *32*, 236–241. [CrossRef]
36. Zach, J.; Korjenic, A.; Petránek, V.; Hroudová, J.; Bednar, T. Performance Evaluation and Research of Alternative Thermal Insulations Based on Sheep Wool. Energy Build. *Energy Build.* **2012**, *49*, 246–253. [CrossRef]
37. Galán-Marín, C.; Rivera-Gómez, C.; Bradley, F. The Mechanical Properties and Molecular Bonding Characteristics of Clay-Based Natural Composites Reinforced with Animal Fibres. *J. Biobased Mater. Bioenergy* **2013**, *7*, 143–151. [CrossRef]
38. Araya-Letelier, G.; Antico, F.; Parra Torres, P.; Carrasco, M. Fiber-Reinforced Mortar Incorporating Pig Hair. *Adv. Eng. Forum* **2017**, *21*, 219–225. [CrossRef]
39. Oliveira, M.A.; António, J. Animal-Based Waste for Building Acoustic Applications: A Review. *J. Build. Eng.* **2024**, *84*, 108430. [CrossRef]

40. Eliche-Quesada, D.; Felipe-Sesé, M.A.; López-Pérez, J.A.; Infantes-Molina, A. Characterization and Evaluation of Rice Husk Ash and Wood Ash in Sustainable Clay Matrix Bricks. *Ceram. Int.* **2017**, *43*, 463–475. [CrossRef]
41. Parisi, F.; Asprone, D.; Fenu, L.; Prota, A. Experimental Characterization of Italian Composite Adobe Bricks Reinforced with Straw Fibers. *Compos. Struct.* **2015**, *122*, 300–307. [CrossRef]
42. Grădinaru, C.M.; Bărbuță, M.; Șerbănoiu, A.A.; Babor, D. Investigations on the Mechanical Properties of Concrete With Sheep Wool Fibers and Fly Ash. *Bull. Transilv. Univ. Braşov* **2016**, *9*, 73–80.
43. Arrigoni, A.; Beckett, C.T.S.; Ciancio, D.; Pelosato, R.; Dotelli, G.; Grillet, A.C. Rammed Earth Incorporating Recycled Concrete Aggregate: A Sustainable, Resistant and Breathable Construction Solution. *Resour. Conserv. Recycl.* **2018**, *137*, 11–20. [CrossRef]
44. Abdul Khalil, H.P.S.; Bhat, I.U.H.; Jawaid, M.; Zaidon, A.; Hermawan, D.; Hadi, Y.S. Bamboo Fibre Reinforced Biocomposites: A Review. *Mater. Des.* **2012**, *42*, 353–368. [CrossRef]
45. Parlato, M.C.M.; Cuomo, M.; Porto, S.M.C. Natural Fibers Reinforcement for Earthen Building Components: Mechanical Performances of a Low Quality Sheep Wool ("Valle Del Belice" Sheep). *Constr. Build. Mater.* **2022**, *326*, 126855. [CrossRef]
46. Babé, C.; Kidmo, D.K.; Tom, A.; Mvondo, R.R.N.; Boum, R.B.E.; Djongyang, N. Thermomechanical Characterization and Durability of Adobes Reinforced with Millet Waste Fibers (Sorghum Bicolor). *Case Stud. Constr. Mater.* **2020**, *13*, e00422. [CrossRef]
47. Ouedraogo, M.; Bamogo, H.; Sanou, I.; Mazars, V.; Aubert, J.-E.; Millogo, Y. Microstructural, Physical and Mechanical Characteristics of Adobes Reinforced with Sugarcane Bagasse. *Buildings* **2023**, *13*, 117. [CrossRef]
48. Bouhicha, M.; Aouissi, F.; Kenai, S. Performance of Composite Soil Reinforced with Barley Straw. *Cem. Concr. Compos.* **2005**, *27*, 617–621. [CrossRef]
49. Chabriac, P.A.; Gourdon, E.; Gle, P.; Fabbri, A.; Lenormand, H. Agricultural By-Products for Building Insulation: Acoustical Characterization and Modeling to Predict Micro-Structural Parameters. *Constr. Build. Mater.* **2016**, *112*, 158–167. [CrossRef]
50. Giroudon, M.; Laborel-Préneron, A.; Aubert, J.-E.; Magniont, C. Comparison of Barley and Lavender Straws as Bioaggregates in Earth Bricks. *Constr. Build. Mater.* **2019**, *202*, 254–265. [CrossRef]
51. Cintura, E.; Nunes, L.; Esteves, B.; Faria, P. Agro-Industrial Wastes as Building Insulation Materials: A Review and Challenges for Euro-Mediterranean Countries. *Ind. Crops Prod.* **2021**, *171*, 113833. [CrossRef]
52. Sutcu, M.; Ozturk, S.; Yalamac, E.; Gencel, O. Effect of Olive Mill Waste Addition on the Properties of Porous Fired Clay Bricks Using Taguchi Method. *J. Environ. Manag.* **2016**, *181*, 185–192. [CrossRef]
53. Sierra-Pérez, J.; Boschmonart-Rives, J.; Dias, A.C.; Gabarrell, X. Environmental Implications of the Use of Agglomerated Cork as Thermal Insulation in Buildings. *J. Clean. Prod.* **2016**, *126*, 97–107. [CrossRef]
54. Muñoz Velasco, P.; Morales Ortíz, M.P.; Mendívil Giró, M.A.; Muñoz Velasco, L. Fired Clay Bricks Manufactured by Adding Wastes as Sustainable Construction Material—A Review. *Constr. Build. Mater.* **2014**, *63*, 97–107. [CrossRef]
55. Hung Anh, L.D.; Pásztory, Z. An Overview of Factors Influencing Thermal Conductivity of Building Insulation Materials. *J. Build. Eng.* **2021**, *44*, 102604. [CrossRef]
56. Lv, L.; Bi, J.; Yu, X.; Wang, X.; Wei, C.Y.; Cui, Y.Z. Sound Absorption Properties of Composites Made of Discarded Duck Feathers. *Tekst. Konfeksiyon* **2016**, *26*, 153–158.
57. Kusno, A.; Sakagami, K.; Okuzono, T.; Toyoda, M.; Otsuru, T.; Mulyadi, R.; Kamil, K. A Pilot Study on the Sound Absorption Characteristics of Chicken Feathers as an Alternative Sustainable Acoustical Material. *Sustainability* **2019**, *11*, 1476. [CrossRef]
58. Yang, S.; Yu, W.; Pan, N. Investigation of the Sound-Absorbing Behavior of Fiber Assemblies. *Text. Res. J.* **2011**, *81*, 673–682. [CrossRef]
59. Parlato, M.C.M.; Porto, S.M.C. Organized Framework of Main Possible Applications of Sheep Wool Fibers in Building Components. *Sustainability* **2020**, *12*, 761. [CrossRef]
60. Borlea, S.I.; Tiuc, A.-E.; Nemeş, O.; Vermeşan, H.; Vasile, O. Innovative Use of Sheep Wool for Obtaining Materials with Improved Sound-Absorbing Properties. *Materials* **2020**, *13*, 694. [CrossRef] [PubMed]
61. Berardi, U.; Iannace, G. Acoustic Characterization of Natural Fibers for Sound Absorption Applications. *Build. Environ.* **2015**, *94*, 840–852. [CrossRef]
62. Mohammad Hosein Beheshti Ali Firoozi, M.J.; Tabrizi, A. Acoustical and Thermal Characterization of Insulating Materials Made from Wool and Sugarcane Bagasse. *J. Nat. Fibers* **2023**, *20*, 2237675. [CrossRef]
63. Asdrubali, F.; Schiavoni, S.; Horoshenkov, K.V. A Review of Sustainable Materials for Acoustic Applications. *Build. Acoust.* **2012**, *19*, 283–311. [CrossRef]
64. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; Antes, G.; Atkins, D.; Barbour, V.; Barrowman, N.; Berlin, J.A.; Clark, J.; et al. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Ann. Intern. Med.* **2009**, *151*, 264–269. [CrossRef]
65. Purvis, B.; Mao, Y.; Robinson, D. Three Pillars of Sustainability: In Search of Conceptual Origins. *Sustain. Sci.* **2019**, *14*, 681–695. [CrossRef]
66. Jensen, A.A.; Christiansen, K.; Schmidt, A. *Life Cycle Assessment (LCA)—A Guide to Approaches, Experiences and Information Sources*; European Communities: Brussels, Belgium, 1998.
67. Bilec, M.; Ries, R.; Matthews, H.; Sharrard, A. Example of a Hybrid Life-Cycle Assessment of Construction Processes. *J. Infrastruct. Syst.* **2006**, *12*, 207–215. [CrossRef]
68. Rivas-Aybar, D.; John, M.; Biswas, W. Environmental Life Cycle Assessment of a Novel Hemp-Based Building Material. *Materials* **2023**, *16*, 7208. [CrossRef] [PubMed]

69. *UNI EN ISO 14040:2006*; Environmental management- Life Cycle Assessmente—Principles and framework, II. International Organization for Standardization (ISO): Ginevra, Switzerland, 2006.
70. Füchsl, S.; Rheude, F.; Röder, H. Life Cycle Assessment (LCA) of Thermal Insulation Materials: A Critical Review. *Clean. Mater.* **2022**, *5*, 100119. [CrossRef]
71. Ardente, F.; Beccali, M.; Cellura, M.; Mistretta, M. Building Energy Performance: A LCA Case Study of Kenaf-Fibres Insulation Board. *Energy Build.* **2008**, *40*, 1–10. [CrossRef]
72. van der Lugt, P.; van den Dobbelsteen, A.A.J.F.; Janssen, J.J.A. An Environmental, Economic and Practical Assessment of Bamboo as a Building Material for Supporting Structures. *Constr. Build. Mater.* **2006**, *20*, 648–656. [CrossRef]
73. Cogato, A.; Cei, L.; Marinello, F.; Pezzuolo, A. The Role of Buildings in Rural Areas: Trends, Challenges, and Innovations for Sustainable Development. *Agronomy* **2023**, *13*, 1961. [CrossRef]