A Decade Review of Research Trends Using Waste Materials in the Building and Construction Industry: A Pathway towards a Circular Economy

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Review

A Decade Review of Research Trends Using Waste Materials in the Building and Construction Industry: A Pathway towards a Circular Economy

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Abstract: The construction industry is among the most prominent contributors to global resource consumption, waste production, and greenhouse gas emissions. A pivotal step toward mitigating these sectoral impacts lies in the adoption of a circular production and consumption system. The use of alternative waste materials can mitigate landfill accumulation and the associated detrimental environmental effects. To highlight unconventional materials, this study began with a bibliometric assessment via a bibliography analyzis software called "Bibliometrix" (version 4.1.3). The outputs from the analyzis can assist in identifying research trends, gaps in literature and benchmark research performance. The search engine used for sourcing publications was Scopus, using the main criteria as "Waste materials used in building and construction". The time-period analysed was from 2013 to 2023. The results included publications obtained in journal articles, book chapters and conference proceedings. The assessment reviewed 6238 documents from 1482 sources. The results revealed an array of waste materials; however, rubber, textiles, and ceramics had a significant reduction in research attention. Rubber waste presents promising opportunities in civil concrete construction methods. The preparatory steps of textile fibres in composite materials are frequently disregarded, resulting in structural issues for the end-product. Obstacles persist in ceramic technology due to the absence of transparency, primarily because industry entities closely safeguard proprietary information. While sustainability research often emphasizes emissions, practical trials commonly revolve around integrating materials into current systems. A more comprehensive approach, contemplating the complete lifecycle of materials, could provide deeper insights into fostering sustainable construction practices. Researchers can use these findings when determining trends, research gaps, and future research directions.

Keywords: building and construction; ceramics; circular economy; rubber; textiles; waste materials

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1. Introduction

A substantial portion of materials used in the building construction industry currently follows a linear economic model. This means that raw materials are extracted, processed through manufacturing, utilised for their intended purpose, and ultimately discarded at the end of their lifecycle [1]. This linear approach gives rise to various cross-generational and cross-governmental issues, including challenges related to landfill, waste disposal and resource depletion [2]. In response to these concerns, the concept of a circular economy (CE) has emerged as a countermeasure to challenge and transform the prevailing linear production and consumption patterns within the building construction industry [3]. The concept of a CE presents a chance to decrease the utilization of primary materials and the environmental consequences linked to them. This can be achieved through a variety of strategies, including alternative systems to the traditional end of life disposal. However, the alteration of strategies such as material reduction, reuse, and the recycling processes must happen during the production and distribution when material consumption is required.

Inefficient resource management within the building and construction industry leads to the generation of significant quantities of construction and demolition waste each year. Consequently, the building and construction industry is the largest waste generator within the economy [4]. This is shown in the United States where building and construction waste accounts for approximately 40% of total waste generated. Moreover, 30% of solid waste generated in Europe is derived from building and construction related activities [5]. Future projections indicate that by the year 2025, the global volume of building and construction related waste will reach approximately 2.2 billion tones [6]. In the pursuit of addressing climate change and environmental deterioration, local governments across the world are reviewing their policies and procedures related to environmentally detrimental areas of their economy. For example, the European Green Deal endeavours to reshape the European Union into a contemporary, resource-efficient, and competitive economy. This transformation aims to achieve several objectives, including net-zero greenhouse gas (GHG) emissions by 2050 and the detachment of economic growth from resource consumption. In alignment with the updated EU circular economy action plan, particular emphasis should be placed on low carbon emitting materials utilised in construction [7]. However, cost related concerns and the research development of unconventional materials pose risk to current building and construction standards and practices. For example, utilization of waste in structural elements can pose potential unknown material durability risks [8].

Identifying potential waste materials for further use in the building and construction is a step toward the CE approach. This has been shown in published literature with the utilization of waste materials such as fly ash (FA), ground blast furnace slag (GBFS) and silica fume (SF) within concrete and cement-based materials [9–11]. These materials are known as supplementary cementitious materials (SCMs) and have an ease of transferability when integrated with cement-based applications [12]. However, not all waste materials can be transferred directly or create additional benefits when added into other materials or systems. Researchers have focused on alternative waste materials to supplement the requirement of natural resource extraction as well as reduce waste accumulation in landfill areas [13–15]. This has been especially critical to assist in the research toward the reduction of climate change and adhere to the sustainability development goals (SDG) set out by the United Nations (UN) in 2015 [16]. Waste materials such as plastics, glass and steel have been a prominent research focus due to the abundance created in the economy and the negative impact the material has on the environment [17–19]. Although glass has a high recyclability rate, contamination, and high energy recycling requirement often leave the material disposed of in landfill areas [20]. Moreover, this is further shown with other waste such as paper and cardboard that have a 60% recycling rate with the remaining 40% disposed of in landfill due to contamination [21]. As the CE principles become more prominent in the construction industry and the research develops, it is important to identify current waste materials that have a potential to be utilised further. This study will aim to highlight the current trends, and limitations of specific waste materials that are not commonly used. The findings will demonstrate potential areas to research when using unconventional waste materials that could be used in the building and construction industry.

2. Research Significance and Methodologies

Embracing the principles of a CE represents a sustainable and profitable alternative that promotes the efficient utilization of resources and delivers socio-economic advantages, including heightened gross domestic product and expanded employment prospects [22]. It is important to recognize that various definitions of a CE exist, and in the construction industry, a clear and universally accepted definition remains elusive [23]. Consequently, CE initiatives in the construction sector appear to be heading in diverse directions, encompassing areas such as innovative design for deconstruction, the hierarchy of construction and demolition waste, secondary materials markets, building information modelling and urban mining. This fragmented development and the presence of misconceptions pose challenges to advancing the concept of a CE within the sector [24]. Therefore, the integration of unconventional waste materials relies upon promotion of the sustainability aspects and discovery of the utilization in the building and construction industry [25].

The findings of this review aim to enhance the understanding of current trends, and priorities associated with utilising different waste materials and their associated final outputs in the building and construction industry. Additionally, stakeholders will gain insights into the factors to consider when selecting suitable waste materials for the development of sustainable building materials. This research will begin with a focus on current waste materials and associated trends when integrating them further in the building and construction industry via bibliometric assessment. A bibliometric assessment is a comprehensive quantitative science mapping analyzis of published literature. The bibliometric assessment is conducted via a bibliography analyzis software called "Bibliometrix" (version 4.1.3). The outputs from the analyzis can assist to identify research trends, gaps in literature and benchmark research performance [26]. The search engine used for sourcing publications was Scopus, using the main criteria as "Waste materials used in building and construction". Scopus is a comprehensive abstract and citation database, widely used for research evaluation. The database has extensive coverage, global content, citation tracking and metric and analyzis tools. The time-period analysed was the last decade from 2013 to 2023. The results included publications obtained in journal articles, book chapters and conference proceedings. The PRISMA (preferred reporting items for systematic review and meta-analyzis) framework was used in conjunction with the bibliometric assessment. The PRISMA methodology is primarily designed for systematic reviews that focus on summarizing and synthesizing evidence from primary research studies. While PRISMA itself may not directly apply to bibliometric analyzis, it can offer a structured and transparent reporting structure, especially when combined with bibliometric studies or used to report the systematic review of bibliometric research. This methodology is shown in Figure 1. The final output of this research is a systematic approach of current literature as well as the observations obtained from the bibliometric assessment. The review aims to highlight waste materials that are less research focused and determine optimal applications for further research and integration with the building and construction industry.

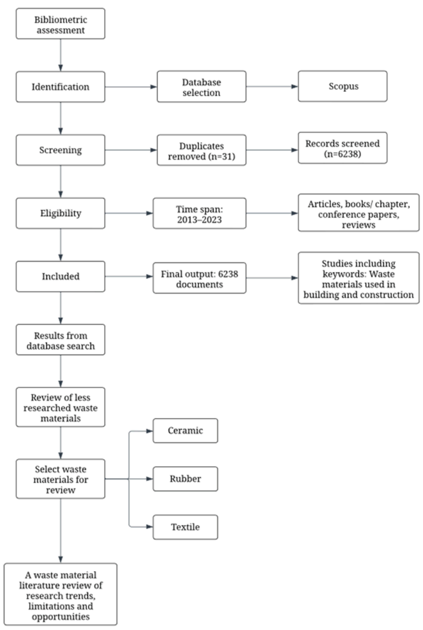

Figure 1. Research methodology based on PRISMA.

3. Bibliometric Assessment Findings

The main information derived from the bibliometric assessment is shown in Table 1. The assessment reviewed 6238 documents from 1482 sources. The average number of authors per document is represented at 3.93. This is calculated via author appearance and documents. Total number of authors was 17,022, demonstrating the topic is a highly researched focus area with multiple co-authors. Journal articles were the predominant source of publications with 3775 however, conference papers and review papers were 1738 and 432, respectively. Figure 2 graphically depicts the annual scientific publications from 2013 to 2023. As shown, there is a steeper rise of publications since 2019. From 2013, there has been a 71% increase of publications on waste materials used in the building and construction industry. This corresponds to the adoption of the United Nations sustainable development goals (SDGs) in 2015 [16]. Moreover, since 2020, there has also been a 22% increase on publications. In 2020, the UN secretary general addressed the acceleration of the SDGs with a decade of action, urging countries and local Governments to act [27]. This was adopted with the European Union's Green Deal, aiming to be climate neutral by 2050 [27].

Table 1. Main information derived from the bibliometric assessment.

Description	Results
Timespan	2013:2024
Sources (Journals, Books, etc.)	1482
Documents	6238
Document Average Age	3.75
Average citations per doc	14.68
References	1
Authors	17,022
Authors of single-authored docs	384
Single-authored docs	561
Co-Authors per Doc	3.93
Document types	
Article	3775
Book	20
Book chapter	273
Conference paper	1738
Review	432

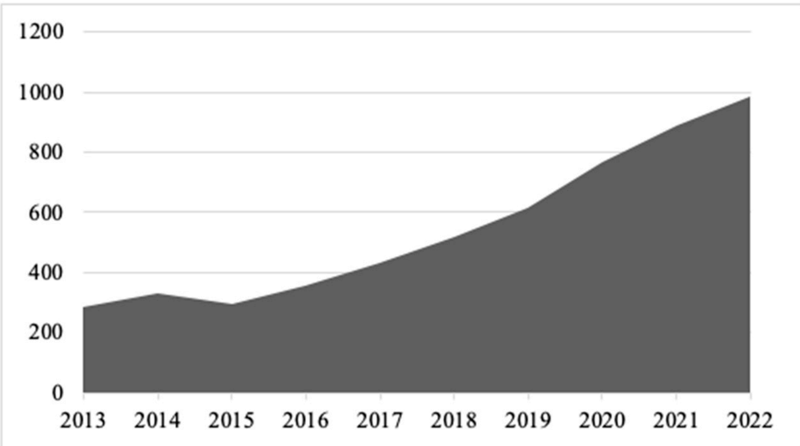

Figure 2. Annual publications.

Figure 3 illustrates the most frequently published sources of publications from the analysed time-period of ten years. The Journal of Building and construction materials is the most prominent source of publications in the last decade. The Journal scope welcomes a research focus toward experimental research, demonstrating alternative methods to improve the building and construction industry. There is further indication of the bespoke methods with the proceeding of high publications in the material focused publication sources. The scope of these publication sources is highly focused on experimental material designs and alternative materials.

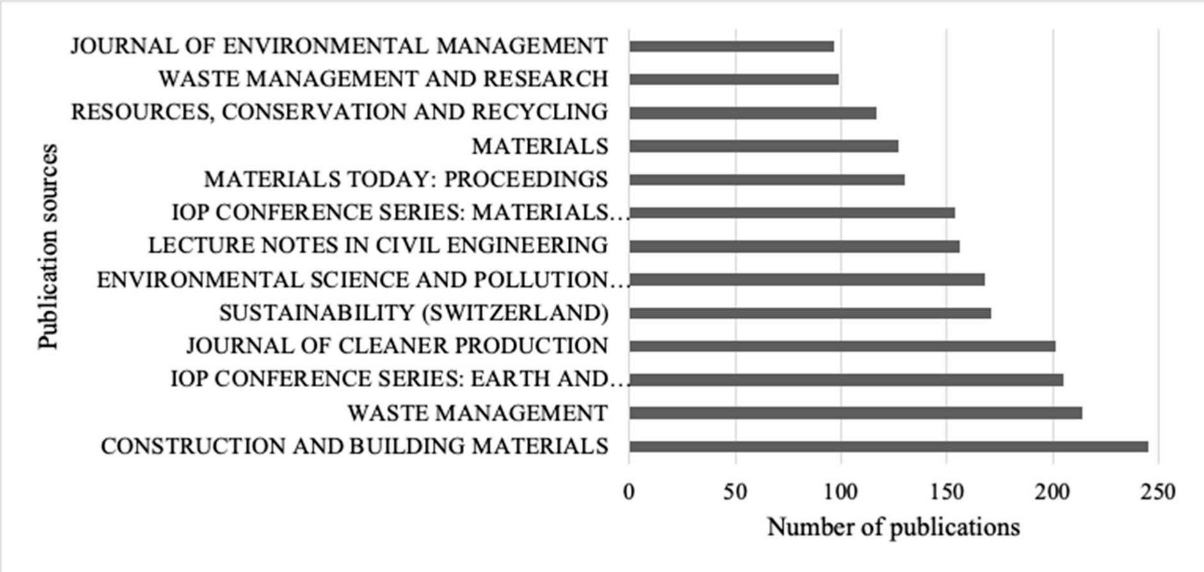

Figure 3. Publishing source vs. number of publications.

Figures 4 and 5 illustrate the research focus areas and thematic word occurrences, respectively. As shown in Figure 4, the most prominent research focus areas are divided into three main categories. This includes experimental, computer modelling and sources of material procurement with the colours of red, blue and green, respectively. The dimensions of the corresponding areas are relative to the publications on that chosen topic. For example, FA is a heavy experimentally researched material. This is further shown in the red pattern with compressive strength and durability analysis. Moreover, computer modelling has been a prominent research focus for life cycle assessment and analysing energy efficiency when using waste materials. This is demonstrated in the blue configuration when relating the findings to circular economy principles and sustainability benchmarks. Figure 5 illustrates the waste material thematic keyword occurrences from the 6238 documents analysed. As shown, concrete materials have been the most prominent research area with high publications focusing on waste related concrete materials. This is demonstrated with high occurrences of FA, aggregates, GBFS and cement waste materials. Demolition waste is also a prominent material however, the specifics of those materials could be shown with the less common occurrences. For example, bricks, glass, steel, wood, and gypsum are all building materials and could be recovered from the demolition process. There have been less research publications on municipal solid waste materials such as textiles, rubber, and ceramics.

Figure 6 illustrates the research trends corresponding with the publication years over the last decade. As shown, the larger the dimension of the circle corresponds to the frequency of the research topic. This image shows three dominant research areas that are focused on. As the years progress, trends and limitations change and thus research focus also pivots to adjust with the changing world. As shown, machine learning, cements and alkali-activated binders are the current trending topics. Research utilising machine learning correlates with the availability of artificial intelligence among local communities. New systems propel innovative techniques and thus can adjust how research is conducted. Moreover, as shown, concrete is a highly researched building and construction material that has been heavily researched over the decade. Concrete materials contribute significant carbon emissions via the use of cement materials and the depletion of natural resources.

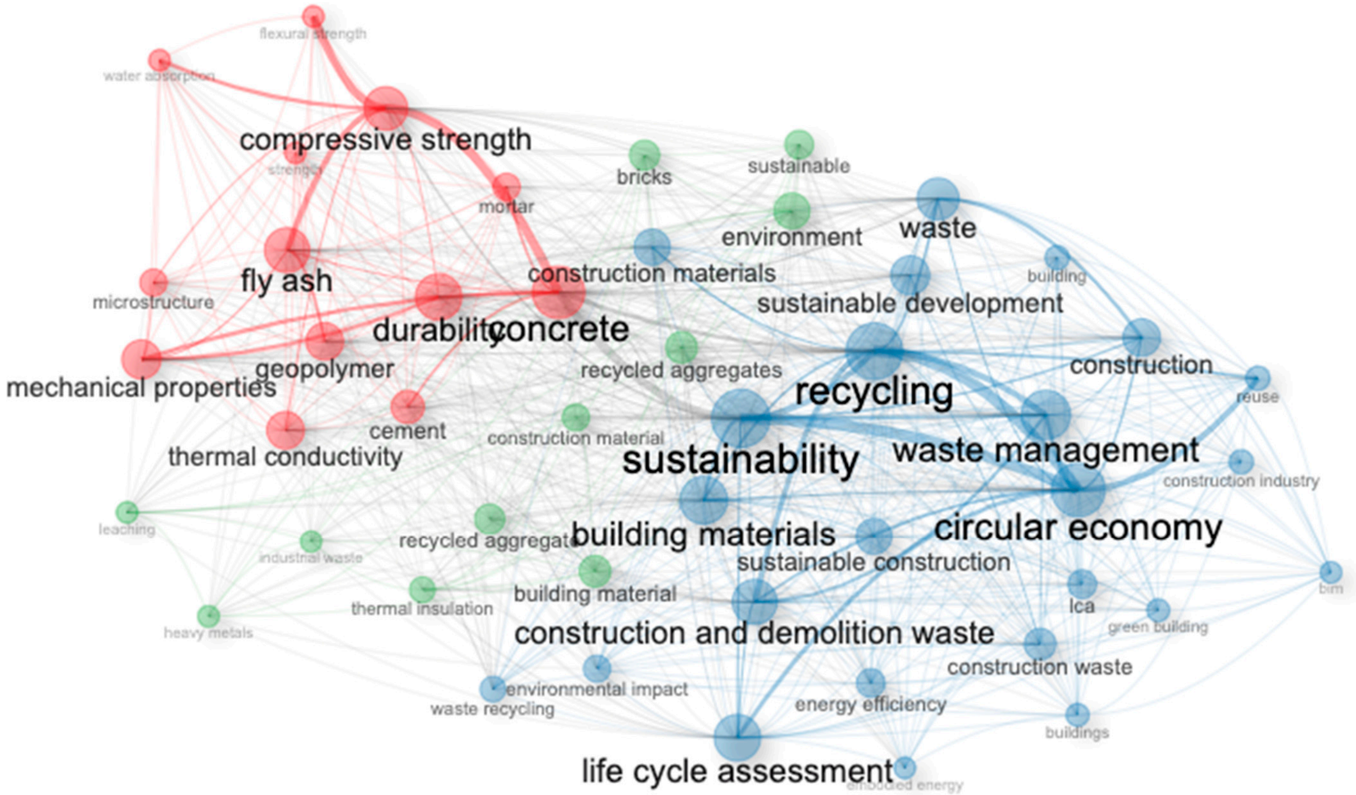

Figure 4. Research focus network.

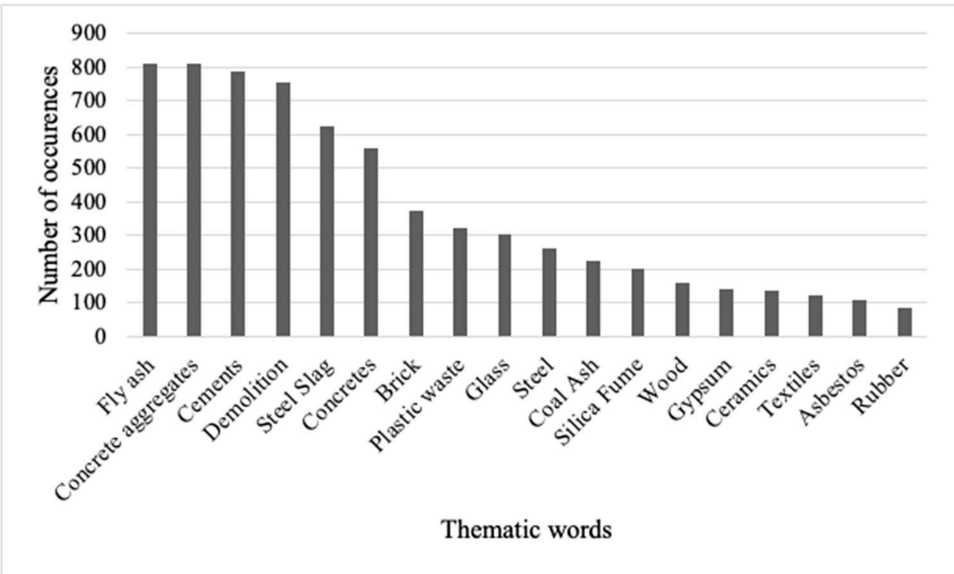

Figure 5. Thematic word occurrences.

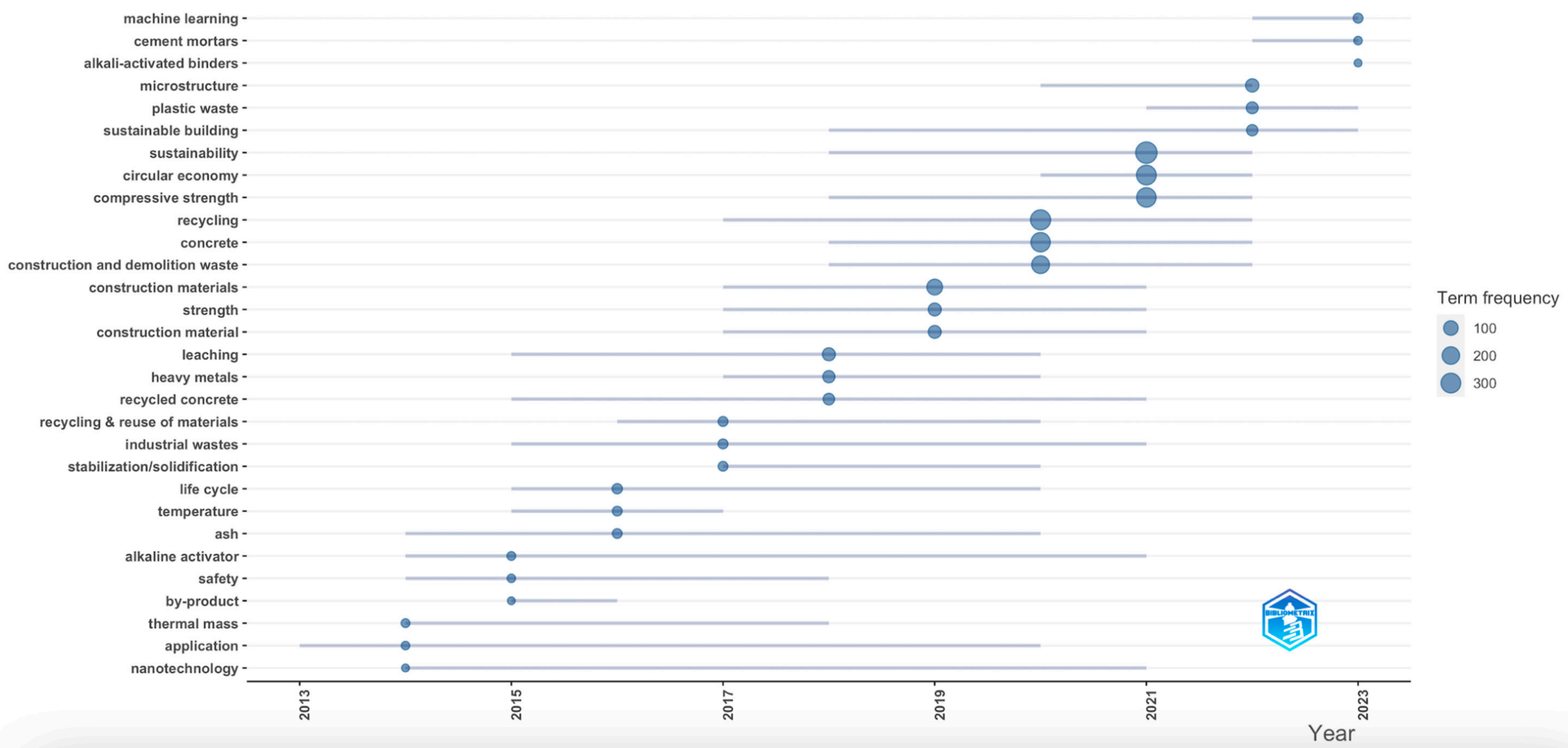

Figure 6. Research trends vs. publication year.

Summary of Bibliometric Assessment

The bibliometric assessment revealed the following key findings and observations.

- Rubber was the least researched waste material.
- Mechanical testing of compressive, tensile, and flexural is a key research focus.
- Fly Ash and slags are the dominant additives in concrete materials.
- Sustainability is a key driver of waste material research.
- Glass, steel, and plastics are heavy research focused.
- Gypsum, ceramics, and wood had similar trends of research focus.

The bibliometric assessment results have enabled upcoming researchers to pinpoint influential journal sources and concentrate their research efforts on areas with higher potential impact. Based on the findings, it was shown that major research has been conducted on steel, plastics, glass, and recycled aggregates. Whereas in comparison, textile and rubber waste had minimal research focus. Due to the array of waste products, this review will systematically focus on the less researched focused municipal solid waste materials including rubber, textiles, and ceramics. The results will determine common research focus areas and discuss the sustainability benefits when using these materials in various building and construction applications.

4. Waste Materials

4.1. Rubber Waste

Rubber waste is primarily sourced from truck and passenger vehicle tires, with a smaller percentage derived from manufacturing and miscellaneous products. The durability requirement for tire products make them difficult to reuse or recycle, this creates complex composite rubber products. Transport tires are made from natural rubber (19%), synthetic polymer (24%), textiles (4%), reinforcing steel wire (12%), and carbon black or silica filler (26%). Other products such as antioxidants and antiozonants (14%) are also applied for degradation resistance [28]. In Australia, there are approximately eighty-five million tires in use annually, which equates to the generation of 459,000 tonnes of waste each year. Following the SDGs, the National Tire Product Stewardship Scheme recovers and recycles tire derived products with the aim to reduce negative environmental, health and safety impacts. However, only 330,000 tonnes of tire waste is recovered and recycled, which equates to approximately 70% of tire waste generated [29]. The increase of the population creates a higher tire demand in the United States, where 246 million tire waste is created equating to four million tonnes produced annually [30]. Although this number is significant, it is only equal to 3.1% of municipal solid waste produced annually [31]. Due to this low percentage, research has been focused on the investigation of other waste materials. This has been shown with the use of fossil fuel by-products such as FA [32]. Although the generation of tire waste is significant, research industries are partnering with tire companies to produce renewable tire products and recycle up to 88% of the waste material generated [33].

4.1.1. Sustainability Aspects of Using Rubber Waste

Reducing the amount of waste created from tire and rubber products is critical for the sustainability of the material. This coincides with the design of the product to ensure maximum usage and enhanced longevity. To measure the sustainability of a product, researchers often use life cycle analysis (LCA) and optimization techniques to investigate a materials impact. This has been shown with other municipal solid waste materials such as cardboard, plastics, and glass materials [34–36]. The sustainability of reusing waste rubber is dependent on the recycling technique. For example, the pyrolysis technique to burn rubber tires for energy can create additional detrimental gases and chemicals within the local environment [37]. Moreover, granulizing tire rubber can be an effective method to further integrate the material within composite materials. However, it is critical to ensure leaching of the particles does not interfere with relative water tables and bodies of water. This has been shown to create additional dangers and pollute the local areas [38]. Despite the natural rubber in tires, the additional materials required to create tires have been problematic when recycling. Therefore, researchers have been repurposing the tire products into non-structural applications and eco-friendly systems [39,40]. For example, the divergence of crumb rubber from landfill into asphalt systems has been shown to reduce carbon emissions by 71% [41]. Moreover, when 466,000 tonnes of crumb rubber sourced from waste tires is utilised for road base surfaces, there is a potential saving of 16.1 million USD. This is a significant saving when diverting from natural resources and using waste products. The re-processing methods of tires into useable products can be costly, therefore burning tires for fuel consumption has been shown to be a viable option [42]. This method can assist in lowering fossil fuel derived energy requirements and ultimately lower carbon emissions.

4.1.2. Applications and Viability of Using Waste Rubber

For many years, rubber tire waste has been incorporated as a ground stabilization technique in decaying land erosion areas [43]. This has been due to the materials ability to withstand pressure based on the density and materials composition. Moreover, because of the durability requirements for transportation vehicles, tire waste slowly decomposes when entrenched in soil. However, as researchers have discovered, particles of tire waste have been found in waterways and in the ocean [44]. Other applications of tire waste have been within playgrounds, sporting fields, and artificial turf for domestic use [45]. In civil construction, tire waste powder has been used in modified asphalt due to the elasticity and absorption characteristics of the material [46]. The use of waste rubber in road applications has shown to increase the life span of road surfaces, increase the safety in wet road conditions and reduce noise pollution [47]. Although there are positive benefits when using waste tires in civil construction, the material has not been commonly adopted across the world. This has been due to the complex shredding techniques and machinery required to complete the transition from tire products into ready-made waste derived materials for future use. The economic feasibility to complete the transition often hinders the concepts of a CE in developing countries [48]. Other issues when utilising tires for future use are the dangers associated with the product. For example, using waste tires within building and construction systems can pose risks to associated fire hazards. This has been shown when stockpiles of tires are being burned or used as a fuel system, creating toxic chemicals. This technique produces health and safety concerns, as hydrocarbons, chromium, mercury, arsenic cadmium and organic compounds pollute the local atmosphere [49]. Therefore, the utilization of waste tires in building and construction systems must be within protected areas that cannot harm or create further risks for human life. Because of the potential hazards using waste tires, derivatives of tire waste are created. This has been shown with crumb rubber aggregates, chipped rubber aggregates, rubber powder and ternary blends of fibre composites. Current literature of rubber waste focuses on the integration of waste tires within concrete and cementitious composites [50]. The workability of rubberized concrete diminishes as the percentages of rubber aggregate replacements and their size increase. Additionally, it is observed that mechanically ground rubber yields lower slump values compared to cryogenically ground tire rubber. To mitigate these challenges, various pre-treatment methods can be employed, in conjunction with superplasticizers. Moreover, substituting traditional aggregates with rubber granules results in notable reduction in the compressive strength of rubberized concrete. However, when integrating rubber fibre as a reinforcement agent, it increases the compressive strength. Fibres possessing a higher elastic modulus facilitate the efficient dispersion of stress throughout the concrete mix, thereby constraining the development of cracks and ultimately improving the load-carrying capacity. Table 2 is a systematic review of published research on various rubber materials within building and construction applications. The research studies vary; however, the predominant focus has been toward experimental applications.

Table 2. Rubber waste in building and construction materials.

Material Type	Material Application	Main Study Focus	Ref.
Tire rubber and steel fibres	Geopolymer concrete	Mechanical, microstructure, environmental and economical	[51]
Rubber fibres	Cement	Mechanical and microstructure	[52]
Crumb rubber	Geopolymer concrete	Mechanical and microstructure	[53]
Rubber	Concrete	Optimisation, economic, environmental, and mechanical	[54]
Crumb rubber	Geopolymer concrete	Mechanical	[55]
Crumb rubber	Concrete	Mechanical	[56]
Tire rubber	High strength concrete	Mechanical and microstructure	[57]
Rubber granules	Concrete	Mechanical	[58]
Tire rubber	Asphalt	Economic and environmental	[59]
Tire rubber	Concrete	Mechanical, environmental, and economical	[60]
Tire rubber and Fly Ash	Composite	Mechanical and microstructure	[61]
Tire rubber and waste glass	Concrete	Mechanical and microstructure	[62]
Tire rubber	Composite	Mechanical and microstructure	[63]
Tire rubber	Syntactic foam	Mechanical and microstructure	[64]
Tire rubber, steel fibre and porcelain	Concrete	Mechanical and microstructure	[65]
Rubber tube and cow dung ash	Concrete	Mechanical and microstructure	[66]
Tire rubber	Clay soil-rubber	Mechanical and microstructure	[67]
Tire rubber and recycled aggregate	Pavement	Mechanical and microstructure	[68]
Rubber fibre and recycled aggregate	Concrete	Machine learning modelling	[69]
Tire rubber	Composite	Mechanical and microstructure	[70]
Tire rubber and agricultural waste	Composite	Mechanical	[71]
Tire rubber powder	Asphalt	Mechanical and microstructure	[47]
Polyvinyl alcohol and rubber	Cement paste	Mechanical	[72]
Tire rubber	Pavement	Mechanical and microstructure	[73]
Tire rubber and fly ash	Composite	Mechanical and microstructure	[74]
Tire rubber	Cement mortar	Mechanical and microstructure	[75]
Tire rubber	Self-compacting concrete	Mechanical and microstructure	[76]
Crumb rubber and quarry dust	Concrete	Mechanical	[77]
Tire rubber and plastic waste	Concrete blocks	Mechanical, economical, and environmental	[78]
Crumb rubber and recycled aggregates	Mortar	Mechanical and microstructure	[79]
Rubber particles	Self-compacting concrete	Mechanical and microstructure	[80]
Rubber tire, waste paint and silica	Cement paste	Microstructure	[81]

Table 2. *Cont.*

Material Type	Material Application	Main Study Focus	Ref.
Tire rubber	Asphalt	Mechanical and microstructure	[82]
Tire rubber and recycled concrete	Concrete	Mechanical and microstructure	[83]
Rubber powder and polypropylene fibre	Concrete	Mechanical and microstructure	[84]
Tire rubber	Concrete blocks	Mechanical	[85]
Tire rubber	Asphalt	Mechanical	[86]
Rubber powder granules	Asphalt	Thermal	[87]
Tire rubber	Composite	Mechanical and microstructure	[88]
Tire rubber	Pervious concrete	Mechanical and simulation	[89]
Tire rubber	Composite	Mechanical and microstructure	[90]
Tire rubber	Concrete	Mechanical and environmental	[91]

The research investigations indicate that rubber tire waste pose significant challenge when used in proximity to water tables or waterways. The porous nature of rubber can lead to leaching of toxic chemicals and pollutants into the surrounding environment, posing risks to aquatic ecosystems and human health. Proper containment and management are crucial to prevent such contamination. Moreover, the disposal of rubber tire waste can give rise to the production of toxic by-products. When subjected to heat or combustion, rubber tires release harmful substances into the air, including carcinogenic compounds like benzene and toluene. This not only jeopardizes the environment but also endangers the well-being of individuals living nearby. To address these concerns, it is imperative to incorporate rubber waste into safe building and construction systems. Implementing stringent regulations and guidelines can help ensure that rubber tire waste is used responsibly, minimizing its adverse environmental and health impacts. Nonetheless, rubber waste presents promising opportunities in civil construction methods. Innovative approaches, such as using rubber as an additive in concrete, can lead to improvements in both material performance and sustainability. As discussed, fibre-reinforced concrete with rubber waste, exhibits enhanced mechanical properties, offering a potential avenue for environmentally friendly construction practices.

4.2. Textile Waste

The textile industry holds a prominent position in the global economy, generating $3 trillion in revenue worldwide and accounting for approximately 2% of the global gross domestic product [92]. The industry creates upward of 80 billion new garments annually, resulting with the additional generation of 92 million tonnes of waste [93]. The production of textile materials is a significant contributor to pollution and environmentally detrimental effects worldwide. This is shown across the lifecycle of the materials with 1.2 billion tonnes of carbon dioxide (CO_2) produced annually [94]. Moreover, this equates to approximately 8% of the global total of CO_2 produced. Each year, 108 million non-renewable resources including oil, fertilisers and chemicals are consumed for the creation of textile materials [94]. This is shown with the requirement for synthetic counterparts such as polyester, nylon and acrylic which is derived from plastics. Industrial water contamination is also a high concern, with an estimated 17–20% of water contamination is due to the textile dyeing and treatment processes [95]. The production rate of textile materials has doubled over the last two decades. In 2000, global textile fibre production was approximately 58 million tonnes, whereas in 2020 the production rate was 109 million tonnes. This figure is expected to increase to 145 million tonnes by 2030 [96]. As the rate of material production increases, waste accumulation will also follow. As shown in the United States, 14.5 million tonnes of textiles were landfilled in 2018 [97]. Moreover, in Australia, approximately 800,000 tonnes of textiles are sent to landfill annually and historically more have been exported overseas [98]. With the current rate of textile waste, it is imperative to investigate alternative systems to incorporate textiles and reduce the material ending its life cycle in landfilled areas.

4.2.1. Sustainability Aspects of Using Textile Waste

The environmental impacts of textile materials vary depending on the fibre type. For example, it has been shown that the production and manufacturing of natural fibre have a lower negative effect on the environment compared to their synthetic counterpart [99]. On the basis of emissions created energy and water requirements during the production stages, flax fibre has the lowest impact whereas acrylic has the highest [100]. Natural fibres such as flax, are derived from renewable sources and are biodegradable. This equates to less energy consumption during the manufacturing process compared to synthetic materials. However, cotton fibre textile materials require 2700 litres of water to produce one t-shirt, as well as the large requirement of pesticides and fertilisers [101]. Therefore, the utilisation of recycled textiles is the most prominent answer to reduce further negative effects of the environment. Although there are production requirements to reprocess textile materials, there are savings of approximately 60% of the emitted CO_2 emissions, 80% water requirement and a reduction of 11% of oil consumption [102]. The resource savings combined with the diversion of materials being sent to landfill, recycling and repurposing textiles is a sustainable option for future researchers. However, barriers remain for the rapid conversion of waste textile materials into ready-made products. For example, there remains a lack of capabilities for the separation of fibre types between blended textile materials [103]. This is shown with interwoven blends such as polyester and cotton that are dominant in the textile industry. Advancements in sustainable textile recycling technologies are required, particularly those capable of efficiently handling intricate blends. These technologies have the potential to broaden the range of textile waste materials that can undergo reprocessing, thus would diminish the volume of textile waste destined for landfills or incineration. Other issues with the recycling process are the additional materials associated with textiles, such as buttons, zippers, plastic prints and impurities [104]. Often these materials can reduce the service life of machinery when being shredded or additionally require significant human resources to separate before thermal and chemical processing [105,106].

4.2.2. Applications and Viability of Using Textile Waste

Closing the loop on textiles has been a difficult task due to the complex blended and interwoven materials often associated with them. The degradability of the fibres can vary greatly, thus reducing service life of the chosen applications. This is especially shown in concrete and cementitious composite materials [107]. Natural fibres are more susceptible to degradation due to the high alkalinity of cement. Calcium hydroxide ($Ca(OH)_2$) within cement, attacks the outer lumen on the fibre walls, reducing the mechanical strength of the material [107]. However, synthetic fibres such as polyester and nylon, pose a viable option when integrated within those cementitious materials. This has been shown when there is a reduction of degradation on the synthetic fibres causing enhanced mechanical properties of the composite materials [108]. For example, the addition of 1% cotton fibres derived from denim within concrete increased the flexural strength by 7%. Additionally, the compressive strength also increased by 40% [109]. It is important to note that a pre-treatment of the cotton fibres was undertaken by gamma radiation. Other research including nylon fibres within cement mortar increased the tensile and toughness capacity by 35% and a multitude of 13 times, respectively [110]. Rahman et al. (2022) [111], explored the utilization of various pre-consumer waste materials to enhance the stability of weak soils. They observed a 170% increase in compressive strength through the introduction of fabric reinforcement. Echeverria et al. (2019) [112] researched the use of textile fibre-reinforced particleboards. The materials consisted of sandwiched panels crafted from recycled polypropylene fibres on both sides, with a core of multi-material blended waste textiles. These boards exhibited notable resistance to moisture and substantial improvements in mechanical and load-bearing properties when compared to conventional wood-based boards available in the market. Other waste textile applications demonstrating promising results are kemafil ropes. This rope system is where non-woven materials are bound together and sheathed with polypropylene twine. They are arranged in a grid-like pattern beneath a layer of vegetation to prevent topsoil erosion, enhancing stability [113]. Similarly, multi-material blended waste textiles can contribute to enhancing the thermal and acoustic insulation properties of a soil mass, provided they are maintained in a fabric state. It is important to note that the specific spinning technique used for each fabric will play a critical role in determining key physical characteristics such as bulk density, porosity, and air permeability of the mass [114]. Table 3 is a systematic review of textile waste in building and construction material applications. As shown, the prominent research focus has been toward experimental studies. The fibre types vary as textile materials pertain both natural and synthetic variations.

Table 3. Textile waste in building and construction materials.

Material Type	Material Application	Main Study Focus	Ref.
Jute yarn, flax yarn	Reinforced polyester bars	Mechanical,	[115]
Multifilament carbon yarns	Fabric cement-based composite	Mechanical, microstructure	[116]
Carbon fibre yarn	Geopolymer concrete composites	Mechanical, thermal	[117]
Textile yarn	Alkali resistant glass textile reinforced concrete	Mechanical, physical	[118]
Poly-acrylonitrile based carbon fibre yarn	Concrete	Mechanical, microstructure, thermal	[119]
Textile carbon mesh yarn	Textile reinforced concrete	Mechanical, physical	[120]
Glass fibre yarn	Reinforced cementitious composite	Mechanical	[121]
Textile carbon fibre yarn	Fibre reinforced cementitious matrices	Mechanical, microstructure,	[122]
Glass fibre yarn	Composite reinforced mortar	Mechanical	[123]
Basalt, AR-glass, carbon fibre and PP filament yarn	Textile reinforced concrete	Mechanical	[124]
Textile carbon yarns	Reinforced concrete beams	Mechanical	[125]
Carbon multifilament yarn	Cement based composites	Mechanical, microstructure	[126]
Textile carbon multifilament yarn	Fibre reinforced concrete	Mechanical, microstructure	[127]
AR-glass multifilament yarn	Cement based composites	Mechanical, microstructure	[128]
AR-glass and basalt yarn	Cement based composites	Mechanical,	[129]
Glass and polyester fibre	Polymer concrete	Mechanical, durability	[130]
Polyester fibres	Concrete	Mechanical, physical	[131]
Polyester fibres	Asphalt concrete	Mechanical, durability	[132]
Polypropylene and polyester fibre	Asphalt	Physical	[133]
Waste denim jeans	Concrete	Mechanical, thermal, microstructure	[109]
Glass fibre reinforced polyester	Concrete	Mechanical	[134]
Polyester fibres	Concrete	Mechanical	[135]
Steel and polyester fibres	Concrete	Mechanical	[136]
Polypropylene and polyester fibres	Concrete	Mechanical, microstructure, thermal	[108]
Polyester and polyurethane	Concrete	Mechanical	[137]
Polyester waste fibres	Asphalt	Mechanical	[138]
Rayon textile fibre	Polyhydroxy butyrate nanocomposites	Mechanical and microstructure	[139]
Bamboo, cotton, and rayon fibre	Composites	Mechanical	[140]
Rayon based carbon fibres	Fibre investigations	Microstructure	[141]
Polypropylene, PET, and rayon fibres	Hybrid composites	Mechanical	[142]
Rayon fabric and glass epoxy	Polymeric composites	Mechanical	[143]
Sheep wool	Insulation	Thermal, acoustic	[144]

Table 3. *Cont.*

Material Type	Material Application	Main Study Focus	Ref.
Sheep wool	Concrete composites	Mechanical, acoustic	[145]
Flax wool twine	Mortar composites	Mechanical, microstructure, durability	[146]
Sheep wool	Concrete composites	Mechanical, microstructure,	[147]
Sheep wool	Fibre reinforced concrete	Mechanical	[148]
Sheep wool	Mechanical insulation	Thermal	[149]
Sheep wool	Hybrid bio-composites	Thermal, acoustic	[150]
Sheep wool	Insulation	Thermal, acoustic, microstructure	[151]
Sheep wool, shell pinecone and paper	Thermal insulation	Mechanical, thermal, microstructure, absorptivity	[152]
Sheep wool	Thermal insulation	Mechanical, thermal, microstructure	[153]
Sheep wool	Reinforced concrete	Mechanical, thermal,	[154]
Wool	Mortar	Mechanical, microstructure	[155]
Hemp wool	External wall panels	Thermal, economic	[156]

Textile reprocessing is a complex challenge. Integrating textiles into construction materials, particularly concrete, is hindered by difficulties in managing degradation properties and achieving adequate bonding. Pre-treatment of textile fibres is often overlooked, leading to issues in the structural integrity of the final product. While composites are commonly explored for textile recycling, there may be more viable alternatives outside of composite materials. Exploring diverse avenues for textile waste utilization, such as insulation or acoustic materials, could yield more practical solutions.

4.3. Ceramic Waste

Ceramic materials are used across the economy within both building and construction and residential purposes. Often, the materials are linked to toilets, kitchen utensils, floor, and wall tiles. Approximately 65% of that raw material waste is recycled back into the manufacturing process however, 35% of tile manufacturing is pure waste and ends up in landfills or as a filler in other materials [157]. It is difficult to reuse the raw materials because the waste contains soluble salts in the form of polishing sludge and kiln filter waste. These materials cannot be processed as a raw material thus, ending up in landfill. However, technological advancements in the ceramic industry are beginning to close the loop on the ceramic waste problem. This has been shown with the Italian ceramic tile industry where their production process now reuses all waste products and wastewater [158]. Italy is one of the largest producers and exporters of ceramic tiles. In 2021, Italy exported 367 million square metres of tiles with domestic sales reaching 91 million square metres [159]. For this reason, Italy can invest significant resources in the sustainability of the industry. In developing countries, the technology to increase sustainable measures remains economically challenging. This is shown in India where the production of ceramic waste is approximately 100 million tonnes annually, with 15–30% resulting in landfill [160]. Nonetheless, ceramic composites are being researched to integrate other waste materials such as, FA, rice husk ash, GBFS and glass waste [161]. Ceramic materials possess a unique standpoint for building and construction purposes where the material is not required to be structural. Therefore, ensuring durability and toughness is a key component of ceramics which is less challenging than concrete and cementitious materials. For this reason, ceramic waste materials remain unique where there are opportunities for ceramic waste to be utilised but also other waste materials to be integrated within the industries current production and manufacturing systems.

4.3.1. Sustainability Aspects of Using Ceramic Waste

The sustainability of ceramic waste has progressed significantly over the last 25 years. Specifically, within the EU, where the industry has halved its energy consumption as a result of switching fuel usage [162]. However, there are still environmental concerns with the negative environmental emissions and waste materials created. The production of refractories, walls and floor tiles, roof riles, and bricks emit approximately 19 million tonnes of CO_2 whereas globally brick manufacturing accounts for 2.7% of total carbon emissions [163]. In China, the energy-intensive manufacturing process accounted for 37.58 million tonnes of carbon emissions in 2020 [164]. Although leading industries are navigating sustainable practices with recycling waste in their manufactured products, many companies around the world do not have the capacity to compete with their technologies. The ceramic industry still relies on natural resources such as clay and minerals that are energy intensive during the extraction process [165]. As the drive toward sustainable energy becomes more prominent by 2050 [166], negative environmental effects caused by energy consumption will reduce the industries impact. This will enhance the sustainability of the ceramic industry. However, the issue remains for raw materials and waste creation. Construction and demolition activities create additional ceramic waste that are not often accounted for and are often separate to the quantifiable waste created from the ceramic industry [167–169]. For this reason, it is difficult to quantify the total life cycle and impact of ceramic waste within the building and construction industry. Ceramic waste is typically non-biodegradable and once derived from construction activities often has various contamination elements attached such as glues and substrate sheeting attachment. This creates additional challenges when attempting to recycling the material for further use.

4.3.2. Applications and Viability of Using Ceramic Waste

The material composition of ceramic waste contains high amounts of silica and alumina, which is like other natural pozzolans that can substitute as a partial cement within composite materials [170]. For this reason, extensive research has been applied to integrate ceramic waste within concrete materials. For example, ceramic waste powder has been applied as a cementitious blend in self-compacting concrete [171]. Joshi and Parekh [171], discovered the use of ceramic waste provided a better flowability without loss in strength. This was observed due to the increased amount of powder content. Other studies have focused on using brick waste as aggregates or as partial replacement of raw materials in concretes and mortars [172,173]. Tiles, solid and hollow bricks have been used in ceramic-based geopolymers, with promising results demonstrating 40 MPa after 7 days [174,175]. Researchers utilising polyethylene glycol 6000 (PEG) as an internal curing material with crushed ceramics demonstrated both enhanced mechanical and durability properties [176]. The results indicated an optimum amount of 50% coarse aggregate replacement with crushed ceramics used in conjunction with 1% PEG increased the compressive, tensile, and flexural strength by 55.6%, 54.47% and 28%, respectively. Research studies by Iravanian and Saber [177] investigated the use of ceramic waste as a soil stabilization technique. Approximately 30% of the waste material can be used as pavement subgrade in civil construction applications. The use of the material reduces other natural resource requirements and increases the bearing capacity of the localised soil. Table 4 demonstrates ceramic waste research used in building and construction materials. As shown, the main research focus has been toward experimental applications and largely focus on concrete material applications. As discussed, ceramic waste has an ease of transferability within cementitious materials based on the composition of the waste material.

Table 4. Ceramic waste in building and construction materials.

Material Type	Material Application	Main Study Focus	Ref.
Ceramic sanitary waste	Geopolymer concrete	Mechanical and microstructure	[178]
Fired clay ceramics	High performance concrete	Mechanical and microstructure	[179]
Ceramic tiles	Geopolymer concrete	Optimisation, mechanical and microstructure	[180]
Ceramic roof tiles	Geopolymer concrete	Mechanical	[181]
Ceramic waste	Concrete	Machine learning and mechanical	[182]
Ceramic waste and nylon fibre	Concrete	Machine learning and mechanical	[183]
Ceramic foams	Electrical insulating material	Microstructure	[184]
Ceramic powder	Concrete beams	Mechanical	[185]
Tiles with waste glass particles	Roof applications	Mechanical and microstructure	[186]
Ceramic powder	Concrete	Optimisation, mechanical and environmental	[187]
Ceramic powder	Concrete	Optimisation and mechanical	[188]
Ceramic electrical insulator	Concrete	Mechanical	[189]
Ceramic bricks	Soil stabilization	Mechanical and microstructure	[190]
Ceramic mould shells	Mortar	Mechanical and microstructure	[191]
Tile waste	Concrete	Mechanical	[192]
Tile waste	Concrete aggregates	Mechanical	[193]
Ceramic waste powder and sisal fibre	Concrete	Mechanical	[194]
Ceramic and slag wastes	Sandwich panels	Environmental	[195]
Ceramic waste	Mortar	Microstructure	[196]
Tile powder	Concrete	Mechanical	[197]
Ceramic waste powder	Concrete	Mechanical	[198]
Tiles	Self-compacting concrete	Mechanical and microstructure	[199]
Tiles	Self-compacting concrete	Mechanical, durability and microstructure	[200]
Ceramic waste powder	Cement	Mechanical	[201]
Ceramic waste and polypropylene fibres	Self-compacting concrete	Mechanical, durability and microstructure	[202]
Tiles	Mortar	Mechanical and microstructure	[203]
Tiles	Self-compacting concrete	Mechanical, durability and microstructure	[204]
Ceramic waste	Geopolymer concrete	Mechanical	[205]
Ceramic waste and glass powder silica fume	Concrete	Mechanical	[206]
Ceramic waste, brick powder, marble powder, glass powder and rice husk ash	Composite	Mechanical and microstructure	[207]
Ceramic waste	Geopolymer concrete	Mechanical and microstructure	[208]
Ceramic mould casting waste	Lightweight concrete	Mechanical and microstructure	[209]

Ceramic materials, although known for their sustainability potential, present unique complexities due to variations in production processes. Quantifying the overall environmental impact of ceramic materials is challenging as different ceramics involve slightly different manufacturing methods. The lack of transparency in ceramic technology remains a hurdle, as proprietary information is closely guarded by industry bodies. This opacity limits the ability to optimize ceramic materials with specific waste percentages, both internal and external. In sustainability research, many studies focus on emissions, while practical experimentation often centres on integrating materials into existing systems. A more holistic approach, considering the entire lifecycle of materials, could yield greater insights into sustainable construction practices. Addressing these challenges and exploring untapped opportunities is essential to harness the full potential of waste materials in construction and contribute to a more sustainable future.

5. Conclusions, Limitations, and Future Research

The building and construction industry has long been a major contributor to the generation of waste materials. Alongside the creation of building materials, the extraction process of raw materials places a significant environmental burden. This is shown from the depletion of natural resources but also the high energy demands. In response, research has focused on the utilization of waste materials to replace various material proportions in construction materials. However, not all waste materials have been fully optimized, and the potential valorisation of rubber, ceramics, and textiles, remain early in research investigations. This current study seeks to address this research gap by examining the use of unconventional waste materials used in building and construction. Initially, a bibliometric analysis was conducted, reviewing 6238 documents from the years 2013 to 2023. The results of this analysis have shed light on influential journal sources and highlighted the growth of research in this field. Moreover, the study identified keywords associated with these articles and sources, providing valuable insights into the current research focus areas and potential gaps. However, it is essential to acknowledge the limitations and assumptions within this review. While the bibliometric analysis offers valuable insights, it may not encompass every relevant research article or capture past trends before the year 2013. Additionally, the review may not cover every possible aspect of waste material utilised in building and construction, and individual research studies may have unique methodologies and limitations that should be considered in a comprehensive assessment. The findings from this study can be invaluable for future researchers seeking to delve into this subject matter. By identifying current research trends and focus areas, researchers can streamline their efforts and conduct more targeted investigations. The implications of this study not only facilitate a more efficient targeted research process, but also enhance the depth and quality of potential future assessments and findings.

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