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Review

Waste Management for Green Concrete Solutions: A Concise Critical Review

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Abstract: Reinforced concrete based on ordinary Portland cement (OPC) is one of the most commonly used materials in modern buildings. Due to the global growth of the building industry, concrete components have been partially or completely replaced with waste materials that can be used as binders or aggregates. Besides the ecological aspects, modern architecture widely needs materials to make the concrete durable, resisting large loads and various detrimental forces in the environment. This opens the possibilities of managing waste materials and applying them in practice. This paper presents a concise review of the green solutions for ecofriendly materials in the building industry that deal with the practical application of materials commonly treated as waste. The main emphasis was placed on their influence on the properties of the building material, optimal composition of mixtures, and discussion of the advantages and disadvantages of each of the "green" additives. It turned out that some solutions are far from being ecofriendly materials, as they leech and release numerous harmful chemicals into the environment during their presence in concrete. Finally, the paper suggests a research direction for the development of an ecofriendly structural material for a sustainable future.

Keywords: green concrete; waste management; waste as a cement filler; secondary raw materials; alternative cements

1. Introduction

Constant technological progress and increasing expectations of the market determine the growing demand for modern technologies and products used in everyday life. Many of the technologies known and used for years are based on the linear economy model: take–make–dispose [1]. Nevertheless, the depletion of natural resources of many types of raw materials, the deteriorating quality of the environment, issues with the management of increasing amounts of waste, and thus the environmental and climatic changes taking place currently as a result of pollution have contributed to a shift in the public awareness and have significantly influenced economic models and legal regulations. The past few years have brought changes in the industry that have led to a trend of replacing the classic linear economy models in material manufacturing to a closed circular economy model. The circular economy model is constantly being introduced in various industrial sectors, and one of its main assumptions is the reuse of raw materials contained in waste. This concept can be applied widely to manufacturing processes of concrete with reused additives, resulting in materials with altered properties.

1.1. The Composition of the Ordinary Portland Cement

Due to the constantly increasing world population and economic growth, one of the most developing industries is the building sector, in which a wide variety of novel materials are used. Despite many technological innovations in the building industry, cement remains the main concrete component, acting as a strong binding agent or adhesive material strengthening constructions. Concrete includes mainly ingredients such as an ordinary Portland cement (OPC), based on tricalcium silicate ($3CaO{\cdot}SiO_2$), dicalcium silicate ($2CaO{\cdot}SiO_2$), tricalcium aluminate ($3CaO{\cdot}Al_2O_3$), and a tetra-calcium aluminoferrite ($4CaO{\cdot}Al_2O_3Fe_2O_3$) made by heating limestone and clay up to 1400 °C. The most commonly used OPC is calcium–silicate–hydrate (C–S–H) hydraulic cement [2]. The cement market is booming and the global cement market will grow from USD 326.80 billion in 2021 to USD 458.64 billion in 2028, with a compound annual growth rate (CAGR) of 5.1% in the 2021–2028 forecast period, while the global green cement market will record an increase of 14.1% CAGR in 2017–2023. The driving force behind the global green cement market is, among others, the growing awareness of the reduction in carbon dioxide emissions and their harmful impact on the environment. Moreover, the building industry, to meet the requirements of Leadership in Energy and Environmental Design (LEED), focuses on green construction [3,4]. Additionally, a new sustainability index for mortars and concrete as a modification of the Empathetic Added Sustainability Index (EASI) was proposed [5].

1.2. Environmental Hazards

Production of the main ingredient of cement, i.e., OPC, contributes to tremendous air pollution, as it is a source of noxious gasses emissions such as carbon dioxide. In fact, the OPC manufacturing process covers about 8% of the world's human carbon dioxide emissions [6,7], while depending on the type of cement and the production process used, each ton of OPC produced requires 60–130 kg of heating oil or other substance and approximately 110 kWh of electricity [8]. Since climate change occurs because of the release of greenhouse gasses into the environment, the building industry began to implement a carbon-retaining production process. This has resulted in the manufacturers applying recycled ingredients, low-emission fuels, or the combination of low-carbon content materials, which have a cement property with clinker [9]. The price of cement is rising because of both depletion of natural resources and an increase in the environmental taxes [10].

1.3. Modification Methods

The development of improved production methods and concrete composition to ensure the reduction or elimination of CO_2 is highly important. In recent years, this has increased the need for changes in concrete and its components' manufacturing, particularly waste additives. Green concrete consists of a binder made from supplementary cementitious materials (SCMs), in which the OPC has been partially or entirely replaced with another material and/or waste and recycled materials as aggregates [11]. The materials of waste origin used in fresh concrete can be divided into three main groups: industrial, agricultural, and municipal waste. To improve concrete properties like workability, structure, and later-age strength properties, the waste material in concrete is often activated by physical, chemical, or physicochemical processes. The first one is breaking down the ingredients into smaller particles, which increases their effective surface area. The second one, the most efficient and widely used type of activation, is the use of a chemical substance, which activates the pozzolanicity of cement's ingredients. Concrete is chemically activated with the help of substances such as sodium sulfate anhydrite, sodium silicate, acid, or calcium formate [12]. In turn, both activation methods are combined to reduce or even remove inconsistencies in their chemical properties [13]. Because of this, depending on the additives within the concrete, the physical properties of the concrete can be improved.

In this paper, we discuss the recent solutions in applying waste materials as ingredients of the concrete that are treated as green additives and compare them with the typical solutions used in concrete. Waste-based additives offer a sustainable stream to the future demand for concrete preparation, enhancing concrete's mechanical properties, lowering the production costs, and opening up sustainable avenues for waste management. We present different concrete additives, with their varying mechanical properties, and discuss their advantages and disadvantages, including the economic and environmental aspects. Figure 1 presents the most common additives in the preparation of the green concrete that are mentioned in this paper.

Figure 1. Schematic diagram presenting the variety of cement additives to prepare green concrete.

2. Methodology

The research methodology was based on the PRISMA statement [14] and its extensions: PRISMA-S [15,16], as well as our personal experience. We considered recent publications, reports, protocols, and review papers from the Scopus databases. The documents used in the presented study were selected based on a two-step search procedure. First, we performed an initial Scopus search using the keywords "green concrete"; as a result, we obtained 729 research papers, 480 conference papers, and 80 reviews. After that, a more focused specialized search was conducted in the Scopus database, with keywords "green concrete", "waste management", "green additives", "alternative cement", "secondary raw materials", and their variations. The selection process was done according to the following overall criteria regarding ecological aspects, types of waste additives, and the influence of the additive on the mechanical properties of the concrete, considering the p of the additive in the total weight of the concrete. Finally, 162 papers were taken into account. The 480 conference papers, as well as papers without connection to the criteria above, have been excluded from the study. The literature search process was summarized in Figure 2.

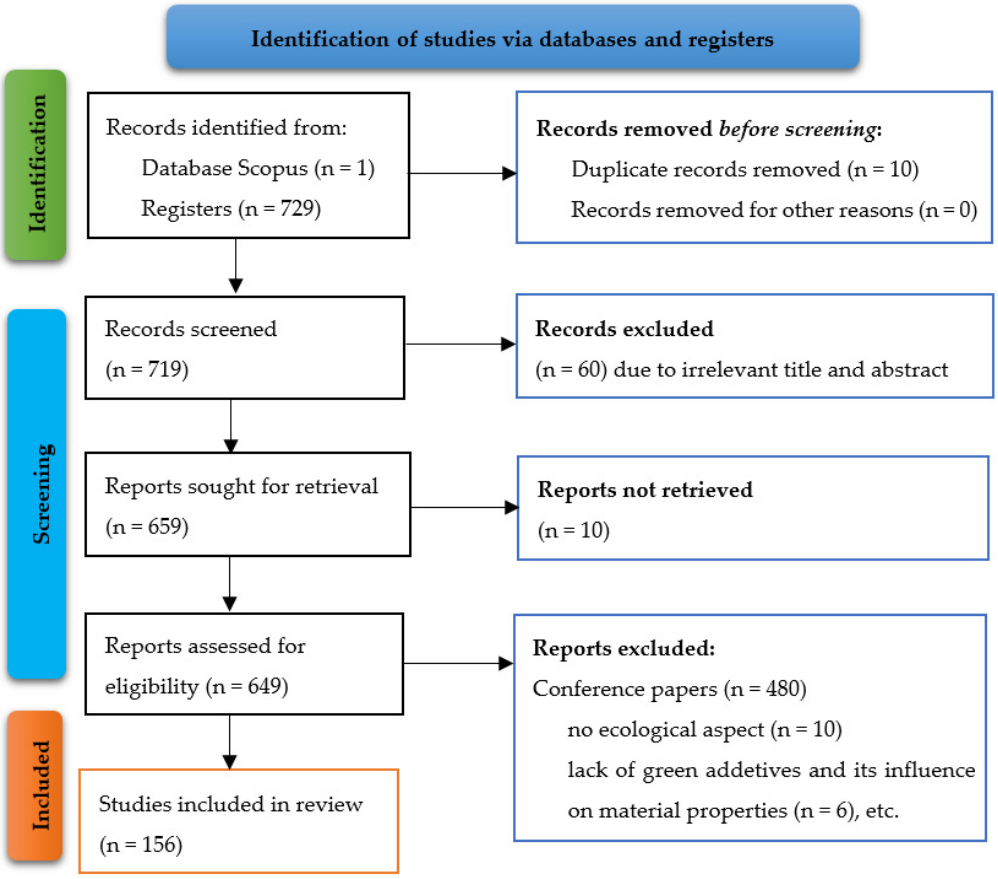

Figure 2. Literature search flowchart.

3. Green Additives

3.1. Supplementary Cementitious Materials as a Binder

One of the green alternatives is supplementary cementitious materials (SCMs) used as binders in the concrete, which are mainly waste from other industries, selected while ensuring adequate waste management. While it is known that SCMs can override the OPC in the range of 10–50% of the wt.% [17], it is not a rigid regulation; the percentage of SCMs is selected depending on the desired characteristics of the building material. Such cement additives may be natural, such as quartz, mica, pyroxene, and feldspar, or of industrial origin, such as calcined clays. The first is rich in silica, while the latter requires prior activation to react with the calcium hydroxide [18]. SCMs provide better pozzolanic and filler properties of concrete and can also improve the mechanical and strength properties. One of the popular materials used as an SCM is a by-product of the production of FeSi, the so-called silica fume (SF) [19]. It contributes to the enhancement of the concrete's mechanical properties. Studies show that adding microsilica to concrete in a percentage share of 10% results in a material that is characterized by a higher level of cubic and prismatic compressive, axial tensile, and bending strength, and a higher value of the modulus of elasticity [20]. In addition, slag (SL) is commonly used instead of OPC or its parts. It improves concrete's mechanical and strength properties [21]. Other SCMs can be made from wheat straw ash (WSA) containing high silica [22]. In another work, WSA was applied as an internal hardener to reduce the spontaneous shrinkage of high-performance concrete (HPC) [23]. The study demonstrated that the addition of WSA reduces the final autogenous contraction of concrete. Figure 3 shows the properties of silica fume, slag, and WSA compared with ordinary Portland cement based on the literature.

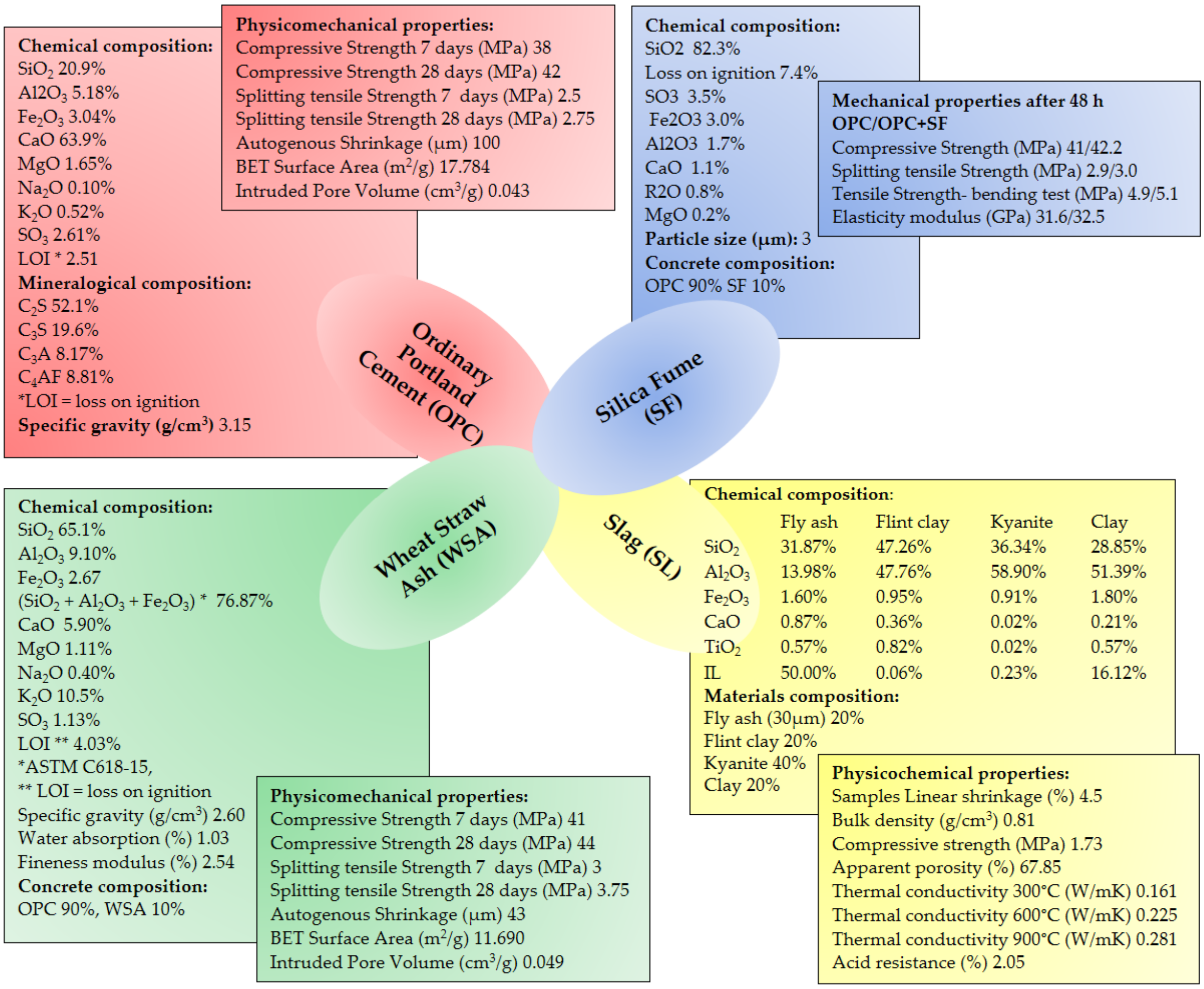

Figure 3. Diagram presenting the properties of silica fume, slag, and WSA compared with ordinary Portland cement based on the literature.

Other alternatives provide alkali-activated materials (AAM) [24]. Such material is formed by the alkaline activation of silica and alumina-rich materials using alkaline activators. Slag and fly ash with rich silica-alumina sources can be used as reaction precursors. Moreover, these components affect the more favorable properties of the entire concrete, such as low thermal conductivity, high volume stability, rapid strength gaining, fire, and chemical erosion resistance. In turn, the complete elimination of OPC is provided by alkali-activated binders (AAB), which are hydraulic cements with a high aluminosilicate binder phase content. In fact, aluminosilicates do not react too slowly in an aqueous medium, while because of the high amorphous content, they undergo hydrolysis and condensation in an alkaline environment. As a result, three-dimensional polymer structures characterized by a load-bearing capacity are created [25,26]. Alkali-activated binders can be split into several categories, including alkali-activated slag-based cement, alkali-activated pozzolan cement, alkali-activated lime–pozzolan/slag cement, alkali-activated calcium aluminate blended cement, and alkali-activated Portland blended cement [27]. The properties of the above-mentioned cement depend on their composition; for example, in the case of the first group of materials, they depend on the properties of the slag and the type and dose of the activator used. A properly selected activator can significantly reduce energy consumption in production and reduce the carbon footprint. An interesting proposal is to add high pozzolanic kaolin to the alkali-activated binders [28]. This proposal study has determined that the higher Fe and Al content in this kaolin lowers the compressive strength. Another interesting study shows that ferrosilicon slag can be applied in the production process of heat-insulating geopolymer bricks, which are characterized by the compressive strength of 6.1 MPa [29]. It also turned out that the increase in alumina waste content decreased the thermal conductivity, water absorption and apparent porosity of the geopolymer brick.

The green concrete-based building solutions may also consist of calcium aluminate and calcium sulphoaluminate [30]. Initially, calcium aluminate was added to the concrete to improve its sulfate resistance. Calcium aluminate concentrate (CAC) can be obtained from various wastes, influencing its mechanical properties. Mineral wool waste CACs are characterized by their increased compressive strength.

Besides alkali-activated OPC, cost-effective cement glass-based binders and additives are attractive solutions, where the glass is used as a sand substitute [31]. Aliabdo and co-authors [32] proposed using the waste glass powder as a substitute for up to 25% of the cement. Waste glass powder refines the pores of mortar and improves the mechanical properties, where the glass powder addition of up to 15% enhances concrete's tensile strength, compressive strength, and voids ratio for 33 MPa concrete grade. Shukla et al. [33] proposed using marble mud dust as a 100% alternative to natural sand in concrete. Authors show that with the addition of 10% of the marble dust, the strength of concrete has increased. Thus, as a case study shows, if 7.5–25% of the aggregate used in concrete production is replaced by glass, better freezing properties and better resistance to thawing and peeling of the concrete surface will be achieved. Rao et al. presented a literature review on the possibility of using aggregates from the recycling of construction and demolition waste as a component of concrete materials. The authors showed that these additives can be effectively used in concrete, especially in lower-level applications. Recycling aggregates can also be applied to produce standard structural concrete supported by additives, e.g., fly ash [34].

The following type of industrial waste is tire rubber-based additives like chopped or shredded rubber in the form of fibers or powder and carbon black as a product of the tire rubber pyrolysis. These materials are used as a substitute for gravel [35–38]. This offers a reduction in the concrete's weight and influences the compressive and flexural strength [39–41]. However, its production costs often exceed the OPC's manufacturing cost, while the production of such concrete releases less carbon dioxide into the atmosphere. Moreover, only half of the end-of-life tires are recycled [38,42]. Recycled rubber aggregate (RA) has concrete lightening properties. It increases the fatigue life and strength of concrete and contributes to the improvement of the dynamic properties and ductility of concrete [43,44]. The disadvantageous effect of the presence of rubber in the concrete is a reduction in compressive and tensile strengths, and a reduction in Young's modulus of elasticity [45]. Thus, adding ground tire rubber (which is a non-biodegradable substance and poses a threat to the natural environment) to concrete reduces its mechanical strength, while the thermal insulation decreases compared to magnesium oxychloride cement (MOC)-based composites [46]. Preliminary results show that in the case of concrete with rubber waste, the workability, compressive, and flexural values increase with the increased substitution rate of rubber; in the case of 50%, rubber waste is the highest [47]. Rubber can also be used as a composite filler with a polymer matrix reinforced with jute for structural applications. The tensile strength and flexural strength in such a composite are higher than in a composite without rubber [48]. The addition of rubber to the sand mortar has a positive effect on the physical properties of the mortar. In turn, adding 5% to 20% of rubber crumbs in the matrix and replacing sand with 20% of the rubber in the quarry mortar reduces thermal conductivity [49]. Sofi 2018 [50] presented the gradual reduction of the compressive strength up to 23% load of rubber against aggregates up to 40% for cement replacement, presenting the optimal results for the max. 12.5% replacement. Table 1 presents the correlation between the filler, chemical composition, and properties of the rubber-based additives that are loaded into the green concrete.

Table 1. The types of rubber-based additives including their filler type, chemical composition, and properties, based on [35–37,40,47,49].

Filler	Chemical Composition	Properties	Ref.
Pyrolyzed carbon black derived from waste tires	Carbon 95.42 ± 0.16% Hydrogen 0.77 ± 0.20% Nitrogen 0.22 ± 0.07% Sulphur 3.29 ± 0.09% Calcium 0.19 ± 0.01% Oxygen 0.12 ± 0.07% (Results in dry basis and ash-free) Other: Ash 16.55 ± 0.34% Moisture 1.16 ± 0.14% Volatile matter 2.50 ± 0.74 %	Higher Heating Value (HHV) 28.70 ± 0.1 MJ/kg Specific gravity around 0.64 Particle size 75 µm to 600 µm	[35]
Carbon black from waste tires	Carbon >98%	Fineness Modulus 0.835 (ASTM C-136 standard) Bulk Density 801 kg/m^3 (ASTM C-29 Standard) Size of most particles was 0.15 and 0.075 mm	[36]
Rubber from car, bus, and truck tyre recycling	Carbon black 25% Polymers 40–55% Softeners and fillers 20–35%	Specific gravity 1.1 Water absorption 7.1% for 4–10 mm particles size Water absorption 1.05 for 10–20 mm particle size	[37]
Self-compacting crumb rubber	Natural rubber 23.1% Synthetic rubber 17.9% Carbon black 28% Steel 14.5% Ash content% 5.1 Fabric, fillers, accelerators, etc. 16.5%	Specific gravity 1.12 Apparent density 489 kg/m^3 Thermal conductivity 0.11 W/k m Tensile resistance 4.2–15 MPa Speed of combustion- very low Water absorption 0.65 (negligible) Particle size 3.35 mm to 10 mm	[40]
Waste Rubber from tires	Rubber hydrocarbon 47.7%, Carbon black 30.7%Acetone extract 15.6% Ash 2.1% Other 3.9%.	Specific gravity 1.14, particle size 4.75 mm Specific gravity 1.03, particle size 5 to 10 mm	[47]
Crumb rubber obtained from recycling tires	Non-specified	Apparent density 0.38 g/cm^3 Absolute density 0.62 g/cm^3 Porosity 75% Water absorption 0.03% Maximum dimension: 1 mm	[49]

Generally, the literature shows that rubberized concrete has a lower density than conventional concrete, which can improve the durability of concrete but reduce the mechanical properties under a high load; however, the compression strength and other properties of the concrete depend on the rubber particles' size and content [50].

As the rubberized concrete is called "green" for its effective rubber waste management, the rubber-based materials can be far from green solutions. Tire rubber is a complex material containing various compounds, including pigments (e.g., zinc oxide, zinc sulfate, and titania dioxide), reinforcing agents (e.g., clays, carbon black, and carbonates), softeners, plasticizers, vulcanization additives, activators, and antioxidants. In contrast, additives like accelerators can contain heavy metals or heavy metal oxides, including white lead, lead monoxide, and even cadmium, that are released into the environment [51]. The literature clearly indicates that tire rubber easily releases aromatic compounds such as high aromatic oils (HA-oils) and polyaromatic hydrocarbons (PAHs) that have a toxic effect on aquatic organisms like *Daphnia magna* when they leak into the water [52]. Another reference presents the toxicity of the leakage on *Ceriodaphnia dubia* and fathead minnows

(*Pimephales promelas*), where the volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and metal ions were released [53]. Recent studies also show the genotoxic effect of chemicals released from the tire particles [53–56]. As can be seen, the rubber can release many compounds that can harm human health, wildlife, and biological diversity. So, their use in concrete, where rubber waste-based materials are exposed to the alkali media, may even enhance the leakage.

In industrial and household waste, many plastic waste products (e.g., nylon, polypropylene, polyesters, etc.) need to be managed. Recently, plastic fibers have been used as concrete fillers, improving its compression performance [57,58]. Several sources present control of spalling cracks for high load levels [59]. Moreover, plastic waste additives improve durability [60–62], flexural strength [61], and splitting tensile strength [63], and reduce the weight of concrete [64]. Kaur and Pavia [65] present the mortars enhanced with plastic wastes such as polycarbonate (PC), polyoxymethylene (POM), acrylonitrile-butadiene-styrene (ABS), and polyethylene terephthalate (PET) granules, consisting of 5–20% by volume of the mortar leading to the enhancement of the compressive strength reaching 37–71 MPa and 4–9 MPa improvement of the flexural strength for 20% substitution. They also show the tensile strength improvement in mortars with more than 15% of substitute during exposition to loading, frost expansion, salts, or swelling clays. Other alternative waste includes wood–plastic composites (WPCs) [66], which include multilayer packaging wastes (PCRs), recycled high-density polyethylene (rHDPE), and wood powders. It has been shown that WPCs that contain 10 wt.% of PET/PE PCR exhibit better mechanical properties than WPCs without PCR, i.e., a 23% higher flexural modulus. In turn, considering frost resistance, the best concentrate-based composite containing nano-silica is 2.5%, and PVA fiber is 0.4% [67].

Despite improving the mechanical properties of the concrete and reducing concrete production costs, within the application of the plastic and rubber waste, these solutions also have disadvantages [68]. Plastics can contain plasticizers, flame retardants, pigments, and even heavy metals that can be quickly released and, once they are released, they may leak into the environment, becoming secondary pollutants [69–71]. The number of compounds released into the environment is significant, including compounds that can act as endocrine disruptors or even cause genotoxicity.

With the growing use of electronic devices and portable electronics, electronic waste (e-waste) has increased dramatically within the last decade. For that reason, sustainable waste management methods are of great importance. Therefore, the literature presents the exotic possibility of e-waste management by utilizing it as an additive concrete filler. The e-waste includes cathode ray tubes (CRTs), liquid crystal displays (LCDs), plastics, metal wires, printed circuit boards (PCBs), spent batteries, smoke detectors, cables, computer moldings, light-emitting diodes, switches, thermostats, solder, bulbs, etc. These numerous waste products have become one of the most problematic waste types for sustainable management. Therefore, e-waste was proposed to be used as a concrete additive, even though because of the complex composition of the e-waste, it needs to be pretreated before use in concrete. Ullah et al. [72] proposed the application of e-waste as a substitute for the fine aggregate with 7.5% of the aggregate mass. The authors presented the improvement of the compressive strength of the concrete; however, above the 15% additive content, the compressive strength gradually decreased. Balasubramanian et al. [73] have developed a green concrete blending e-waste based on PCBs by the weight of coarse aggregate for 5%, 10%, 15%, 20%, 25%, and 30%. The authors presented the highest increase in the compressive strength for the 15% content of e-waste compared to the conventional OPC. Another reference also shows the compressive strength improvement when the e-waste content is below 15% substitution of the aggregates [74]. In work presented by Arora and Dave [75], the authors suggested using 4% of e-waste as an aggregate substitute to improve the gained strength of the concrete. In Luhar and Luhar [76], the broad discussion about the management of the e-waste within its incorporation in concrete is presented, indicating the need for the separation of the particular components of the e-waste such as glass, plastic, metal, etc. Depending on the type of components used as a substitute for aggregates, the properties of concrete can differ drastically. The addition of e-waste to concrete changes the mechanical strength properties of concrete such as compressive strength, split tensile, flexural strength, shear strength, and durability properties. Usually, the optimal content of the e-waste substitute is below 15–20% of the aggregate added to the cement. Despite these advantages, e-waste can release many harmful compounds, including heavy metals that are proven to be toxic to human health and the ecosystem, contaminating water, soil, and air, including polyaromatic hydrocarbons, metals, and metal ions, including lead and cadmium [77–80]. Since e-waste has been an emerging environmental health issue, its application in concrete needs adequate procedures that require additional chemicals and energy to separate toxic compounds from the e-waste to obtain safe materials that can be incorporated into the mortar. To avoid the leakage of harmful substances, special procedures need to be implemented before the concrete application of e-waste to prevent environmental and health consequences.

3.2. Biochar as a Concrete Composite

The following group of materials that can be used as binders is biochar obtained from controlled thermal decomposition (pyrolysis) of biomass. Due to the growing agricultural waste production, biomass needs management, and its management within concrete application seems to be a promising solution. The physicochemical properties of biochar dependent on different factors are presented in Table 2.

Table 2. Features influencing physicochemical properties of biochar, based on [81–89].

BIOCHAR	
Physical Properties	**Chemical Composition**
Porosity (from micro–to macropores) depends on the source of biomass and pyrolysis time	Depends on the pyrolysis temperature
Moisture sorption ability	The high content of the total and organic carbon
Different morphology (from granular and wire-like structure to irregular shapes)	Content of micro-and macroelements such as potassium, sodium, magnesium, calcium, copper, zinc, iron
Specific surface area (dependent on the pyrolysis temperature)	The high content of surface functional groups

The biochar's porosity and moisture sorption ability are added to cement as a filler, enhancing the compressive strength and durability of concrete [81–83]. Depending on the source of the biomass and the pyrolysis conditions, biochar can have different morphology—from the granular to wire or highly irregular shapes [84–86]. Besides shape, the biochar can also have different chemical compositions depending on the pyrolysis temperature, time, and feedstock [87–89]. As an effect, biochar may have different mechanical properties and different functional groups on its surface, which can influence the pH of the suspension under the mortar preparation and, as an effect, the mortar hydration, as well as the mechanical strength of the concrete [90–92]. Bearing in mind the reduction in carbon dioxide emissions, an interesting addition to the concrete is biochar and calcium carbonate as a part of the carbon storage system [93]. The biochar–calcium carbonate–cement would save the carbon storage places on land and/or at sea and help reduce cement usage.

One of the main forms of agricultural waste in Eastern countries is a rice husk that can be used as a cement binder after the pyrolysis. Zunino et al. [94] describe rice husk ash (RHA) as a mortar component, showing that incorporating RHA decreases flowability and increases water requirements. It can also affect the mechanical and durability properties of concrete by reducing compressive strength and increasing the permeability of the concrete.

In turn, in [95], RHA-based concentrate, composed of amorphous silica made by the charcoal incinerator, 15% OPC can be successfully replaced with RHA without loss of strength with a w/b ratio of 0.50. Moreover, an increase in RHA content causes an increase in split tensile strength.

Taking into account the mechanical properties, flexibility, and low production costs, a plant that is an excellent additive to cement is bamboo and bamboo waste, in particular bamboo fibers and bamboo leaf ash (BMBLF), which indicates a considerable potential as a pozzolanic material [96,97]. In [97], bamboo-based biochar was added in the 0.2–4% wt.%, and the compressive strength of the biochar-filled mortar was tested. It is shown that the 1% wt.% replacement of bamboo biochar with cement has the best strengthening effect, making concrete the most crack-resistant compared to the different percentages of biochar and to the neat mortar without biochar filling. Tan et al. [89] presented biochar based on waste wood as a binder in the 1–10% wt.%. Replacing the cement with wood-waste biochar by 1–3% improved mechanical properties, while it did not change the flexural strength such as the elasticity of the mortar compared to the neat mortar without biochar. It is also shown that the biochar addition decreased linearly with the biochar content.

Depending on the source of biomass, the binding properties of biochar vary. Zeidabadi et al. [93] proposed the application of the rice-husk biochar and bagasse biochar obtained under identical pyrolysis conditions, comparing the mechanical properties of the concrete. Authors show that incorporating such agricultural waste into concrete had beneficial effects on the compressive and tensile strengths, where the replacement of 5% wt.% of the cement improved the mechanical properties of the mortar compared to other mixes and control concrete. However, a further increase in the biochar content decreased the tensile strength of mortar.

Akhatar and Sarmah [98] show the utilization of biochar based on poultry litter, rice husk and pulp, and papermill sludge as a cement binder, where cement content up to 1% of total volume was replaced. Authors show that rice-husk biochar, paper mill, and pulp at 0.1% of total volume are the most effective binders compared to the neat concrete, while tensile strength values for the paper pulp and papermill sludge biochar doped concrete obtained comparable values. Generally, all used biochars significantly improved the flexural strength of concrete, while poultry litter and rice-husk biochar at 0.1% produced optimum results with a 20% increment to control specimens. Rice straw is also a promising source of biochar. Even a 1% addition of that type of biochar to cement improves compressive strength and thermal conductivity [99]. Gupta et al. proposed biochar prepared from food and wood waste, investigating fresh and hardened properties of mortar, proving an increase in the compressive strength, sorptivity, resistance to water penetration, and ductility compared to conventional mortar [100]. The best effectiveness of the biochar addition is 1–2% wt.%. Praneeth et al. presented biochar derived from corn-stover biomass added in the cement–fly ash blocks as 2%, 4%, 6%, and 8% of wt., where the optimal content was about 4–6% depending on the admixture. Moreover, the proposed material had increased CO_2 uptake [101]. Biochar is also widely derived from biomass-based fly ash [102–106]. Chen et al. have presented fly ash-based biochar as an additive promoting cement hydration reaction via pozzolanic reaction and internal curing [102]. Qin et al. [107] described the use of the biochar obtained from the eucalyptus plywood boards incorporating 0.65–13.5% wt.% into the concrete. It has been found that the BC content has little and/or no impact on the porosity and water permeability of the BC-modified concrete samples considered here and that the water absorption increases with BC contents. This concrete also shows a greater compressive strength and splitting tensile strength than conventional ones when the BC content is 0–6.5%; above this percentage, these strengths are compromised. This is because a small amount of BC will promote cement hydration, so the products of this process generated in a higher amount concerning those without BC contribute to the development of the strength of pervious concrete. It has also been found that 6.5% BC in the cement paste can decrease the albedo by 0.05, while it can be compensated for by the water absorption increment and strength improvement. So far, pervious concrete could be replaced by up to 6.5%, in weight, of cement with pulverized BC and it is feasible to curtail CO_2 emissions and lock up BC.

Sirico et al. [108] proposed using biochar from wood chips of local forests (alder, beech, poplar, chestnut, oak, and hornbeam), where biochar was subjected to gasification and used as a cement binder. The authors showed that fracture energy was improved by using a 1 wt% addition of biochar. However, this also slightly decreased the flexural strength. Recently, biochar was proposed to be applied in higher content than described elsewhere. Chen et al. [109] used a content of biochar of about 30% wt.% and 9% wt.% metakaolin to reduce the CO_2 emissions. The authors presented the ability of the created concrete to squeeze 59 kg of CO_2 per ton and enhance economic profits in concrete production with such a significant content of biochar.

As an additive to a concrete-based composite, metal-supported biochar seems to be a promising solution. It may improve the properties of conventional concrete, i.e., bending strength and splitting tensile strength. Moreover, a carbon storage system in concrete would limit clinker production and consequently reduce the production of carbon dioxide. The presence of biochar influences concrete properties, but biochar-based composites' characteristics require further research. Biochar acts as a gravel substitute leading to the reduced production costs of the concrete, making it possible to produce climate-positive concrete whose properties are comparable to or can even exceed those of a corresponding conventional OPC-based concrete. At the same time, the biochar as a product of pyrolysis is dependent on the experimental conditions during heat treatment. If treated as a waste source, it reduces the concrete costs.

3.3. Non-Carbonized Agricultural Waste

Agricultural waste is a global problem, so its incorporation into concrete reduces both the energy consumption for its regular utilization and during concrete preparation [110]. Natural, organic fibers and particles can provide significant advantages over biochar obtained within the pyrolysis process because of the lower costs and omission of energy consumption during pyrolysis. Dry biomass contains many fibers that may work as a reinforcement of cement. In contrast to the classical reinforcement based on natural minerals and reinforcement with steel or synthetic materials, plant-based additives cannot be compared in the case of their mechanical properties because of the soft structure. However, plant-based additives can also improve the characteristics of mortar, such as changes in the hydration rate, elasticity, volumetric changes, porosity, etc.

Sellami et al. [111] presented results where the wild vegetal diss plant was used as a lignocellulose-based fibrous reinforcing additive. The authors show that the pretreatment of the plant has a significant role in the final product properties, where the boiling and washing of fibers results in higher mechanical strength than in the case of dry fibers. It is shown that the resistance against fracture can be improved within the arrangement of the fibers. Positioning of fibers horizontally enhances adhesion with the cement paste. In other work, agricultural waste products obtained from palm oil and coconut oil processing were added to the cement [112]. The authors presented concrete containing coconut shell (CS) and palm kernel shell (PKS) as a facile method for utilizing waste and reducing the costs of the concrete production, where agricultural waste was used in two nominal mix ratios (1:1:2 and 1:2:4) involving crushed, granular CS and PKS as substitutes for gravel in gradations of 0%, 25%, 50%, 75%, and 100% and water/cement ratios of 0.75 and 0.50 for both mix ratios 1:2:4 and 1:1:2. Results showed that the compressive strength of the concrete decreased with the increase of the percentage of shell, while the compressive strength can be modified by varying the ratio of the shells vs. OPC. Kriker et al. [113] also presented palm-based waste as a cement additive. Date palm fibers were proposed to replace cement in dry environments where there is a need for strengthening against high temperature amplitudes. The authors showed that fibers can provide technical solutions for improving the mechanical performance of the mortar, while male date palm surface fiber (MDPSF) has the most tensile strength among the other types of date palm-based fibers. Due to the brittle nature of concrete in dry environments, moisture has a curing effect on the cracks. An increase in the MDPSFs and their length has a beneficial effect on the self-curing of the concrete under the moisture presence. It is also shown that the optimal compressive strength is obtained with a lower percentage and shorter fiber length, as that minimizes the flaws in the matrix and gives a more uniform distribution in the concrete. Another work presented by Lim et al. [114] showed the effects of palm oil empty fruit bunch (POEFB) fibers on the compressive strength of foamed concrete (FC) and shrinking under drying were 0.25% and 0.5% based on dry mix weight with 1–2 cm in length fibers were used.

Commonly used fibers improve the concrete characteristics, durability, mechanical strength, and thermal properties and reduce costs of mortar production [115–117]. In contrast to the other green additives, hemp fibers are even treated as the main component of the mortar, making up over half of the filling of the cement. The hemp bast fiber can be considered a greener and sustainable industrial waste for producing cellulose nanofibers, which have good crystallinity and thermal stability [118]. The mechanical properties of hemp-based composites are affected by many factors, including the type and length of fibers, their matrix, and the manufacturing process [119]. The adhesion issues between the fibers and the matrix are among the main issues in the hemp-concrete manufacturing process [120]. The advantage of natural fiber reinforcements is that the required fiber ratio is much lower than in conventional reinforcements. In Davino et al., the application of the hemp fibers to improve the thermal stability of mortar and the compressive strength was proposed [121]. Another work researched the compounds obtained with hemp fibers and found [119] that the bending strength of concrete that contained hemp braid increased only in some of the samples, while in all of them, the average of the ultimate deformations increased by 74%.

In work presented by El-Feky et al., the nanocellulose fibers in 0.02–0.08% wt.% were used as an alternative to the carbon-based nanotubes (CNTs), enhancing the mechanical strength and microstructure of the concrete [122]. To improve the ductility and toughness of concrete, fiber can be added to create a composite material. At present, scientists and technicians have conducted a considerable amount of research on applying natural plant fibers such as those from banana, sisal, hemp and flax, jute, coconut, oil palm, and wheat straw in cement-based composite materials [123–128]. The use of natural plant fibers in cement composites requires their prior treatment. An example of chemical treatment of fibers is soaking them in an alginate solution and then in calcium chloride. However, most often, the fibers are soaked in NaOH solutions to remove amorphous biological residues, e.g., waxes, and increase their compatibility with the alkaline matrix [124,126–132]. The research showed that additional mechanical properties and strength of concrete are achieved because of the vegetal fibers. Table 3 shows the influence of various natural fiber materials on the mechanical properties of concrete. Based on the analysis, compressive strength was reduced with the fiber fraction in the concrete composite. Nonetheless, fibers considerably improved the flexural and the splitting tensile strength of the concrete. Additionally, concrete composites with waste vegetable fibers showed a change in thermal properties such as lower thermal conductivity and specific heat capacity, and higher thermal diffusivity compared to the control mix. [129,133]. Besides the above-mentioned examples, another article proposes the application of the palm oil fuel ash, showing that it reduces the negative impact of steam curing for long-term transport properties [134].

Agricultural waste such as natural plant fiber, agricultural waste ash, and multi-application waste is a low-cost material that can be used as a concrete filler that offers excellent value in developing environment-friendly concrete. Depending on the source and the properties of the material, such as the size of granules or fibers, their concentration, and surface activation, the mechanical properties of the concrete are altered.

Table 3. Mechanical properties of cement composites with vegetable fibrous filter, based on [126,129,130,135–141].

Type of Cement	Fibers	Concrete Mix Proportion	Fiber Content	Compressive Strength, (MPa) Concrete/Composite	Splitting Tensile Strength, (MPa) Concrete/Composite	Flexural Strength, (MPa) Concrete/Composite	Ref.
Ordinary Portland Cement: Type I 42.5R	Prickly pear	Gravel 910 kg/m^3, Sand 444 kg/m^3, Cement 350 kg/m^3, Water 175 kg/m^3	15 kg/m^3	32/22.8 after 28 days	-	2.8/7 after 28 days	[129]
Ordinary Portland Cement: Type I 42.5R	Pine needle	Water, Cement, Sand Stone, mix ratio 0.49:1:1.615:2.636	1 vol.%	40.8/42.13	2.65/2.85	-	[126]
Ordinary Portland Cement: Type I 42.5R	Coconut (coir)	Cement 353 kg/m^3, Water 194 kg/m^3 Fine aggregate 698 kg/m^3, Coarse aggregate 1257 kg/m^3	0.5 wt.%(by wt. of cement)	24/27.5 after 28 days	8.5/8.7 after 28 days	-	[135]
Ordinary Portland Cement	Banana	Cement, Sand, Water, mix ratio 1:1.5:0.45	0.4 wt.%	5.20/8.31 after 28 days	0.64/1.65 after 28 days	0.98/2.13 after 28 days	[130]
Ordinary Portland Cement: Type I	Coconut (coir)	Cement 461 kg/m^3, Water 240 kg/m^3 Fine aggregate 739 kg/m^3, Coarse aggregate 898 kg/m^3	1 vol.%	35.23/31.3 after 28 days	3.35/3.58 after 28 days	4.58/5.44 after 28 days	[136]
Ordinary Portland Cement	Sisal	Cement, Fine aggregate, Coarse aggregate, mix ratio 1:1.92:3.24, mix ratio Water/ Cement 0.52	1.5 vol.%	22.00/23.88 (KN/m^2) after 28 days	2.31/3.88 (KN/m^2) after 28 days	3.20/4.92 (KN/m^2) after 28 days	[137]
Ordinary Portland Cement	Bamboo	Cement, Fine aggregate, Coarse aggregate, mix ratio 1:1.86:2.51, mix ratio Water/Cement 0.47	2 vol.%	36.23/36.95 after 28 days	4.84/5.00 after 28 days	5.16/6.13 after 28 days	[138]
Ordinary Portland Cement	Coconut (coir)	Cement, Sand, Water, mix ratio 1:2:0.55	0.3 wt.%	6.5/8.1 after 28 days	0.93/1.53 after 28 days	3.25/4.53 after 28 days	[139]
Ordinary Portland Cement	Oil palm trunk	Cement 360 kg/m^3, Water 180 kg/m^3 Fine aggregate 530 kg/m^3 Coarse aggregate 1075 kg/m^3	1 Vol.%	30.5/39.6	1.6/2.0	27.2/32.2	[140]
Ordinary Portland Cement	Kenaf	Cement 418 kg/m^3, Water 230 kg/m^3 Fine aggregate 725 kg/m^3 Coarse aggregate 1002 kg/m^3 Super plasticizer (1%) 4.18 kg/m^3	0.5 Vol%	36.03/31.04 after 28 days	3.68/3.95 after 28 days	4.65/4.98 after 28 days	[141]

4. Discussion

The classification of acceptable types of cement in Europe is given by BS EN 197-1: 2011. It is divided into five groups: Portland cement and up to 5% of minor additional constituents, Portland cement with up to 35% of other SCM, Portland cement with a higher percentage of blast furnace slag, usually around 60% to 75%, Portland cement with up to 55% of selected pozzolanic constituents, and Portland cement blended with GGBS or fly ash and pozzolanic material [8]. The American Society for Testing and Materials provides other classifications, which include the original OPC, cements that contain no more than 8% tricalcium aluminate (Ca_3Al) for moderate sulfate resistance, cements with moderate heat of hydration characteristic, more finely ground OPCs able to produce higher early strengths, cement with no more than 5% $Ca_3Al_2O_6$ for high sulfate resistance, and cement that allows the minimization of the rate and amount of heat generated by hydration. It is expectable that the strong trend to reduce carbon dioxide emissions from cement production will continue in the coming years. This is due to both concern for the environment, as well as strong economic conditions, including counteracting the impact of new regulations, green taxes, and rising fuel prices on product costs. The SCM application can significantly contribute to the reduction in CO_2 emissions; in particular, ceramic waste reduces emissions by about 29% [142], fly ash by 14% [143], and condensed silica fume by 15% [4,9], while geopolymers by even 80% [144]. As a consequence, the above division and standard may change, while the green transformation of the world is in progress [145], in particular in the cement industry [146].

4.1. Green Additives to Concrete

Based on the review of selected literature sources, the main types of green additives used in the production of concrete were determined. The summary being an introduction to the green additives section is presented in Table 4.

Table 4. The types of additives used for the production of green concrete, based on [19–153].

Green Additive	Application	Influence on Properties of Concrete
Slag [21,29]	Binder component	Improvement in mechanical and strength properties
Wheat straw ash [22,23,147]	Binder component	Reduction in the spontaneous shrinkage of high-performance concrete and the final autogenous contraction of concrete
Alkali-activated materials [24]	Binder component	More favorable properties of the entire concrete, such as low thermal conductivity, high volume stability, rapid strength gaining, fire, and chemical erosion resistance
Calcium aluminate and calcium sulphoaluminate (mineral wool waste) [27,30,148]	Binder component	Improvement of sulfate resistance, enhancement of mechanical properties, increase in compressive strength
Waste glass powder [31,32]	Sand substitute	Improvement of concrete mechanical properties, such as concrete tensile strength, compressive strength, and porosity
Marble mud dust [33]	Sand substitute	Improvement of the strength of concrete, freezing properties and resistance to thawing and peeling of the concrete surface
Aggregates from the recycling of construction and demolition waste [34,149–153]	Component of concrete materials	Improvement of the concrete, especially those used in lower-level applications
Tire rubber-based additives [34–37,41,43,46,148]	Gravel substitute, composite filler, additive to sand mortar	Reduction in the concrete's weight, improvement of the compressive and flexural strength, reduction in compression and tension and a reduction in Young's modulus of elasticity, reduction in thermal conductivity

Table 4. *Cont.*

Green Additive	Application	Influence on Properties of Concrete
Plastic fibers [57,58]	Concrete filler	Improvement of compression performance, durability, flexural and tensile strength, reduction in the weight of concrete possible release of plasticizers, flame retardants, pigments and heavy metals to the environment
E-waste [72–79]	Concrete filler	Improvement of the comprehensive strength of the concrete, tensile, flexural and shear strength, and durability properties, possible release of many harmful compounds to the environment
	Biochar	
Rice husk [13,89,92,94,95,99]	Cement binder	Reduction in compressive strength, increase in the permeability of the concrete
Bamboo waste [96,97]	Pozzolanic material	Improvement of mechanical properties, resistance to cracks
Rice straw [99]	Cement binder	Improvement of the compressive and tensile strengths, and thermal conductivity
Food and wood waste [100]	Mortar component	Increase in the compressive strength, sorptivity, resistance to water penetration, and ductility compared to conventional mortar
Forest wood chips [100]	Cement binder	Improvement of the fracture energy, slight decrease of the flexural strength
	Agricultural waste	
Wild vegetal plant [111]	Fibrous reinforcing additive	Improvement of the mechanical strength, positioning of fibers horizontally enhances adhesion with the cement paste
Waste products obtained in palm oil and coconut oil processing [114,135,136,139,140]	Gravel substitutes	Reduction in concrete production costs, improvement the mechanical properties of the mortar, such tensile strength, with the decrease of the compressive strength of concrete
Hemp fibers [119–121]	Mortar component	Improvement of the thermal stability of mortar and compressive strength
Nanocellulose Fibers [122]	Composite material	Improvement of the mechanical strength, microstructure, the ductility and hardness of concrete
Vegetal fibers (i.a., prickly pear fibers, pinpeare needle fibers, banana fibers) [127,129,130]	Concrete composites	Reduction in the compressive strength, improvement in the flexural and the splitting tensile strength of the concrete, change in thermal properties such as lower thermal conductivity and specific heat capacity, and high thermal diffusivity

As a concrete substitute, high-quality supplementary cementitious material, composed of waste from other industries, constitutes waste management and can also be applied. The amount of traditional SCMs such as fly ash and slag is limited, particularly in underdeveloped countries. Other materials to partially replace ordinary Portland cement are of high importance. For example, calcium aluminate concentrate products from the recycling of sanitary waste improve mechanical properties and the high-temperature behavior of Portland cement [148]. CAC provides a practical possibility of recycling glass waste in the production of building materials. Moreover, CAC is also a promising additive to Portland cement to produce 3D-printing mixtures, which are characterized by very good mechanical properties. Other widely available waste materials that can be used as components of green cement are sugarcane bagasse ash (SCBA) [154], geopolymer metakaolin (MK), and millet husk ash [147]. These compounds provide higher compressive strength and split tensile strength than conventional concrete. Factors such as the presence of uncalcined kaolinitic clay or swelling clays affect the fresh and hardened properties of the concrete [155]. Other alternative binders in concrete provide the alkali-activated binders, which require a significant amount of energy and generate a considerable amount of carbon dioxide during the production process.

Since the literature widely describes the application of many waste materials from demolition waste, glass waste, plastic fibers, carbon black from spent tires, alkali-activated binders, biomass-derived biomass, and non-carbonized plant-based materials, primarily the mechanical strength of the modified concrete is described [149–152]. So far, in this paper, focus has been placed mainly on the mechanical properties of green concrete.

Agricultural waste shows excellent potential in the building industry, particularly in areas with high agricultural production, which results in enormous environmental liabilities in some countries. It can improve the mechanical strength, working performance, and durability of concrete, as these parameters depend on the number of materials incorporated in cement. Both agricultural waste and biochar particle application as a concrete filler reduce waste accumulation and prevent natural resource depletion, reducing environmental pollution caused by carbon dioxide emissions. However, these materials can be at different maturity levels and derived from various regions, so their physicochemical properties may vary, influencing the concrete's properties. For that reason, natural biomass sources require pretreatment methods to improve the mechanical properties and durability of green biomass-based waste concrete. At the same time, the mechanical, compressive, and flexural strength along with the stability of the non-carbonized waste-based concrete needs improvement to increase the loads of the concrete; however, the addition of natural crops or fibers is a lightweight solution. Pyrolyzed biomass acts well as a gravel substitute, making it a promising aggregate, especially for its small size and usually alkali pH that improves the stability of the concrete. That feature enhances the corrosion resistance, especially in steel-reinforced concrete, where the alkali media can delay the corrosion. Hence, the application of the carbon-based particles in the concrete seems to be the most promising solution for the wide availability of biomass waste, physicochemical properties, and low production costs. In turn, concrete containing biochar has a lower density than conventional concrete, and consequently, its scope of application is greater. In addition, the compressive strength, flexural strength, and splitting tensile strength in the case of biochar-based concrete present a substantial increase. Another interesting alternative is the usage of marine brown algae as a natural polymer in concrete [156].

The e-waste can be used as a concrete additive; however, its use requires adequate safety procedures. E-waste contains many harmful chemicals from heavy metals such as lead, cadmium, and mercury, and many organic compounds that can be easily released into the soil, water, and air. The concrete-filled e-waste is still called green as an effective way to manage the spent electronic materials; however, from the ecological point of view, that type of concrete is far from the "green" approach and requires much more materials and energy consumption than the other concrete additives. Moreover, the e-waste addition to concrete seems controversial and non-ecological, and may generate severe health problems if the harmful materials were to leak under the concrete operation because of exposure to environmental elements.

Another important environmental issue is connected with the high level of freshwater consumption during the manufacturing process of the concrete, in particular in the countries in which the supply of fresh water is limited. Freshwater, a hydration reagent and the ion transport medium, can be replaced with recycled water from wastewater. Therefore, wastewater can be used for the concrete preparation, reducing production costs. However, as water is a good solvent, it would need pretreatment depending on the wastewater source to avoid releasing chemicals that would be harmful to the environment and health. Besides the many concrete applications, steel-reinforced concrete is one of the most widely used materials in the building industry, and each additive can affect the corrosion of the reinforcement. The application of waste materials also needs to be tested on reinforced concrete. Green concrete offers many advantages, such as reducing concrete production time, shortening the waiting time for curing, lowering construction costs, and, consequently, earlier construction project completion. Still, building regulations, including such data as the levels of clinker and chemical concrete, the cement's composition, or insufficient data on the long-term durability of the structure, and the selection of green concrete depending on its application, are the main challenges in the use of green concrete. The critical issue is also the development of new and affordable activators.

4.2. Future Directions

Despite the recent developments in building engineering, there is still a need to fill the gap between the laboratory studies and real application. Some of the recommendations for future research are:

- CO_2 emission reduction within the green concrete production.
- Improvement of the waste-modified concrete with the controlled properties such as the chemical composition and morphology of the used waste-based materials with the minimization of the pretreatment energy consumption.
- 3D printing capability of the green concrete.
- Light-generating studies enabling application of the green concrete for the light absorption capability and light emission.
- Durability, compression strength, tensile strength, flexural strength, ion penetration, long-term environmental conditions treatment studies of the modified concrete.
- Improvement of the electrical conductivity and acoustic wave damping of the waste-loaded concrete as intelligent materials for versatile applications.
- Improvement of long-life cycle of the green concrete and reusability.
- Investigation of volume change, such as shrinkage and expansion of the waste-modified concrete in various experimental conditions such as salinity, humidity, and temperatures to simulate other geographical regions.
- Water storage studies and application.
- Heat storage studies and application in passive buildings.
- Abrasion resistance, chlorine and sulfate ions resistance, acid resistance, and toughness of the proposed concrete should also be investigated deeper.
- One of the most important issues is safety, so despite the leakage studies, the materials proposed for the concrete application should be carefully selected to reduce the risk of leakage of harmful chemicals.
- Improvement of concrete durability, especially towards the seismic damping.
- Sustainable waste management within the concrete application.
- IT tools based on Artificial Intelligence towards prediction of the mechanical properties of the green concrete.
- Scalability towards industrial scale application of green concrete.

5. Conclusions

Green concrete opens the possibilities of managing waste materials and applying them in practice. Nevertheless, from the environmental perspective, incorporating waste materials that may leak harmful compounds (waste plastics, some demolition waste, and some chemicals) generates secondary pollution that can affect health and ecosystems [153]. So far, the last point should be the most important in the sustainable building industry and it should be prioritized. By mixing waste materials with mortar, green concrete production is important for energy consumption reduction; still, some solutions are far from green when taking into the consideration the leakage of harmful chemicals into the environment under their application in concrete.

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