

Review

Special Issue “Eco-Friendly Building Materials Made from Industrial Waste”—Reasons for Taking Up the Topic

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Abstract

Contemporary research on ecological building materials focuses on the use of industrial waste as an alternative to traditional raw materials. Utilizing byproducts such as fly ash, slag, and plastic waste not only solves the problem of landfill but often improves the technical parameters of the finished products. Contemporary research on sustainable building materials focuses on the use of industrial waste as an alternative to traditional raw materials. This review article, which opens this Special Issue, provides a comprehensive conceptual framework for sustainable materials and introduces clear criteria for selecting the main global waste streams. Besides systematizing the existing literature, the work critically addresses the most pressing challenges in the sector, such as the upcoming shortage of traditional fly ash resulting from the European energy transition and the volumetric instability of steel slag. Looking ahead, as an opening article, it outlines key avenues for further analysis—including advanced chemical surface modifications and supply chain regionalization—necessary to reduce embodied carbon footprints and combat urban heat islands. Ultimately, the work highlights the systemic possibilities of multi-stream waste upcycling, defining ecological and methodological benchmarks that justify and guide further academic research and industrial implementation in sustainable construction.

Keywords: ashes; slags; concrete; artificial aggregates; glass; associated raw materials; powders

1. Introduction

Modern materials science encompasses a range of interdisciplinary topics and extends beyond the curricula of traditional university and technical courses. In today's world, a holistic approach is essential, which is why waste materials should be treated as raw materials. The word “waste” conjures up images of material devoid of value and utility. However, developing technology allows waste to be used to produce a range of high-performance products that can themselves be recycled. There is a significant need for research and development to maximize the benefits of using recovered waste materials in sustainable construction. This Special Issue focuses on a sustainable and economical alternative to traditional building materials. This issue is precisely what industrial waste products represent. This helps protect natural resources, reduce landfill waste, and limit carbon dioxide emissions. The concrete industry is particularly important here. By replacing natural aggregates with processed industrial waste, natural resources such as sand, gravel, and crushed stone from quarries can be preserved. Local ecosystems are also protected. Economic considerations are also crucial, as waste-derived materials are often significantly cheaper. For example, Portland cement produced with the addition of fly ash can cost



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40–60% less than its conventional counterpart [1]. It is crucial to identify the location of post-process or recycled materials. Supply chains can be more stable and shorter when local raw materials are used. This model directly translates into reduced emissions. Reducing the temperature of urban heat spots and greening cities are also crucial in sustainable construction. Lightweight aggregates made from by-products, especially porous ones, can be used as plant substrates in green roofs. A common feature is that waste/recycled raw materials are treated as a full-value component of the manufactured materials.

There are other authors who work on eco-friendly materials. For example, the chapter “Overview of Eco-Friendly Construction Materials” by N. Sharma and A.K. Jha 2021 [2], discusses the use of eco-friendly building materials, focusing on sustainability, energy efficiency, and the use of low-carbon raw materials. The review highlights the benefits of recycling and the health aspects of natural materials and proposes a two-stage implementation in infrastructure [2]. Another review, “Industrial Waste Recycling for Sustainable Building Materials: A Review,” published in 2026 (MDPI Buildings), discusses methods for recycling industrial waste for use as sustainable raw materials in construction. The publication analyzes waste valorization processes, their impact on CO₂ emission reduction, and their impact on the physical and mechanical properties of building materials [3]. The article “Solid industrial waste generation and its valorization in developing sustainable building materials—A state of the art review” 2023 is a review of literature from 2000 to 2022 on the use of solid industrial waste in the production of sustainable building materials. The publication analyzes the possibilities of replacing natural sand in mortars with glass, ceramic, plastic, and demolition waste, pointing to factors affecting their durability [4]. The common denominator of these works is the desire to reduce greenhouse gas emissions (especially CO₂) generated by the traditional construction industry.

As an opening article for this Special Issue, it is essential to establish a rigorous conceptual framework for what constitutes an ‘eco-friendly’ building material. In this context, environmental sustainability cannot be merely assumed based on the presence of recycled content. A material is defined as eco-friendly only if its integration contributes to a net reduction in life-cycle environmental stress. This introduces a critical distinction between simple waste substitution (downcycling) and advanced technological synthesis (upcycling), where the structural or thermal performance of the material is enhanced without shifting the ecological burden to other phases of the product life cycle. In recycling and upcycling, a very wide range of materials can be used. The topic of processing is modern and relevant, which is why we are launching a Special Issue to which you are invited to submit articles. Research topics may include (among other things) building materials produced from industrial waste, such as all types of ash, slags of various origins, recycled plastics and glass, as well as powders and fibers from agricultural and food industries. In addition, there are many other materials and composites not listed above.

2. Impact Assessment

2.1. Search Strategy and Selection Methodology

The impact of a specific topic can be assessed accurately based on the number of scientific publications on the topic. Bibliometric analysis is a useful tool for the qualitative and quantitative assessment of scientific publications recorded in databases and yields interesting results. In general, a relatively large number of publications on the use of waste materials in the production of useful construction materials can be observed. However, to validate this, a detailed analysis was carried out of the records registered in the Web of Science (WoS) database [5]. This platform was selected as the primary data source due to its comprehensive coverage of high-impact journals in civil engineering, materials science, and environmental management. The WoS Core Collection database was selected, and

eco-friendly building materials was set as the primary search criterion. For the documents being searched, the ‘all fields’ option was selected, and the analyzed period included all available years until 2025 (Figure 1). Search-friendly keywords were also added, such as eco-friendly construction, eco-friendly concrete, and industrial waste. To ensure transparency, traceability and reproducibility of bibliometric analyses, a rigorous search strategy was conducted in the database. The search was conducted between 26 and 31 March 2026, and yielded 4353 records. It should be noted that publications on recycling only began to appear in 1997. Figure 1 shows the number of publications recorded in the WoS database by year of publication. To delimit the scope of this comprehensive review, specific inclusion criteria were applied to the global waste streams. The analysis strictly focuses on high-volume industrial by-products (fly ash, metallurgical slags), widespread municipal consumer waste (recycled glass, post-consumer polymers), and renewable regional residues (agricultural and food industry powders). These categories were selected because they represent the highest volumetric amount in global landfills and offer the most significant technological compatibility.

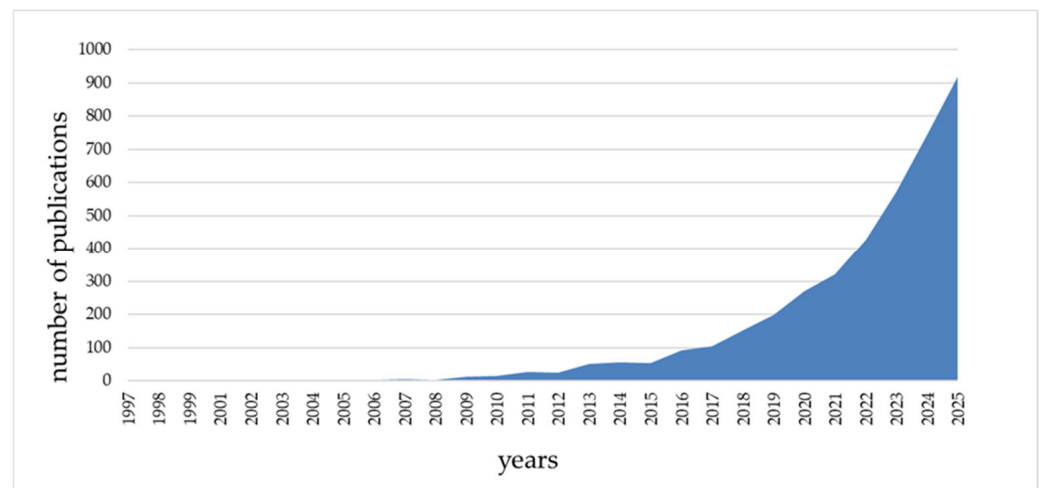


Figure 1. Number of publications available.

The number of publications has been growing exponentially since the 2000s. The findings suggest that the issue of using industrial waste and recycled materials in construction is of considerable interest and has increased, especially in the last decade. The next step was to narrow down the scope of the search, and articles from the last 10 years, from 2015 onwards, were included for further analysis to take into account the latest research achievements. The 3854 results obtained were analyzed by region/country, publication source (journal name), research area, scientific institution, and keywords. The following document types were recorded: 3177 articles, 383 reviews, 296 proceeding papers, and 15 book chapters. Unfortunately, 6 publications from 2020 to 2025 were retracted. Table 1 presents the most common research areas for the searched topics. These are primarily interdisciplinary materials sciences, but also include engineering and environmental sciences. The three most popular fields are Materials Science Multidisciplinary, Civil Engineering, and Construction Building Technology. It is worth noting that a single record (publication) can be assigned to multiple areas, so the cumulative percentages in Tables 1 and 2 exceed 100%. This is clearly evident in the first three categories: as the combined percentage exceeds 100% for these areas, many publications addressing waste materials used in ecological construction must be related to at least two of the leading areas. It should be noted that publications by multiple authors often cover different fields of research.

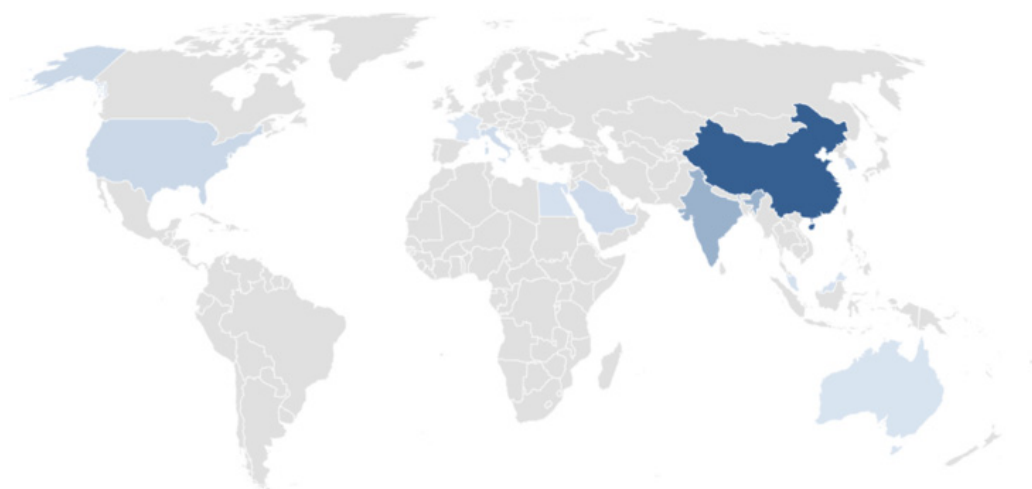
Table 1. The most common research areas related to publications on the topic (TOP10).

No	Eco-Friendly Building Materials Made from Industrial Waste		
	Research Area	Number of Publications	%
1	Materials Science Multidisciplinary	1663	43.15
2	Civil Engineering	1529	39.67
3	Construction Building Technology	1462	37.93
4	Environmental Sciences	375	9.73
5	Green Sustainable Science Technology	368	9.55
6	Chemistry Physical	283	7.34
7	Physics Applied	257	6.67
8	Engineering Environmental	242	6.28
9	Chemistry Multidisciplinary	231	5.99
10	Energy Fuels	210	5.45

Table 2. The most common regions related to publications on the topic (TOP10).

No	Eco-Friendly Building Materials Made from Industrial Waste		
	Region	Number of Publications	%
1	China	1309	36.63
2	India	599	16.76
3	South Korea	273	7.64
4	USA	264	7.39
5	Saudi Arabia	236	6.60
6	Italy	225	6.30
7	Egypt	184	5.15
8	Malaysia	182	5.09
9	Australia	160	4.48
10	France	142	3.97

The regions of the world where issues related to the use of industrial waste in sustainable construction are most frequently discussed are primarily Asian countries: China (36.6%), India (16.8%), and South Korea (7.6%). This is due to the fact that China and India are the most populous countries in the world, so they pay special attention to the development of construction, including environmentally friendly construction (Table 2, Figure 2).

**Figure 2.** Regions of the world with the highest interest in eco-friendly building (*the intensity of the color indicates the most articles on the topic discussed*).

The disparity in publication numbers between China and India cannot be attributed solely to demographics. It also reflects extensive research institutions and deliberate state policies on sustainable development. Both nations are characterized by a high density of technical universities and specialized research institutes, funded by significant government grant programs (such as the National Natural Science Foundation in China and the Department of Science and Technology in India). Furthermore, these trends are strongly linked to the enormous activity of domestic industries. As the largest global steel producers and energy consumers, China and India generate unprecedented amounts of industrial byproducts (e.g., metallurgical slag and fly ash). Consequently, the goal is to reduce pressure on landfills and lower the carbon footprint of rapidly expanding urban infrastructure. Generally, activities and implementations in this area are concentrated in highly developed countries with stringent environmental regulations. It can also be concluded that research is proceeding in two directions: first, it focuses on advanced recycling and innovation, and second, it focuses on developing proposals for managing and disposing of the growing volume of waste.

An overview of the records retrieved from the WoS database, sorted by publisher, is presented in Table 3, which lists the TOP 10 publications with the largest number of publications related to eco-friendly materials. The first three publishers closely related to this research topic are, in both cases, Elsevier and MDPI. It should be noted that many of the journals belong to the same publisher.

Table 3. Top 10 journals publishing articles related to the topic.

No	Eco-Friendly Building Materials Made From Industrial Waste				
	Journal	Number of Publications	%	IF	Publisher
1	Construction and Building Materials	927	54.02	8.0	Elsevier
2	Journal of Building Engineering	245	14.28	7.4	Elsevier
3	Materials	97	5.65	3.2	MDPI
4	Sustainability	91	5.30	3.3	MDPI
5	Journal of Cleaner Production	86	5.01	10.0	Elsevier
6	Case studies in construction materials	73	4.25	6.6	Elsevier
7	Buildings	68	3.96	3.1	MDPI
8	Materials Today: Proceedings	47	2.74	discontinued	Elsevier
9	IOP conference series	41	2.39	0.6	IOP Science
	Materials Science and Engineering				
10	Scientific reports	41	2.39	3.9	Springer

2.2. Research Evolution and Time Trends (1997–2025)

Initially, research was niche in nature and focused on basic attempts to utilize fly ash as a cement substitute. The period 2006–2014 saw a broadening of the raw material spectrum to include glass cullet and blast furnace slag. Research focused primarily on simple mechanical parameters (compressive strength). This was followed by an exponential phase from 2015 to 2025. Over 88% of all identified records (3854 of 4353) were published during this decade. A shift from disposal (landfill) to a circular economy (upcycling) and advanced material synthesis (e.g., foam ceramics) occurred. A shift from a purely mechanical approach to an interdisciplinary one (Materials Science, Civil Engineering, Environmental Sciences) was observed. This can be seen in scientific articles describing the introduction of advanced surface and chemical modification techniques (e.g., acid/base activation of ash, UV treatment of rubber) to improve cement matrix adhesion. Most studies declare a priori “ecological” based solely on the use of waste.

3. Qualitative Analysis and Discussion—Overview of the Most Important Publications

It is impossible to review every work on ecological construction using industrial waste materials. The author considers the most important aspects of its applications below. Numerous research studies were analyzed, with an emphasis on review articles.

3.1. Ashes of Various Origins

Many studies present important, cost-effective, and environmentally friendly approaches to utilizing various types of ash resources. Various types of ash are used, including fly ash, sewage sludge incineration, and biomass ash. Fly ash is the main byproduct of coal combustion in conventional energy production at temperatures ranging from 1200 to 1700 °C. Ash is collected from the flue gases through special filters and stored. Its specific advantages include fine-grained microspheres, high thermal resistance, and low plasticity. The main oxides in fly ash are SiO_2 , Al_2O_3 , and Fe_2O_3 , which together constitute approximately 80% by weight of the total composition. Other elements such as Ca, Na, and Mg are also present, as well as compounds of other trace metals. Due to its composition, fly ash can be used as an inorganic raw material for the production of construction materials thanks to technological innovations, thus reducing the use of natural resources [6,7].

For example, ash is used to produce foamed and conventional ceramic building materials [6–12], or other sintered materials such as ceramic membranes [13]. High-temperature sintering produces a three-dimensional, porous, and low-density material. Producing ceramic foam using solid industrial waste as a primary raw material is a key method for achieving high-quality recycling. The produced porous materials were characterized by low bulk densities below 0.8 g/cm^3 and high total porosity of approximately 65%. In the case of modified traditional materials, the produced ceramics met performance standards. Foamed ceramics are widely used in applications such as lightweight insulation materials, thermal insulation materials, moisture-resistant materials, sound-absorbing materials and other building materials [8,9,11].

The most widely used construction material worldwide is concrete. Annual concrete production is currently projected at over 4.4 billion tons, although this is expected to increase to over 5.5 billion tons by 2050 due to the rapid urbanization of developing countries [14]. Portland cement production significantly impacts the environment. These include the depletion of natural resources, landscape degradation, noise, and dust. Furthermore, carbon dioxide emissions have become a growing concern in the cement industry in recent years. Post-industrial ash is of great importance in the production of structural materials, i.e., concrete in its broadest sense. Generally, researchers strive to replace as much cement as possible with ash while maintaining applicable standards [14–18]. As an additive, fly ash has a significant positive impact on increasing the strength of modified concrete and has been used in recent years. Industrial and agricultural waste is inexpensive and offers an environmentally friendly alternative to solid waste disposal. Fly ash can be used as a mineral admixture in concrete, improving workability, mechanical properties, thermal conductivity, and durability. It is also used for foamed and lightweight concretes [19–21]. Foam concrete, characterized by its lightness, thermal insulation, and soundproofing properties, is widely used in construction. Thermal conductivity depends on particle size, so fly ash processing methods are extremely important. These processes include mechanical grinding and modification with acids, bases, and salts. Foam concrete depends significantly on the stability of foams. If the foam is not sufficiently stable and does not maintain the concrete structure before the cement paste sets, it will lead to structural damage. Therefore, increasing foam stability is crucial for progress in the use of foam concrete. It turns out that fly ash, especially modified fly ash, can stabilize concrete foams [22].

Some researchers have attempted to use ash and silica fume in repair mortars for historic lime plasters and building materials. The results showed that fly ash-based mortar is suitable for sustainable renovation procedures of historic limestone structures in terms of physical and mechanical properties [23]. Unfortunately, fly ash is becoming scarce, especially in European countries. The energy transition is already phasing out coal combustion, which generates large amounts of fly ash.

3.2. Recycled Glass as Filler

The use of recycled glass as filler is an increasingly popular method of managing cullet that does not meet standards for the production of new packaging. According to the literature, the global amount of recycled glass waste was 27 million tons, and the recycling rate of total glass waste was approximately 20%. Container glass waste had a recycling rate of 32%, while flat glass waste had a recycling rate of only 11% [24]. Depending on the degree of fragmentation, this raw material finds applications in many industries, including construction. It is often used as an active additive to cement and concrete (improving mortar properties) and as a substitute for quartz sand in silicate products. Recycling window glass as a component of concrete is one of the most promising directions in ecological construction. Glass from window dismantling is characterized by high purity and a repeatable chemical composition. In concrete technology, it is used in two different ways: as aggregate or as a cement substitute (glass powder), with each form having a radically different impact on the material's structure. Powdered glass bottle waste acts as an effective pozzolanic material due to the presence of non-crystalline aluminum and silica (high amorphous silica content) [24–26]. Researchers observed that incorporating 10% and 20% ground glass powder as a cement substitute significantly improved strength parameters after 28 and 120 days of aging [24]. Recycling glass from electronic devices (TVs, monitors, mobile phones) is popular as a partial and complete replacement for sand and cementitious materials. For example, cathode-ray tube glass was previously a common component of old televisions and desktop computers. Such glass has steadily increased in electronic waste over the past decade. This is primarily due to the development of better, cheaper, and lighter panels, including plasma, LED, and LCD screens. Recycling this glass is problematic due to its lead content. It is important to minimize the leaching of lead and other heavy elements from discarded CRT glass. Researchers have shown that using CRT glass waste for cement-based products is a sustainable option, alongside other recycling processes that immobilize toxic industrial byproducts. Unfortunately, research also points to negative effects of CRT glass use, such as enhancing the alkali-silica reaction in concrete [24–27]. Another source of industrial glass is mobile phones. The most frequently damaged part of a phone is the glass screen, which serves protective and visual functions. Glass containing Bi_2O_3 shows particular promise, as it exhibits properties that absorb various types of radiation [26]. Glass from bottles, both in the form of microparticles [14] and in coarser fractions [28,29], is also used as a filler and substitute for natural aggregates. Recycled glass is also used in linear construction, i.e., transportation infrastructure. Global urbanization is necessitating the construction of infrastructure such as roads and railways to meet the mobility needs of a growing population. Currently, natural aggregates are primarily used in linear infrastructure. Global demand for natural aggregates is approximately 40 to 50 billion tons of aggregate, sand, and gravel per year, half of which is used for construction purposes [30]. Incorporating recycled waste glass as a construction aggregate in linear infrastructure is a promising solution for reducing landfill waste and minimizing reliance on natural aggregates. Unfortunately, the brittle nature of glass creates challenges during its reuse/recycling. The main problem is its breakage during transportation and installation. On the other hand, glass powders are successfully

used as fillers in mineral-asphalt mixtures [30,31]. An innovative thermal and acoustic insulating material is foam glass, made from foamed glass cullet, used in foundation and roof insulation. Glass foam has very favorable properties, including low density, high chemical and biological resistance, and excellent thermal and acoustic insulation. Foaming involves incorporating a foaming agent into the initial powder mixture, which has the ability to release gases at high temperatures (usually between 750 and 1150 °C). When the glass reaches its softening point, it reduces its viscosity to a point where the gas spreads throughout the material without being trapped in bubbles. Sintering at approximately 900 °C produces glass foam with good thermal insulation properties (apparent density of approximately 0.4 g/cm³, porosity of approximately 80%, and thermal conductivity of 0.09 W/m·K [32–34]). Many other pure inorganic or organic materials, as well as by-products and wastes, may be suitable as safe foaming agents, and researchers around the world are currently focusing in this direction.

3.3. Slags from the Steel and Copper Industry as an Alternative Aggregate

Steel slag is a byproduct of the steelmaking process, which usually contains a high content of CaO, SiO₂ and a small amount of Al₂O₃ and MgO. It is characterized by high density, strength, and durability, making it a potentially sustainable alternative to building materials. Unfortunately, the potential for recycling and reusing slag in the construction industry is limited. This is due to its unstable and complex chemical composition, which typically includes elevated levels of heavy metals. Slag is also characterized by low hydration ability [35,36]. The search for suitable applications for the vast amounts of steel slag produced is ongoing. The use of slag as a building material in the concrete industry seems particularly promising. These include cement additives, fine aggregates, and coarse aggregates. Traditionally, steel slag was processed into dust and used as an additional cement substitute. High iron content is unfavorable because it increases the energy consumption of processing (crushing and grinding). Unfortunately, the hydration capacity of slag is poor due to the low content of hydratable components. Slags contain significant amounts of CaO, and the addition of water to calcium oxide causes excessive volumetric expansion of the building material. The use of steel slag as a partial substitute for natural coarse or fine aggregates in concrete would be a promise for large-scale utilization of steel slag. In mixed concrete, natural aggregates constitute over 60% of the concrete's volume. Despite its disadvantages, it is mainly used as an aggregate in road construction, concrete and asphalt mixtures. The literature indicates that steel slag was used in the sub-base and base courses of road pavements. Some data shows its potential for use in structural concrete. As a filler in mortars, it can reduce porosity and thus create a denser structure. The use of slag as a substitute for aggregate improves the mechanical properties of concrete. Unfortunately, due to the potential for swelling, volume stability may be an issue. [37–39]. Some authors indicate that it also causes increased portlandite crystal separation in mortars [40]. Foamed materials with insulating properties can also be created with the addition of slag and steel dust. Fly ash and steel slag consist of oxides that are the same as the main components of foam materials and can be used as a good alternative raw material. Chemical modifications achieve high small-hole closure rates and increased flexural strength. Using a high-temperature direct foaming process, the effects of different compositions and sintering conditions on the crystalline phases, pore structure, and physical properties of the foam are investigated [41,42]. Interesting research concerns the alkaline activation of slags. Modified sodium silicate is used as the activator. The silicate gel network encloses the slag particles, creating a mechanical interlocking effect, which densifies the material. [43,44]. There are also studies describing the use of slag in asphalt mixtures. Slag is alkaline in nature, which means it adheres well to asphalt, making it a promising material for road construction with

excellent performance. Many scientists have therefore begun to investigate its potential as a substitute for natural aggregates in asphalt pavement construction [45–47]. Using steel slag as an aggregate in asphalt pavements is an excellent solution to counteract the shortage of natural aggregates. Steel slag aggregates are characterized by excellent performance properties. They are physically and mechanically resistant, have high density and hardness, and low shrinkage. They also have high polishing properties. Proper preparation can achieve a good particle size distribution, and appropriate particle shape, surpassing traditional aggregates such as limestone and basalt. Thanks to these properties, they are a suitable substitute for asphalt concrete surfaces [48–51]. In developed countries, almost 100% utilization of steel slag is achieved.

Progressive electrification and the development of advanced technologies (including renewable energy systems, robotics, and electronics) determine the strategic importance of the global copper metallurgy sector. Copper slag generated in production processes is a significant anthropogenic by-product in terms of volume, demonstrating a wide range of applications in the area of environmentally friendly construction materials. For example, copper slag is known to be used as a sustainable substitute for sand in masonry mortars. Replacing aggregate with this industrial waste significantly improves ecological parameters, including a 76% reduction in embodied energy at optimal proportions. Research indicates that optimal mixtures meet construction standards and support a circular economy while reducing the carbon footprint [52]. Finely ground copper slag exhibits pozzolanic properties, and research is underway to use it as a substitute cementitious material. It can replace up to 20% of cement in the mix, which helps reduce the carbon footprint of concrete and improve its long-term durability [53–55]. Aggregate made from shaft slag (slowly cooled) is characterized by excellent abrasion resistance and high roughness, which is why it is used in road wearing courses [56,57].

3.4. Clay Secondary Materials That Are Not Used in Other Industries

Clay raw materials have the potential to be transformed into safe and durable industrial products. However, processing them poses significant challenges. Many countries possess rich clay deposits, which are the basis for the production of ceramic materials. These include porcelain, sanitary ware, and even construction ceramics such as bricks and roof tiles. However, the pursuit of sustainable development and concerns about resource depletion are forcing a reassessment of clay extraction, processing, and use in various sectors. Low-quality clays have often been rejected due to higher levels of contamination and mineralogy that is unsuitable for technological requirements. However, such raw materials offer significant potential if carefully characterized and strategically deployed. Clay raw materials that are not used in typical, mainstream building industries such as construction ceramics or cement production are often referred to as raw materials with specific properties or waste materials [58,59]. They most often find their “second life” in environmental protection (insulation) or specialized products such as lightweight aggregates. Certain conditions are required for their formation. Clay-containing post-process materials can be used to produce lightweight aggregates provided their chemical composition and distributions of particle sizes are suitable for sintering. Appropriate ranges of clay chemical compositions have been proposed to make them suitable for lightweight aggregate production. The compositions are as follows: 48–70% SiO₂, 8–25% Al₂O₃, 3–12% FeO + Fe₂O₃, 1–12% CaO + MgO, and 0.5–7% K₂O + Na₂O. Iron, calcium, sodium, and potassium oxides are essential fluxes. Sintering should begin at a temperature of approximately 1150–1200 °C. This process must result in the formation of a glassy surface with appropriate viscosity. Once the glassy layer has formed, the sample must be able to release sufficient gas during the swelling process. The sintering reaction must occur at the latest during the swelling

process so that the released gas can be trapped beneath the glassy surface. Swelling mechanisms are often related to the presence of iron oxides, which are common in large quantities in post-processed clays. The decomposition of Fe_2O_3 upon heating to Fe_3O_4 , FeO , and O_2 is often used to explain the swelling phenomenon. Artificial lightweight aggregates can be produced from raw materials previously deposited in settling tanks [60–62]. Many of them are used in lightweight concrete. Particle densities of lightweight aggregates range from 1010 to 1380 kg/m^3 . Standards define them as granular material with a bulk density below 1.2 g/cm^3 or a particle density not exceeding 2.0 g/cm^3 . The compressive strength of concrete made with lightweight aggregates after 28 days ranges from 19.8 to 34.7 MPa [63–65]. The ideal lightweight aggregate obtained from waste clay material is therefore spherical, with a diameter of 4 to 14 mm, with a strong, porous, sintered core and an impermeable, rough surface that strengthens the bond between the hydrated cement and the aggregate. The pore structure is a key factor in determining the suitability of aggregate for concrete. The aggregate should consist of pores evenly distributed throughout the core matrix, surrounded by a non-porous, glassy surface. This structure is called closed porosity. There are also specially sintered aggregates that have different properties from classic aggregates obtained from swelling clays. They are characterized by high open porosity, which on the one hand limits their strength but on the other allows them to retain excess water and allows plant roots to grow. Aggregates used as plant substrates contain various types of pores. We can define macropores, mesopores, and micropores. Macropores, i.e., those with a diameter greater than 100 μm , constitute the dynamic part of the space within the grains. It is through these pores that water, air and carbon dioxide flow rapidly. This process is known as gravitational infiltration. In pores with a smaller diameter, i.e., between 30 and 100 μm , water can accumulate and be retained. This is particularly important during dry periods. The smallest pores, i.e., micropores with a diameter of less than 30 μm , act as a reservoir for capillary water and a substrate for microorganisms. Capillary water can be retained for a very long time due to adhesive forces, but it is inaccessible to plants. This aggregate is ideal for roof gardens [66–69]. To achieve the porosity described above, the sintering process must be skillfully performed. It is typically conducted to obtain a solid material, as its high mechanical strength is desirable. In the case of aggregates with open porosity, the process is performed differently. The temperature had to be high enough to cause a liquid phase to form, clumping the clay particles together. When the open porosity transforms into closed porosity, the process should be terminated. Such sintering is carried out in such a way as to prevent the material from becoming denser. Another equally useful application is clay-cement barriers used in hydraulic engineering. Sealing slurries used in hydraulic engineering are systems created by adding structuring agents to clay suspensions. Cements are typically used as reactive additives. These barriers are characterized by their plastic behavior and lack the crystalline structure typical of concrete. This means they are susceptible to deflection and do not crack. Furthermore, they do not damage the surrounding soil structure by bonding with it. The formation of the internal structure is controlled over time. The sealing masses are not washed out of the joints, and the finely ground clay particles they contain ensure a high level of watertightness. Clay suspensions with a density of 1.2–1.23 g/cm^3 and containing 8–10% cement by weight are the most effective. Various substances and chemical reagents can be used as rheology-modifying additives, for example polyacrylates and sodium silicates in the form of water glass, as well as pozzolanic compounds (metallurgical slag, fly ash, etc.) [70–72].

3.5. Rubber Plastics and Polymers in Concrete and Asphalt

Developed countries are grappling with enormous amounts of landfilled plastics. Over the past 20 years, legislation has been introduced to reduce the amount of waste

sent to landfills. It has been proven that the landfilling of used tires and plastics has a negative impact on human health and the environment. Currently, landfilling used tires is unacceptable, as available space is becoming limited. Rubber and plastics degrade very slowly, damaging natural resources surrounding landfills and which may increase the occurrence of unintentional fires. Therefore, the safe recycling and upcycling of tires and other plastics is a challenge. Given the enormous global production of used tires, developing technologies that can process large quantities of used tires is highly attractive and urgently needed. Currently, technological solutions exist that allow the recycling of almost any type of plastic and other synthetic materials, with certain barriers represented by technical, economic and logistical factors. Incorporating rubber (tire) and plastic waste into concrete is a sustainable and environmentally friendly method for reducing landfill waste and improving the ductility, acoustic insulation, and thermal properties of concrete. Although these materials generally reduce density, workability, and mechanical strength (compressive/tensile) due to weaker bonding, they are excellent for non-load-bearing or lightweight applications [73]. Research and implementation in the construction sector are known to involve the use of waste rubber in concrete as a partial replacement for aggregates. Researchers are primarily focusing on the effectiveness of bonding rubber particles to cement mortar and improving the mechanical properties and durability of rubber concrete. Waste rubber is more commonly used as fine and coarse aggregate, although some applications also exist as fiber and binder. Several authors have focused their analysis on the mixture of PET and plastic in concrete and cement mortar in the form of aggregates [74–77] and fibers [78,79], highlighting the different properties of the final products. A significant proportion of plastic waste comprises elastomers, such as rubber, primarily from car, truck, and motorcycle tires. Despite its great potential, it presents some challenges, such as the low intrinsic strength of rubber and poor bonding to the cement matrix, which hinder its use as an aggregate in large quantities [80,81]. The addition of elastic fibers, however, supports the micro-bridging of concrete, resulting in increased resistance to compression (tension) and bending. To address this challenge, researchers have analyzed various rubber processing methods: fractionation [82], chemical treatment [83–85], UV treatment [86] and soaking in water and other solutions [87,88]. These processes not only improve bonding but also significantly improve the mechanical properties of rubber concrete [89]. However, it is important to remember that these methods can impact health and the environment. As a result, this material offers better thermal insulation properties than traditional concrete, which optimizes heat management in buildings in both winter and summer.

Rubber can also be used in the construction and infrastructure sectors, for example in asphalt mixtures. The sensitivity of asphalt to temperature changes is crucial. The use of rubber from recycled tires in the binder can be a beneficial additive. Rubber-modified mixtures also contain less bitumen binder, which is an added benefit from an asphalt consumption perspective. When using rubber-based substitute materials, the bitumen content should be optimized. The lower the bitumen content, the greater the likelihood of air voids forming, which increases permeability. Excessive permeability can lead to accelerated pavement degradation. Two methods are known for producing asphalt-rubber mixtures: wet and dry processes. The wet process, introduced in the 1970s, involves adding crumb rubber to the asphalt mix. This modifies its chemical and physical properties, creating more flexible surfaces. This prevents early fatigue cracking. The rubber content ranges from 18 to 22%, and the material is mixed with hot asphalt and appropriate oil modifiers for ease of use. In the dry process, however, some of the aggregate in asphalt mixtures is replaced with crumb rubber waste. This process was also developed in the second half of the last century. Typically, a few percent of the aggregate in the total mix is

replaced. The rubber fractions are prepared to match the grain size of the natural aggregate used in the mix. The dry process has more limitations than the wet process, although it is easier to use. Asphalt mixtures with replaced aggregate are characterized by volumetric instability and reduced strength. The rheological properties of the modified binder are also important; these are influenced by the shape, composition and particle size of the granulate used. To improve the performance properties of the mixtures, recycled rubber is often modified with appropriate coatings [90]. Recycled polymer composite materials offer an eco-friendly alternative to traditional construction materials such as steel, wood, and concrete. They combine plastic waste (polymer matrix) with various fillers (fibers, wood flour, and industrial waste) to create durable, high-strength materials with a low carbon footprint. These materials are most often created by recycling thermoplastics obtained from construction waste, using recycled polyethylene (rPE), polypropylene (rPP), polystyrene (rPS), and polyvinyl chloride (rPVC). Recycled polymer composites are most often used in non-structural applications and small-scale architectural elements, although technology is increasingly enabling their implementation in load-bearing structures. Ground composite waste is added as aggregate or dispersed reinforcement, improving the flexibility and fracture resistance of concrete [91].

3.6. Agricultural, Food and Paper Industry Powders Used as Fillers in Construction Materials

A good natural material used as a filler in the construction industry should meet traditional quality criteria, such as breathability, hygroscopicity, fire resistance, resistance to mold and fungi, odorlessness, lack of radioactivity and hazardous substances, and insulating properties. The thermal insulation market primarily comprises synthetic materials produced from fossil fuels. Therefore, thermal insulation in buildings is an important goal of the global sustainable development agenda and the protection of the environment and human life. An interesting article explored the use of feathers as an insulating material component. Feather waste is proposed as a thermal insulator due to its interesting properties, as well as the large amount of feather waste that is discarded each year. Only a small amount is recycled; most is simply incinerated. The developed nonwoven fabrics demonstrate excellent thermal insulation, with thermal conductivity ranging from 0.031 to 0.044 [W/m·K] [92]. Cellulose pulp is also used to produce insulating materials. Cellulose is considered a plant-based carbohydrate that is resistant to decomposition. When one considers the durability of materials made from it, this is an added benefit. Cellulose is a renewable, biocompatible, and abundant polymer. Another advantage of using cellulose in construction is that it is a cheap and inexhaustible material. The main source of cellulose is trees, and afforestation often occurs on lower-grade lands, so cellulose raw materials do not compete with agricultural fields. There is also enormous potential for using agricultural waste as a source of cellulose [92]. In addition to raw cellulose, recycled paper from the paper industry is also used as a filler. However, the poor properties of paper and cellulose pulp limit the potential of these raw materials as building insulation materials. To increase the mechanical strength and thermal insulation properties of cellulose, silica is incorporated into the materials. The combination of fibers and silica gel reduces brittleness and improves strength. This composite allows the creation of a cross-linked structure that is durable (flexural modulus 430 MPa), insulating (thermal conductivity $35 \text{ mW m}^{-1} \text{ K}^{-1}$), and hydrophobic (water contact angle 159°) [93–95]. Another bio-based material used in the construction sector is hemp. It is primarily used to produce structural panels that fill the interlayer spaces in wooden structures, interior wall cladding, ventilated cladding, interior partitions, suspended ceilings, and floors. A characteristic feature of such panels is their low density and relatively high tensile, compressive, and flexural strength. Hemp can also be used as vegetation mats in roof gardens. Finally, through specialized processing,

a fire-resistant material can be obtained [96]. Raw bales of agricultural straw, whether from wheat, corn, or rice, have long been used as an insulating material in residential buildings due to their hollow structure, low cost, low density, and low thermal conductivity. Current, modern modifications of such materials result in prototype boards with a thermal conductivity of 0.046 W/mK, which is directly comparable to other thermal insulation materials, such as polystyrene with a density of 10 kg/m³. Therefore, agricultural straw can be used to produce thermal insulation materials, which will contribute to improved energy efficiency and thermal comfort in homes. “Eco-sandwich” materials containing various biomass compositions are the most promising [97]. Food industry waste, such as rice husks and corn husks, is increasingly being used in building materials. Such bioinsulating boards can achieve thermal conductivity values ranging from 0.0585 to 0.0518 W/m²K at densities of 150–450 kg/m³, which is similar to expanded perlite and vermiculite in the same density range [98]. There are also publications using nutshells as filler to replace fine aggregate. Strength results indicate that nutshell panels are not suitable for structural purposes, but are suitable for partition walls. However, they must be used interchangeably with traditional technologies. Replacing approximately 50% of the panels demonstrates adequate strength and can be used for this purpose [99,100]. Agro-waste is also used in bricks. Generally speaking, lightweight bricks are produced by adding organic and inorganic additives as foaming agents. Organic foaming additives include sawdust, polystyrene, paper sludge, and various types of biomass. Inorganic foaming substances are those that decompose at high temperatures, generating gases, such as perlite, diatomite, calcite, and pumice. These are nonrenewable resources. Lightweight bricks can also be obtained by using various types of agricultural waste. This allows for products with a unique combination of properties while also enabling the recycling of growing amounts of agricultural waste. Typically, oat husks, rice husks, wine industry waste, and coconut fibers are used. However, in order to produce bricks with an acceptable increase in porosity, thermal conductivity and mechanical resistance, the addition of such waste should not exceed 10 wt% [101–103].

4. Critical Synthesis, Contradictions, and Future Horizons

In the literature presented, there is a clear consensus regarding the properties of waste-derived materials. There are both enthusiastic and critical voices regarding the use of waste materials in sustainable construction. Despite the consensus, the literature reveals clear contradictions and technical compromises. For example, researchers report that the incorporation of byproducts (e.g., ash microspheres, foam glass, and agricultural biomass) significantly reduces bulk density, improving thermal and acoustic insulation performance. While some authors report that chemical and UV surface modifications of tire rubber effectively restore mechanical performance, others demonstrate that these processes can introduce environmental toxicity and accelerate microcracking due to volumetric instability over time. Regarding materials that can react with alkali, the main point of contention concerns glass recycling. While some studies recommend immobilizing glass in cement matrices as a safe disposal method, others demonstrate that high amorphous silica content strongly activates the destructive ASR, leading to long-term structural damage. Two trends are significant regarding materials from the steel industry. Positive—the use of metallurgical slag as a coarse aggregate improves the short-term polishing resistance of asphalt and concrete surfaces. Negative—volumetric swelling caused by delayed hydration of free lime, which leads to early surface degradation. However, it can be clearly stated that contemporary research indicates a transition from simple waste substitution (recycling) to advanced technological engineering (upcycling).

To go beyond descriptive laboratory tests, future research must systematically address three important aspects:

1. Standardized Life Cycle Assessment (LCA): Moving beyond the a priori assumption of environmental sustainability by quantifying the true energy costs of processing operations. For example, high-temperature sintering processes, chemical modifications using multiple expensive and specialized reagents, the energy required to obtain fine-grained forms, and much more.
2. Long-term durability modeling, shifting the focus from standard laboratory tests and assays to long-term studies, multi-year aging, heavy metal leaching kinetics and freeze–thaw cycles under real environmental stress conditions.
3. Adapting supply chains and material sustainability. Developing local capabilities to address waste utilization shortages. Systems for standardizing and homogenizing waste used in construction.

Table 4 summarizes the reviewed studies, including key information such as material type, industrial waste source, application, main findings, and identified research gaps.

Table 4. Synthesis of reviewed industrial waste applications in eco-friendly building materials.

Type of Building Material	Source of Waste	Main Use	Key Parameters	Identified Problems	References
Foam ceramics and lightweight concretes	Fly ash (coal), sewage sludge, silica dust.	Thermal and acoustic insulation, repair mortars, lightweight concretes.	Porosity ~65%, density <0.8 g/cm ³ . Improved strength, rheology and stabilization of foams.	Lack of raw material availability in Europe in the era of energy transformation	[3–20]
Artificial aggregates and glass fillers	Glass cullet, window glass, CRT tubes, smartphone screens.	Substitute for sand and cement, road aggregate, anti-radiation screens.	Replacing 10–20% of cement increases strength. Glass with Bi ₂ O ₃ absorbs radiation. Glass powder can be used as a mineral-asphalt filler.	Risk of increased alkali-silica reaction (ASR); brittleness making transportation difficult.	[21–28]
Asphalt and concrete structural mixtures	Steel slags (metallurgy).	Cement additives, coarse and fine aggregates for roads and asphalt.	High density, hardness and polishing resistance; excellent alkali adhesion to asphalt.	Volumetric instability (swelling by CaO); high energy consumption of grinding iron-rich phases.	[29–48]
Artificial lightweight aggregates and barriers	Low-quality waste clays, sediments from retention reservoirs.	Substrates for green roofs, lightweight concretes, ecological sealing barriers.	The decomposition of iron oxides, carbonates, and biomass creates open porosity ~50%. Water retention in the pores. Clay-cement suspensions exhibit high water tightness.	There are no long-term studies of resistance to frost cycles in changing roof conditions.	[49–63]
Elastic composites and asphalts	Used tires (rubber), PET waste and polymers.	Non-structural lightweight elements, binder modifiers	Increased flexibility, acoustic and thermal insulation. Reduced fatigue cracking of asphalt.	Decrease in structural strength due to poor rubber-cement adhesion; environmental cost of chemical/UV modification	[64–82]
Bioplates and insulating materials	Agricultural waste (straw, rice/corn husks), cellulose, feathers, hemp.	Wall panels, eco-sandwiches, lightweight porous bricks.	Very low thermal conductivity λ 0.031–0.058 W/m·K) comparable to polystyrene foam. Hydrophobicity of composites with silica.	High hygroscopicity; drastic decrease in brick strength when biomass dosage exceeds 10 wt%.	[83–94]

5. Conclusions

- The building materials industry generates the largest global production volume, which translates into huge consumption of natural resources.
- The rapid development of cities and population growth dramatically increase the demand for raw materials, the resources of which are limited on Earth.
- The only effective solution to the problem of depleting resources is to implement a circular economy by reusing waste materials.
- Analysis of the Web of Science (WoS) database proves that environmental aspects have become a key and dominant direction in contemporary engineering research.
- Modern civilization must evolve towards ecological construction to solve two crises simultaneously: the lack of raw materials and the excess of solid waste.
- Industrial and construction waste management eliminates the problem of landfilling and at the same time transforms worthless waste into valuable construction products.

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