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REVIEW

Biochar vs. Hydrochar in Cementitious Materials: A Comparative Review of Properties, Performance, and Circular-Economy Trade-Offs

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ABSTRACT

The environmental burden of cement production, responsible for nearly 7% of global CO_2 emissions, has intensified the search for low-carbon, resource-efficient alternatives in the construction sector. Biochar, a carbon-rich byproduct derived from the thermochemical conversion of agricultural and urban biomass, has emerged as a multifunctional additive in both cementitious and non-cementitious systems. Its high porosity, alkaline pH, and stable carbon content enable improvements in hydration, mechanical strength, thermal insulation, and durability, while simultaneously offering long-term carbon sequestration. This review critically evaluates the morphological, physicochemical, and functional characteristics of biochar and its effects on cement-based materials, drawing from over 127 published studies. It also highlights the potential of hydrochar, produced through hydrothermal carbonization, as a complementary material in low-carbon construction systems, although research in this area remains limited. Key parameters such as feedstock type, pyrolysis conditions, particle size, and dosage are identified as major factors influencing performance. Beyond technical performance, the use of biochar aligns with circular economy principles by valorizing organic waste streams, reducing reliance on virgin cement and aggregate resources, and enabling industrial symbiosis. Emerging applications in thermal and acoustic panels, multifunctional coatings, and lightweight composites further reinforce its versatility. However, challenges remain regarding workability, performance vari-

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ability, scalability, and the lack of standardized production and application protocols. Future directions include the standardization of biochar characteristics, large-scale durability validation, integration with life cycle assessment (LCA), development of technical guidelines, and cost–benefit analyses. Overall, biochar and hydrochar represent viable strategies to decarbonize the construction sector and promote sustainable material flows in alignment with global climate and resource-efficiency goals.

Highlights:

- Biochar enhances hydration kinetics, durability, and thermal and acoustic insulation in cementitious composites.
- Low dosages (≈0.5–2.0 wt%) can improve 28-day compressive strength, while higher contents (>3 wt%) often reduce it due to increased porosity or weak interfacial bonding.
- Silica-rich biochars, such as those derived from rice husk, exhibit pozzolanic reactivity and enable partial substitution of Portland cement or silica fume.
- Hydrochar (1.25–2.5 wt%) improves thermal insulation and electrical resistivity but delays cement hydration and reduces early-age strength.
- Standardization of char production parameters and long-term durability testing are critical for safe and scalable implementation in construction materials.

Keywords: Biochar; Hydrochar; Waste Valorization; Cementitious Materials; Building Materials; Circular Economy

1. Introduction

Sustainable development was first defined by the World Commission on Environment and Development (WCED) in the late 1980s as a pathway for economic growth that preserves planetary well-being. This vision materialized in the 1992 Rio Earth Summit through Agenda 21, which laid the groundwork for sustainability action plans across sectors, including construction [1]. Since then, global policy frameworks have evolved significantly. The United Nations' 2030 Agenda, anchored in the 17 Sustainable Development Goals (SDGs), and the European Green Deal (EGD) emphasize decarbonization, circular economy, and climate neutrality by 2050 [2,3].

The construction sector plays a pivotal role in this transition. It accounts for nearly 40% of global resource consumption and contributes approximately 7% of CO_2 emissions, largely due to the production of Portland cement [4]. In response, researchers and industry stakeholders have turned to innovative materials and strategies to reduce the environmental footprint of concrete-based systems.

One such strategy is the valorization of biomass residues through thermochemical conversion into carbonaceous materials like biochar and hydrochar. These approaches align with circular economy principles by diverting organic waste from landfills and reintroducing it as functional additives in construction materials [5,6].

Biochar, defined as a carbon-rich, porous material produced by pyrolysis of lignocellulosic biomass under limited oxygen conditions, has shown promising results in cementitious systems. It enhances hydration, strength, durability, and thermal insulation, while also acting as a long-term carbon sink [7,8]. Hydrochar, in contrast, is generated through hydrothermal carbonization (HTC) at lower temperatures in aqueous environments. While less studied, it offers advantages in energy efficiency and feedstock flexibility [9].

What distinguishes this review is its structured, side-by-side comparison of biochar and hydrochar, focusing not only on their physicochemical and functional properties, but also on their respective trade-offs in performance, environmental impact, and scalability in real-world construction applications.

Despite encouraging findings, the widespread adoption of biochar in construction faces several bottlenecks: performance variability, lack of standardization, and limited long-term durability studies. In addition, hydrochar remains underexplored, particularly regarding its effects on hydration kinetics, mechanical properties, and lifecycle performance [10,11].

Machine learning and data-driven modeling approaches are emerging as valuable tools to address these gaps. They enable prediction of material behavior based on pyrolysis or HTC parameters, feedstock characteristics, and dosage levels [10,12]. Yet, these techniques are still underutilized in char-construction integration studies.

Therefore, this review pursues the following key objectives:

- To critically compare biochar and hydrochar in terms of morphology, chemical structure, and effects on cementitious properties;
- To assess their compatibility with circular economy strategies, including carbon sequestration and waste valorization;
- To identify knowledge gaps and propose a research agenda for hydrochar in low-carbon construction systems;
- To outline technical and regulatory challenges for real-world application, including standardization and occupational safety.

By integrating recent findings from over 127 peer-reviewed studies, this review provides a comprehensive foundation to guide material scientists, civil engineers, and policy-makers toward sustainable innovations in cementitious materials. It emphasizes practical implementation by correlating material characteristics with application scenarios, ultimately aiming to accelerate the transition to a climate-resilient, resource-efficient construction sector.

2. Literature Search Protocol

A structured literature review was conducted to identify and analyze peer-reviewed publications on the use of biochar and hydrochar in cementitious and construction materials. The search aimed to capture the breadth and evolution of the field while maintaining strict relevance through well-defined inclusion and exclusion criteria.

2.1. Background and Rationale

Although biochar was originally developed for agricultural purposes, its relevance in non-soil applications, particularly in construction, has grown considerably in recent years. This increasing interest is reflected in the exponential rise in publications over the last two decades. As illustrated in **Figure 1**, the number of peer-reviewed studies related to “biochar and/or charcoal” has expanded rapidly, highlighting growing interdisciplinary interest.

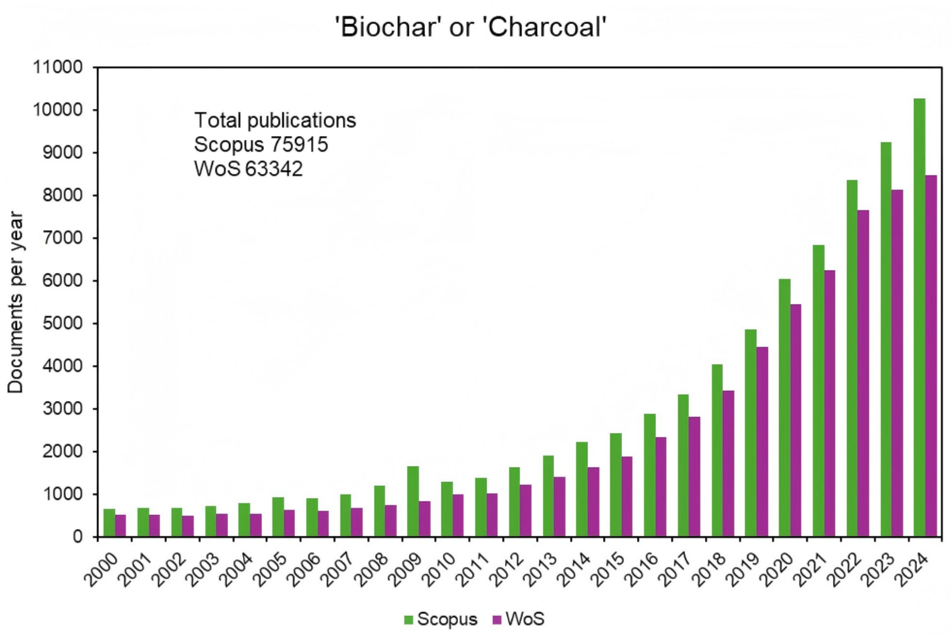

Figure 1. Annual publication trends for ’biochar and/or charcoal’ (Scopus and WoS) on 13.12.2024.

Schmidt[13] identified more than 50 potential applications for biochar across 17 industrial sectors, including construction, chemicals, metallurgy, textiles, water treatment, and pharmaceuticals. Traditionally, charcoal has been produced from slow pyrolysis of woody biomass and used for heating, cooking, and metallurgy[14–16]. However, despite similarities, biochar and charcoal differ significantly. While charcoal serves primarily as an energy source, biochar is optimized for carbon sequestration, environmental remediation, and industrial applications[17].

The first mention of biochar in indexed scientific literature appeared in the year 2000, in the study "Biochar from the straw-stalk of rapeseed plant" by Karaosmanoğlu et al.[18]. Initially examined for its use as a clean biofuel, biochar research later expanded into carbon capture[19] soil remediation[20], and more recently, sustainable construction materials.

2.2. Methodology and Screening Strategy

The literature search was performed on 13 December 2024, using two major databases: Scopus and Web of Science (WoS). The process followed several structured phases:

1. Initial Screening. A broad search using the terms "biochar and/or charcoal" yielded a total of 139,257 articles (see **Figure 1**):
   - Scopus: 75,915 articles
   - Web of Science: 63,342 articles
2. First Refinement – Adding Construction Relevance. To narrow the scope to the construction sector, the keywords "biochar", "charcoal", and "building materials" were applied. This refinement resulted in:
   - Scopus: 524 articles
   - Web of Science: 777 articles (see **Figure 2**)

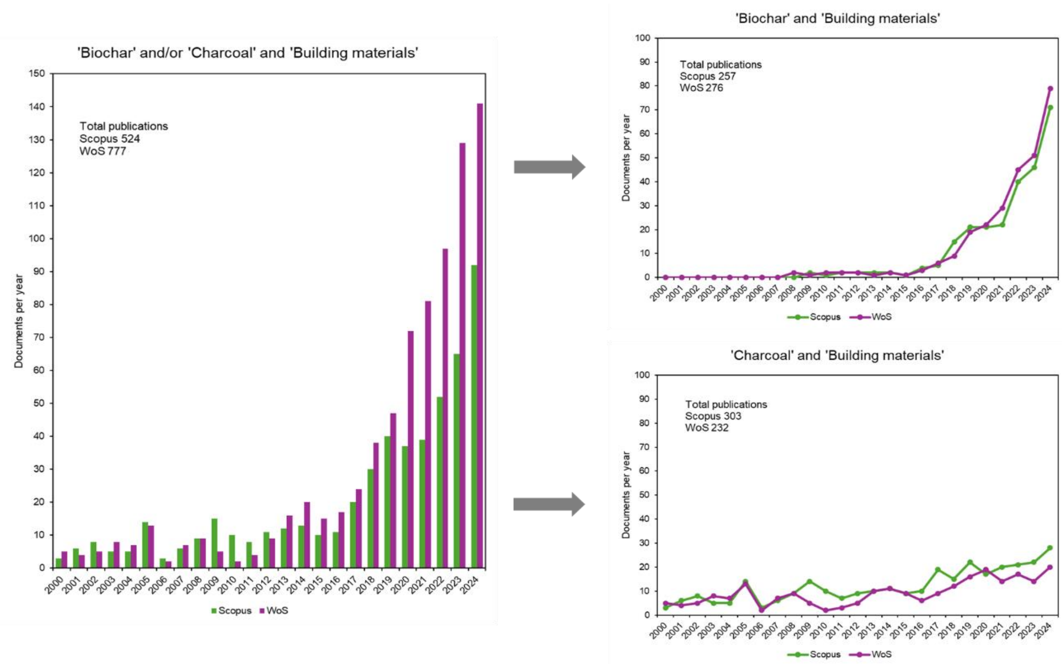

Figure 2. Annual publication trends for 'biochar/charcoal and building materials' (Scopus and WoS) on 13.12.2024.

3. Second Refinement – Specific Keyword Combinations. Separate keyword searches were performed to distinguish between the terms:
   - "Biochar and Building Materials":
     - Scopus: 257 articles
     - WoS: 246 articles
   - "Charcoal and Building Materials":
     - Scopus: 303 articles
     - WoS: 232 articles
4. Final Filtering. The following exclusion criteria were applied to obtain a focused dataset:
   - Removal of duplicate records;

- Exclusion of simulation-only studies without experimental validation;
- Elimination of studies unrelated to the use of biochar or charcoal in construction materials.

This multistep process resulted in a core set of 80 peer-reviewed articles. However, to ensure comprehensive coverage of the topic, the dataset was supplemented using citation tracking, cross-referencing, and expert judgment, leading to a final selection of 127 relevant publications.

It is also important to note that studies on hydrochar in cementitious materials remain limited. Due to this scarcity, all available peer-reviewed publications on hydrochar identified during the search were included in the dataset, regardless of publication date or citation frequency. This inclusive approach ensures the most complete overview possible of this emerging material and its potential contributions to sustainable construction.

The step-by-step screening and refinement process adopted in this review is summarized in **Figure 3**, which illustrates the full flow of the literature selection strategy.

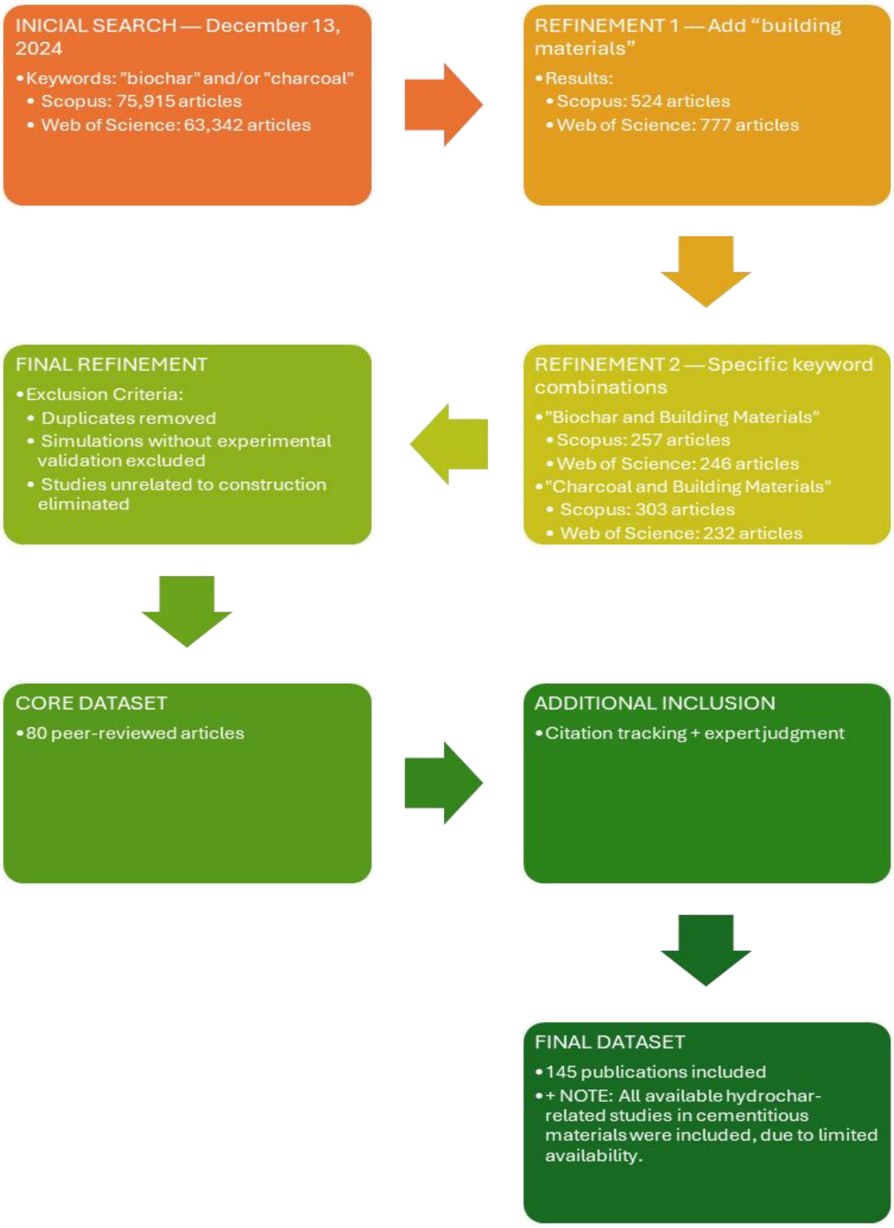

Figure 3. Diagram of the literature selection process used in this review.

Figures 1 and **2** visually support the rationale for this selection, showing the historical increase in publications in the general field of biochar and the more recent emergence of its application in building materials.

3. Results and Discussion

3.1. Sources for Biochar and Production Process

Agro-industrial biomass residues are a widely available, renewable source of carbon-rich materials suitable for thermochemical conversion. Globally, over 140 billion metric tons of biomass are generated annually, primarily from crop residues and agro-industrial waste [21]. These lignocellulosic materials are mainly composed of cellulose (40%–50%), hemicellulose (20%–30%) and lignin (10%–25%), with minor constituents such as resins, fatty acids, phenols, and mineral salts [10,22–25]. This chemical composition varies significantly with feedstock origin, directly influencing the type and quality of the carbon-rich materials obtained.

Several thermochemical pathways are employed to convert biomass into useful carbonaceous products: gasification, torrefaction, hydrothermal carbonization (HTC), and pyrolysis. Among these, pyrolysis is the most suitable for producing biochar tailored for construction applications, due to its tunability and ability to retain carbon in a stable form [12].

- Gasification operates at 600–1200 °C under restricted oxygen to produce syngas (H_2, CO, CO_2). It yields small amounts of biochar (typically <10%), considered a byproduct rather than a main output [26].
- Torrefaction takes place at 200–300 °C in inert conditions, producing a hydrophobic solid with intermediate energy density, but limited structural stability for cementitious use.
- Hydrothermal Carbonization (HTC) processes wet biomass at 180–300 °C under autogenous pressure, generating hydrochar with lower surface area and reactivity, but with potential for thermal insulation.

Pyrolysis, the most widely used process for producing construction-grade biochar, occurs at temperatures >400 °C in oxygen-limited environments. It produces three fractions: solid (biochar), liquid (bio-oil), and gas (syngas), with minimal waste and low emissions [27]. Crucially, its operating conditions can be precisely controlled, allowing customization of the biochar's physicochemical properties [22,25].

Key parameters that influence biochar properties during pyrolysis include [24,25,28]:

- Temperature: Higher temperatures increase aromaticity, porosity, and surface area, but reduce overall yield.
- Heating rate: Affects volatilization rate and microstructure formation.
- Residence time: Determines carbon retention and structural stability.
- Feedstock characteristics: Including moisture, ash content, and particle size, which directly affect the quality and functionality of the biochar.

During pyrolysis, biomass polymers degrade over distinct temperature ranges: hemicellulose (200–300 °C), cellulose (300–400 °C), and lignin (150–900 °C). These thermal breakdowns produce volatile compounds and residual carbon matrices with diverse pore structures and chemical functionalities [29].

Reactor design also plays a decisive role in product yield and quality:

- Fluidized bed reactors enable uniform heating and precise thermal control, ideal for producing high-quality biochar at scale.
- Fixed bed reactors offer simple operation and flexibility in processing various particle sizes, though with lower heat efficiency [30,31].

Optimizing pyrolysis conditions is critical to producing biochar suitable for cementitious materials, as desired attributes include:

- High specific surface area (typically >150 m^2/g),
- Well-developed micro- and mesoporosity,
- Chemical stability (low O/C ratio),
- Functional surface groups (e.g., hydroxyl, carboxyl), which facilitate interaction with hydration products.

These properties support internal curing, improve microstructural refinement, and contribute to enhanced mechanical strength and durability in concrete and mortars[32–34].

In summary, pyrolysis of lignocellulosic residues remains the most effective pathway for producing high-performance biochar for the construction industry. However, achieving consistency and optimal properties requires careful control of process parameters and strategic selection of biomass feedstocks.

3.2. Morphological Characteristics and Chemical Structure of Biochar in Cementitious Materials

The morphological and chemical characteristics of biochar are central to its performance in cementitious systems. These features, including porosity, particle size, surface area, functional groups, and elemental composition, are directly shaped by the biomass origin and pyrolysis parameters. Together, they define biochar's interaction with hydration products, its role in internal curing, and its long-term durability in cement matrices.

3.2.1. Biochar Morphology

Biochar typically exhibits a multi-scale porous structure composed of macropores (>50 µm), micropores (<2 nm), and mesopores (2–50 nm). These are formed during pyrolysis as volatiles are released, creating a carbon-rich matrix with high specific surface area and absorption potential. As pyrolysis temperature increases, the biochar generally becomes more microporous, with improved adsorption properties and water-retention capacity[35,36].

Scanning Electron Microscopy (SEM) images confirm the preservation of plant tissue microstructures, often revealing honeycomb-like pores, elongated channels, or collapsed cellular walls, depending on the feedstock and processing conditions. These features are crucial for: water storage and gradual release (supporting internal curing), interaction with cement hydrates, especially at the interfacial transition zone (ITZ) and, crack-bridging effects that enhance durability[37,38].

For example, Gupta et al.[7] observed distinct morphologies across feedstocks: food waste and rice waste biochars had irregular porous surfaces, and wood sawdust biochar showed angular, elongated particles with structured pore networks, supporting stronger particle–matrix integration.

Macropore diameters in the range of 5–20 µm have been identified as ideal for promoting early-age hydration, water buffering, and microstructure refinement[39].

3.2.2. Biochar Chemical Composition

Biochar is primarily composed of carbon, typically ranging from 50% to over 90%, depending on the feedstock and pyrolysis conditions[6]. Alongside carbon, it contains varying amounts of oxygen, hydrogen, nitrogen, and inorganic elements such as potassium, calcium, magnesium, and trace minerals.

The thermal severity of pyrolysis plays a critical role in determining chemical structure. Higher pyrolysis temperatures promote the formation of aromatic carbon rings and semi-graphitic domains, leading to enhanced chemical stability and thermal resistance. In contrast, lower pyrolysis temperatures preserve a greater proportion of amorphous carbon and oxygen-containing functional groups, improving surface reactivity[40].

Among the key functional groups present on biochar surfaces are:

- Carboxyl (-COOH)
- Hydroxyl (-OH)
- Phenolic groups

These groups facilitate ion exchange and chemical interactions with hydration products, particularly calcium ions, thereby supporting the formation of calcium–silicate–hydrate (C–S–H) gels, the principal binding phase in cementitious matrices.

The development of these functional groups is closely related to the thermal decomposition of major biomass components, lignin, cellulose, and hemicellulose. Of these, lignin contributes most to the stability of biochar due to its resistance to thermal degradation.

The diversity in biochar composition across different biomass sources and pyrolysis regimes is summarized in **Table 1**, which presents selected morphological and chemical properties relevant to cementitious performance. The data highlights how certain biochars, such as those derived from mixed wood sawdust, offer particularly favorable characteristics, including high specific surface area, elevated carbon content, and a low oxygen-to-carbon ratio, which enhance both chemical stability and reactivity.

Table 1. Morphological and chemical characteristics of selected biochars and their relevance to cementitious applications.

Biomass and Treatment	Porosity	Shape and Size	Surface Area	Functional Groups	Carbon Content	Main Chemical Components	Ref.
Mixed Wood Sawdust Biochar	Honeycomb-like structure due to volatile release	Elongated, angular shape; particle size: 5–20 µm	196.92 m^2/g (BET)	Hydroxyl (-OH), carboxyl (-COOH), and aromatic C	87.13%	C (87.13%), O (7.21%), Ca, Mg, Si, Al, Fe	Gupta et al. [7]
Food Waste Biochar	Porous, irregular surface	Irregular particles; particle size: 5–20 µm	9.70 m^2/g (BET)	Hydroxyl (-OH) and fewer aromatic groups	70.90%	C (70.90%), O (8.42%), K, Mg, Fe	Gupta et al. [7]
Rice Waste Biochar	Porous, irregular surface	Irregular particles; particle size: 5–20 µm	35.70 m^2/g (BET)	Hydroxyl (-OH), minor aromatic C	66.22%	C (66.22%), O (13.63%), Mg, Al, Fe	Gupta et al. [7]
Wood waste, pyrolysis at 400 °C	Decreased porosity due to hydration product deposition	Collapse of tube-like structure; size shift (1–500 µm)	Reduced from 67.5 to 2.6 m^2/g (BET)	Reduced oxygen groups; increased C-C bonds	Decreased by 10%–15%; increased defectiveness	Precipitation of Ca, Mg, and Na salts	Xu et al. [41]
Agricultural waste, pyrolysis 450–550 °C	Pores filled with hydration products, enhancing curing	Particle size D50: 14.1 µm; distinct ITZ observed	Not provided but enhanced hydration interaction	Stable functional groups; enhanced C-S-H gel formation	Lignin, cellulose, and hemicellulose partially retained	Promotes pozzolanic reactions and hydration products	Wang and Wang [42]
Food & agriculture waste, 500–800 °C	Higher porosity; mesopores dominate (<10 nm)	AWBC: Fibrous & rough; FWBC: Granular & smooth	AWBC: 371.6 m^2/g; FWBC: 0.99 m^2/g	Higher pyrolysis temperature reduced oxygen groups	AWBC: 84.7%; FWBC: 82.3%	AWBC: High Ca, K, and Cl content; FWBC delayed hydration	Zhang et al. [43]
Rice husk (RHB) & bamboo biochar (BB)	RHB: Lower porosity; BB: Higher porosity	Similar D50 (15–16 µm); RHB more compact	BB: 59.89 m^2/g; RHB: 42.63 m^2/g	BB: Higher carboxyl groups; RHB promotes pozzolanic activity	BB: 53.9%; RHB: 46.6%	RHB enhances C-S-H formation; BB supports hydration	Li et al. [44]
Woodchips, gasification at 900 °C	Porous microstructure aids water retention	Angular, fine-grained (<38 µm)	High surface area increases water uptake	Carboxyl and hydroxyl groups enhance reactivity	Stable carbon; thermal stability >700 °C	Ca-rich composition enhances pozzolanic properties	Sirico et al. [45]
Agricultural/ forestry residues, 500–800 °C	Increased pore volume and diameter at higher temperatures	Angular morphology; particles <63.5 µm	High specific surface area supports hydration product development	Oxygen groups facilitate hydration and carbonation	Stable carbon structure with high aromaticity	Amorphous structure supports pozzolanic activity	Haque et al. [46]

Abbreviations: AWBC = Agricultural Waste Biochar; FWBC = Food Waste Biochar; SSA = specific surface area; ITZ = interfacial transition zone.

3.2.3. Relevance to Cementitious Materials

The morphological and chemical characteristics of biochar directly influence its role and performance within cementitious materials. Its porous architecture and high specific surface area support internal curing mechanisms by promoting water retention and sustained hydration. Additionally, the presence of oxygenated functional groups, such as carboxyl and hydroxyl moieties, enables chemical bonding with cement hydration products, particularly aiding in the nucleation and growth of calcium–silicate–hydrate (C–S–H) gels, which are fundamental to strength development and long-term durability.

Beyond these reactivity-related properties, the carbon content and oxygen-to-carbon (O:C) ratio are critical indicators of biochar's chemical stability. A high carbon content combined with a low O:C ratio typically reflects a greater degree of aromaticity and resistance to degradation, essential for maintaining material integrity under aggressive environmental conditions.

For instance, the mixed wood sawdust biochar detailed in **Table 1** exhibited a specific surface area of 196.92 m^2/g and a low O:C ratio of 0.12. These attributes are indicative of both high reactivity and stability, contributing to enhanced hydration kinetics and improved resistance to chemical deterioration in cementitious systems [7].

In summary, the interplay between microstructural porosity, surface chemistry, and carbon stability underpins biochar's performance as a multifunctional additive. Optimizing these parameters through careful feedstock selection and controlled pyrolysis conditions is essential to maximizing its positive contributions to mechanical performance, durability, and environmental impact reduction in sustainable construction materials.

3.3. Adopting Biochar in Building Materials

Concrete is the most widely used material in the construction industry, accounting for approximately 50% of global cement production [4]. The remainder is used for blocks, mortar, and plaster applications [47,48]. Although cement typically comprises only 7%–15% of concrete by mass, it contributes disproportionately to the material's carbon footprint, primarily due to the energy-intensive clinker production process [49,50]. This process is a major source of greenhouse gases (GHGs) and pollutants, including particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), and volatile organic compounds (VOCs) [51–53].

Globally, cement production contributes approximately 7% of all energy-related GHG emissions. Around 40% of CO_2 emissions stem from the combustion of fossil fuels, such as coal and petroleum coke, required to reach the high temperatures needed for clinker formation [54,55].

In response, short-term decarbonization strategies have emphasized improving plant energy efficiency and replacing fossil fuels with low-carbon alternatives like biomass or renewable waste. However, these measures offer limited mitigation, efficiency improvements can reduce emissions by up to 12%, and fuel substitution by up to 24% by 2050 [54].

Given these constraints, biochar has emerged as a promising supplementary material for sustainable construction. Produced via pyrolysis of biomass in oxygen-limited environments, biochar possesses several desirable attributes: high porosity, large surface area (typically >300 m^2/g), and long-term chemical stability [12,56,57]. Its multiscale pore structure (micro-, meso-, and macropores) enables it to act as an internal curing agent in cementitious materials, improving hydration efficiency, refining microstructure, and enhancing long-term durability [34,58,59].

These effects are largely attributed to biochar's capacity for water absorption and gradual release during curing, which mitigates shrinkage and supports the development of a dense and refined matrix.

Biochar's properties are strongly influenced by feedstock type, pyrolysis temperature, heating rate, and particle size. Higher pyrolysis temperatures (400–900 °C) increase fixed carbon content and enhance chemical resilience while reducing mass yield [60,61]. These thermally stable biochars are more compatible with cementitious systems and less prone to degradation.

In addition to processing and compatibility considerations, health and safety aspects must be acknowledged, particularly when using fine biochar powders. Due to their low particle size and high surface area, some biochars may pose respiratory risks during handling and mixing, especially in poorly ventilated environments. Therefore, appropriate measures such as dust extraction systems, the use of personal protective equipment (PPE), and adherence to occupational exposure limits should be implemented. These precautions are essential not only for worker safety but also to ensure consistency and reproducibility in material performance.

A wide variety of biomass feedstocks have been explored for biochar production, including: rice husk [56,60–70], coconut shells [12,71–74], bamboo [29,75–80], Sugarcane bagasse [81,82], Peanut hulls [83,84], straw [85,86], corn [87], wood waste [88,89], sawdust [90], and food waste [7].

Each feedstock yields biochar with specific morphological and chemical properties, affecting its role as filler, supplementary cementitious material (SCM), or aggregate substitute.

For instance, wood-based biochar produced at 500 °C enhances flexural strength and fracture resistance, while rice husk biochar promotes pozzolanic reactivity and C–S–H formation [74,81,91]. Bamboo and coconut shell biochars improve rheological performance, thermal insulation, and long-term durability [29,74,92].

These diverse construction applications of biochar are visually illustrated in **Figure 4**, and **Table 2** provides a detailed summary of feedstocks, pyrolysis conditions, particle sizes, and corresponding functions in sustainable construction.

A more detailed overview of biochar derived from different biomass sources, along with their respective pyrolysis conditions and applications in sustainable construction, is provided in **Table 2.** For example, biochar produced from corn stover at 550 °C for 25 minutes has been used as a filler material, while biochar from wood waste and rice husk has shown potential as an aggregate substitute or partial cement replacement, depending on particle size and treatment conditions.

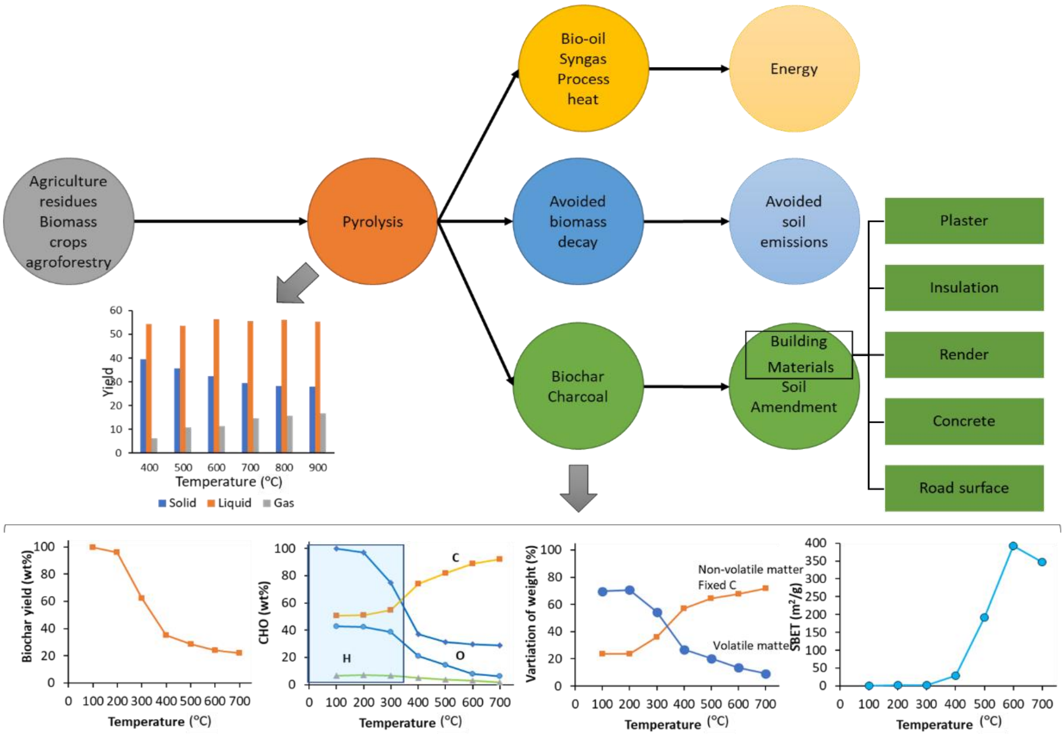

Figure 4. Biochar applications in construction [18,93–95].

Table 2. Summary of biomass types, pyrolysis conditions, and biochar properties for sustainable construction applications.

Biomass	Temp. (°C)	Time	Heating Rate (°C/min)	Particle Size	Biochar Role	Ref.
Corn stover	550	n/d	n/d	4.7–144 μm	Filler in cement composites	Praneeth et al. [96]
Wood	500	1 h	10	5 mm (coarse)	Aggregate substitute	Chen et al. [97]
Wood	500	n/d	n/d	4–190 μm	Filler in mortars	Gupta et al. [98]
Wood	500	60 min	n/d	5 mm	Alternative aggregate/binder	Park et al. [99]
Wood	400–450	20 min	n/d	2–10 μm	SCM; partial silica-fume replacement	Gupta et al. [74]
Wood	500	60 min	10	10–50 μm (coarse)/ 10–18 μm (fine)	Admixture - rheology & strength	Gupta et al. [92]

Table 2. *Cont.*

Biomass	Temp. (°C)	Time	Heating Rate (°C/min)	Particle Size	Biochar Role	Ref.
Mixed wood sawdust	500	60 min	10	GBC 0.1–2 μm; NBC 2–100 μm	Micro-filler	Gupta and Kua [40]
Mixed wood sawdust	900	n/d	n/d	5–200 μm	Additive in cement mortar	Gupta et al. [7]
Woodchips (gasification)	700	n/d	n/d	<63.5 μm	Micro-filler in mortars	Sirico et al. [45]
Sewage-sludge	500–700	n/d	n/d	n/d	Pozzolanic activity	De Carvalho Gomes et al. [100]
Peanut shell	500	40 min	10	1–100 μm	Filler	Zhang et al. [101]
Peanut shell	500	n/d	n/d	5–20 μm	Partial cement replacement; admixture	Han et al. [83]
Rice husk	700	120 min	10	1–100 μm	Filler; partial cement replacement	Tan et al. [91]
Rice husk	500	60 min	10	<100 μm	Cement replacement	Asadi Zeidabadi et al. [102]
Rice waste	450–550	≈1 h	n/d	5–200 μm	Additive in cement mortar	Gupta et al. [7]
Vetiver grass	340	n/d	n/d	n/d	Filler; partial cement replacement	Neve et al. [103]
Almond shell	700	120 min	10	n/d	Partial cement replacement	Ofori-Boadu et al. [104]
Bagasse	500	60 min	10	<100 μm	Cement replacement	Asadi Zeidabadi et al. [102]
Food waste	600	n/d	n/d	5–200 μm	Additive in cement mortar	Gupta et al. [7]
MSW	600	60 min	n/d	48 μm (D_{50})	Alternative aggregate or binder	Jia et al. [105]
Bamboo	≥900	n/d	n/d	1–2 μm	Micro-filler & reinforcement	Ahmad et al. [29]
Coconut shell	400–450	20 min	n/d	Coarse particles	Additive for supersulfated cement	Kang et al. [106]
Coconut shell	500	60 min	n/d	10–50 μm/ 10–18 μm	Admixture - rheology & strength	Gupta et al. [92]
Coconut shell	500	120 min	n/d	2–10 μm	SCM; partial silica-fume replacement	Gupta et al. [74]
Carya cathayensis peel	500	n/d	n/d	<75 μm	Sand replacement	Li et al. [107]
Olive-tree pruning	460–520	n/d	n/d	<100 μm	Filler in mortars	Kalderis et al. [108]
Washingtonia filifera	700	n/d	n/d	n/d	Partial gypsum replacement	Boumaaza et al. [109]

Abbreviations: n/d = not disclosed by the authors; 1 mm = 1000 μm; SCM = Supplementary Cementitious Material; MSW = Municipal Solid Waste; GBC = ground biochar; NBC = nano-biochar.

Beyond cement-based applications, biochar also shows promise as a multifunctional material in thermal and acoustic insulation and as an antibacterial/fungal agent [110,111]. Its low thermal conductivity and sound-absorbing porous structure enable integration into energy-efficient and sound-insulated building components. Its chemical stability under humid conditions supports healthier indoor environments by resisting microbial growth.

Despite the growing number of studies, cement remains the most thoroughly explored domain for biochar integration. However, its potential as a renewable, multifunctional additive with carbon sequestration capacity and circular economy compatibility continues to make it a key enabler of sustainable construction.

Optimizing the pyrolysis process parameters, temperature, heating rate, and biomass type, is essential for tailoring biochar's properties to specific construction needs.

In summary, biochar represents a scalable, renewable, and versatile additive that can lower carbon emissions, enhance mechanical performance and durability, and enable progress toward decarbonized and circular construction systems.

3.4. Effects of Biochar on Cementitious Materials

3.4.1. Physical Properties

Biochar presents distinct physical features, such as high porosity, significant water-retention capacity, and low bulk density, that directly affect the fresh and hardened properties of cementitious materials. These properties influence workability, heat of hydration, density, and functional behaviors like thermal or electrical conductivity.

As summarized in **Table 3**, biochar's performance depends heavily on pyrolysis conditions, particle size, and dosage level.

Table 3. Physical Properties of Biochar and Their Impact on Cementitious Materials.

Property	Key Observations
Flowability and density	Biochar produced at 300 °C (40 min, 10 °C/min) sequestered 1.67 mmol CO_2/g, but a 2 wt% addition reduced mortar flow and density, requiring additional superplasticizer (0.02%–0.05%) [112]. Biochars from food, wood, and rice husk (500 °C, 60 min) decreased flow by 10%–13% at 3 wt% due to high internal porosity [7].
Bulk density (hardened)	Using 15 wt% biochar reduced hardened concrete density to 1454 kg/m^3. This is beneficial for lightweight applications but may impair strength (See section 3.4.2) [83,110,113].
Heat of hydration	Moisture retained within the biochar pores promotes higher early heat release, which is advantageous in cold-weather concreting [114].
Electrical conductivity	A 15 wt% dosage of rice-husk biochar formed conductive pathways that enhanced electrical conductivity, suggesting applications in smart or self-sensing concretes [113,115].
Thermal and acoustic properties	Biochar at 1–2 wt% reduced thermal conductivity to 0.192–0.230 W/m·K. At 10–15 wt%, biochar improved acoustic absorption in the 200–2000 Hz range, achieving an NRC of 0.45, which meets common building standards [113].

These results highlight a trade-off: although biochar's high porosity may reduce workability and density, it also opens pathways for lightweight, insulating, and acoustically enhanced concretes. To mitigate fresh-state penalties and unlock functional benefits, the optimization of pyrolysis temperature, particle fineness, and dosage is essential.

3.4.2. Mechanical Properties

The mechanical behavior of cementitious composites modified with biochar, particularly compressive strength, flexural strength, and fracture energy, is strongly influenced by the type of feedstock, particle size distribution, pretreatment, and replacement level. Key findings across a range of studies are consolidated in **Table 4**.

These results underscore the importance of tailoring biochar type and dosage to specific applications. While certain biochars can significantly improve mechanical properties, others may be better suited for non-structural or functional applications.

3.4.3. Durability Properties

Biochar incorporation can enhance the long-term performance of cement-based materials by reducing water ingress, shrinkage, and improving moisture regulation and dimensional stability. Key findings are summarized in **Table 5**.

These durability improvements are particularly relevant in climates with high humidity or aggressive exposure conditions. When biochar is correctly selected and incorporated, it can extend service life and lower maintenance needs, reinforcing its potential as a sustainability-enhancing additive.

Table 4. Influence of biochar type, production conditions, particle size, and dosage on mechanical performance.

Property	Key Observations
Compressive strength	The response is variable: rice-husk biochar reduced strength by 60% at 10 wt%, while coconut-shell and bamboo biochars enhanced strength at similar or higher dosages [12]. Pretreated bagasse biochar (700 °C) increased strength by 54.8%; untreated rice-husk biochar gave a 20.4% gain at 5 wt% [7,102]. Improvements depend on densification, filler effect, and pozzolanic reactivity.
Flexural strength and fracture energy	Peanut-shell biochar (1–3 wt%) improved flexural strength by 12%–22% due to pore refinement and internal curing [76]. In magnesium phosphate systems, wheat-straw biochar enhanced both compressive and flexural strength [116].
Comparison across biochar types	Wood-waste biochar increased fracture energy by 150% at 2 wt% via crack-bridging mechanisms [56]. Gasification biochar (900 °C) increased fracture energy with minimal compressive loss due to its dense structure [45,117]. In contrast, rice-husk biochar reduced flexural strength by 16%–27%, likely due to weak interfacial bonding and high porosity.

Table 5. Durability Properties of Biochar-Modified Cementitious Composites.

Property Assessed	Key Observations
Reduction in water absorption and permeability	Food-waste biochar (1 wt%) reduced capillary absorption to 0.72% and penetration depth to 9.33 mm [7]. At 5 wt%, wood-derived biochar reduced total water absorption by 16% [74].
Reduction in shrinkage	Internal curing from biochar voids significantly reduced early-age shrinkage. Replacing 33% of silica fume with biochar cut shrinkage by 45%, lowering crack risk [74].
Humidity adsorption and pore structure optimization	Bamboo biochar (~8 μm) increased moisture adsorption due to high surface area and optimized pore structure [76].

The combined data from **Tables 3–5** confirm that biochar's effect on cementitious systems is multifaceted. While fresh-state challenges must be managed, its durability enhancements, mechanical gains, and functional properties justify further investigation. Future efforts should prioritize the development of standardized design protocols and performance evaluation frameworks to guide its safe and efficient use in sustainable construction.

3.5. Challenges and Limitations of Biochar Utilization in Cementitious Materials

Biochar, derived from biomass through controlled pyrolysis, offers promising functional and environmental advantages in cementitious systems. Its incorporation can enhance mechanical performance, increase durability, reduce carbon emissions, and support circular economy strategies. However, several technical and practical limitations still constrain its widespread adoption in the construction industry. These challenges include high variability in biochar characteristics, inconsistent performance, workability issues, and limited standardization frameworks.

Understanding and addressing these limitations is critical to unlocking biochar's full potential. The main challenges, along with strategies to overcome them, are summarized in **Table 6** and further discussed below.

These challenges are not insurmountable but require multidisciplinary strategies that combine materials science, engineering design, economic modeling, and policy development.

Table 6. Challenges and Limitations of Biochar in Cementitious Materials.

Challenge	Description	Proposed Solutions
Variability in biochar properties	Biochar properties (e.g., porosity, surface area, and elemental composition) vary significantly with feedstock and pyrolysis conditions [70,76]. This variability hinders reproducibility in cementitious applications [7].	Establish standardized protocols for production and characterization; use machine learning to predict performance; produce application-specific biochars through controlled pyrolysis.
Influence on mechanical properties	While biochar enhances flexural strength and fracture energy, it can reduce compressive strength when overdosed or poorly dispersed. Agglomeration may cause microcracking and voids [56,59,118].	Optimize particle size and dosage; apply surface treatments; blend biochar with SCMs to balance mechanical and environmental performance.

Table 6. *Cont.*

Challenge	Description	Proposed Solutions
Workability and water demand	Biochar's porous structure increases water absorption, which reduces mix flowability and complicates compaction [7].	Modify biochar surface to reduce hydrophilicity; use high-performance superplasticizers; adapt water-to-cement ratios.
Early-age shrinkage	Although biochar supports internal curing, it can aggravate early-age shrinkage due to water absorption, especially in mixes with low w/c ratios [83].	Control particle fineness and dosage; combine with shrinkage-reducing admixtures or pozzolanic materials such as silica fume.
Durability uncertainties	Poorly carbonized or ash-rich biochars may introduce reactive compounds, increasing risks of carbonation, sulfate attack, or efflorescence [74].	Conduct durability testing under aggressive exposures; use high-temperature carbonization; blend biochar with durable SCMs.
Production scalability	Scaling up biochar production with consistent quality is hindered by feedstock variability and pyrolysis energy demands [116,119].	Integrate biochar production into circular economy systems using local organic waste; invest in energy-efficient pyrolysis with heat recovery; monetize carbon credits.
Lack of standards and guidelines	Absence of universally accepted methods for biochar testing and use limits regulatory acceptance [70,120].	Develop international benchmarks; collaborate with agencies to define biochar specifications for construction applications.
Economic and environmental trade-offs	While biochar offers environmental benefits, production and logistics may be cost-prohibitive without optimization [113].	Conduct full life cycle and cost–benefit assessments; streamline supply chains; implement policy incentives such as tax credits or subsidies.

According to Barbhuiya et al.[121], overcoming these limitations involves a holistic approach that includes: optimizing biochar production, embracing circular economy principles, integrating advanced characterization tools, and aligning performance objectives with sustainability targets. Furthermore, establishing harmonized testing protocols and efficient supply chains is essential to ensure scalability and real-world adoption.

By addressing these barriers, biochar can transition from a niche research material to a mainstream solution for decarbonizing the cement and concrete industry. Its successful integration will support both short- and long-term climate objectives while enhancing the resilience and circularity of construction materials.

3.6. Emerging Non-Cementitious Applications of Biochar

Beyond its established role in cementitious systems, biochar is increasingly recognized for its potential in non-cement-based applications. These include thermal and acoustic insulation, multifunctional surface coatings, and lightweight composites. Such applications leverage biochar's inherent properties, high porosity, low density, chemical stability, and pollutant adsorption capacity, making it a highly versatile and sustainable material for the built environment.

One of the most promising areas is thermal insulation. Due to its low thermal conductivity and porous microstructure, biochar can effectively reduce heat transfer, contributing to enhanced energy efficiency in buildings. Studies have shown that cellulose–biochar aerogels can achieve thermal conductivity values comparable to commercial insulators such as expanded polystyrene, while maintaining mechanical resilience and significantly lower environmental impact[122]. Additionally, when incorporated into mortar formulations, biochar improves thermal resistance, suggesting its suitability for insulating interior mortars and wall coatings[123].

Biochar's acoustic insulation capabilities also show considerable promise. Its internal pore network allows effective absorption of airborne sound, particularly in the mid- to high-frequency range. This makes it a sustainable material for noise-dampening panels, acoustic ceiling tiles, and interior wall claddings in urban and industrial context[124].

Another emerging use is in multifunctional coatings. Biochar-enhanced surface treatments are being developed to regulate indoor temperature and humidity, adsorb volatile organic compounds (VOCs), and improve indoor air quality. These coatings can also contribute to passive environmental control strategies in buildings. Moreover, reflective biochar-based finishes have shown potential for mitigating urban heat island effects, by reducing solar heat gain on building surfaces [125].

In addition, biochar is being explored as a lightweight aggregate substitute in non-structural components. Its low density and high thermal stability enable its use in decorative panels, partition boards, and insulating concrete blocks. Surface modification of biochar particles further enhances their bonding, thermal resistance, and mechanical performance, expanding their applicability in lightweight eco-friendly construction materials [72].

As the construction sector advances toward climate-resilient and resource-efficient design, these emerging applications of biochar can contribute to a more sustainable material palette. Continued interdisciplinary research is needed to optimize biochar's properties for non-cementitious systems, validate long-term performance, and develop application-specific standards. This progress will be key to scaling biochar technologies across the broader construction industry.

3.7. Emerging Applications and Functional Potential of Hydrochar in Construction Materials

Hydrochar has recently gained attention as a promising low-carbon additive for construction applications, owing to its distinct physicochemical properties derived from hydrothermal carbonization (HTC). Unlike pyrolysis-based biochar, hydrochar production does not require biomass drying and can process wet organic feedstocks, reducing energy demand and enhancing its alignment with circular economy principles [126].

Studies indicate that hydrochar can be incorporated into cementitious materials at replacement levels of 1.25–2.5 wt% without severely compromising mechanical performance. Although it typically causes some reduction in compressive strength, hydrochar enhances thermal insulation, electrical resistivity, and can accelerate or delay setting time depending on mix conditions. These characteristics make it suitable for non-structural applications, including plastering mortars, insulating panels, and lightweight composite boards [9,11].

In asphalt systems, hydrochar derived from agricultural residues, such as corn stalks, has been explored as a sustainable bitumen modifier. Its porous microstructure improves rheological properties, including elasticity, rutting resistance, and resistance to oxidative aging under high temperatures. This offers an environmentally friendly alternative to petroleum-based additives in road construction. However, challenges remain concerning long-term performance and storage stability, which must be resolved before broader industrial adoption [11].

Hydrochar is also being investigated for binder-free composite boards, particularly when combined with municipal solid waste. These boards exhibit flexural strength up to 21.6 MPa, densities of 838–883 kg/m^3, and low thermal conductivity values (0.091–0.132 W/m·K), making them suitable for interior insulation panels and architectural applications [9,12].

Microstructural analyses using X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) have revealed that hydrochar may delay early hydration. In mortars containing 2.5 wt% hydrochar (HTC-treated at 195 °C for 3 h), Portlandite ($Ca(OH)_2$), a key hydration product, was observed only after 24 hours, indicating delayed reactivity compared to biochar. Nonetheless, the internal porosity of hydrochar supports internal curing, improving dimensional stability and durability, despite compressive strength reductions [11].

Despite its potential, hydrochar faces limitations. Its physicochemical properties vary significantly based on HTC parameters and feedstock type. Moreover, its lower mechanical performance, particularly in early stages, and the lack of long-term field validation limit its immediate deployment in structural applications.

A comparative overview of biochar and hydrochar, covering production processes, morphological characteristics, reactivity, and influence on cementitious systems, is presented in **Table 7**. This highlights both the advantages and constraints of each material, offering guidance for application-specific selection and performance optimization.

While hydrochar's development is still in the early stages compared to biochar, it offers a complementary pathway to valorize organic waste and decarbonize the construction sector. To realize this potential, future research must focus on optimizing HTC conditions, standardizing testing protocols, and evaluating long-term performance under real-world conditions. Integrating hydrochar into sustainable material systems can support waste valorization, climate mitigation, and the expansion of circular practices across the built environment.

Table 7. Comparison between biochar and hydrochar as additives in cementitious materials.

Criteria	Biochar	Hydrochar	Ref.
Typical production process	Pyrolysis (∼300–700 °C, inert atmosphere)	HTC (∼180–250 °C, aqueous medium)	Santos et al. [9]; Gupta and Kua [40]
Feedstock type	Dry lignocellulosic biomass (e.g., straw, bamboo)	Wet organic waste (e.g., food, sludge)	Santos et al. [9]; Gupta and Kua [40]
Particle morphology	Angular grains with cavities	Spherical/compact microspheres	Amado-Fierro et al. [11]; Shaaban et al. [39]
Specific surface area (BET)	50–400 m^2/g (up to >600 in activated chars)	1–30 m^2/g (rarely exceeds 80)	Maljaee et al. [6]; Santos et al. [9]
O:C atomic ratio	0.05–0.15 (high stability)	0.30–0.50 (lower stability)	Maljaee et al. [6]; Amado-Fierro et al. [11]
Effect on fresh workability	High slump loss (20%–50%) at ≥2 wt%	Mild slump loss (5%–15%) at 1–5 wt%	Maljaee et al. [6]; Amado-Fierro et al. [11]
Effect on 28-d compressive strength	Slight gains (≤10%) at low dosages; losses at >3 wt%	Strength loss (30%–60%) at 1–5 wt%	Amado-Fierro et al. [11]; Sirico et al. [117]
Thermal performance	Thermal conductivity: 0.19–0.23 W/m·K	Further reduction of 20%–30%	Santos et al. [9]; Gupta et al. [59]
Durability effects	Improved carbonation/chloride resistance	Increased resistivity, delayed hydration	Amado-Fierro et al. [11]; Xu et al. [41]
Applications	Concrete, repair mortars, 3D-printed materials, aerogels	Plasters, particleboards, insulating panels	Santos et al. [9]; Qi et al. [28]
Main limitations	Inconsistent properties, lack of global standards	Low early strength, limited field validation	Amado-Fierro et al. [11]; European Biochar Foundation (EBC) [17]; Cosentino et al. [34]

3.8. Resource Efficiency and Circular Economy Implications

The integration of biochar and hydrochar into construction materials aligns strongly with the principles of resource efficiency and the circular economy, both of which are central to global sustainability strategies such as the European Green Deal [3] and the UN Sustainable Development Goals [2].

As products obtained from agricultural, forestry, and municipal waste via thermochemical conversion, both materials exemplify waste valorization, transforming low-value, carbon-rich residues into functional, durable components in construction systems [6,7]. This approach reduces the environmental burden of waste disposal and promotes the efficient use of resources that would otherwise be underutilized or discarded.

This approach reduces the environmental burden of waste disposal and promotes the efficient use of resources that would otherwise be underutilized or discarded [41,127]. In particular, silica-rich biochars, such as those derived from rice husks, exhibit pozzolanic activity, enabling partial clinker replacement in cementitious systems and thereby contributing to embodied carbon reduction [42,44].

The use of biochar also facilitates industrial symbiosis, where waste from one sector (e.g., agriculture, food processing, forestry) becomes a valuable input for another (e.g., construction), improving systemic efficiency and reducing landfill pressures [6,7,42]. In doing so, biochar supports the development of closed-loop material cycles and enhances the resilience of material supply chains, an increasingly relevant consideration given resource scarcity and climate-related disruptions [42].

From a climate perspective, biochar's stable carbon structure enables long-term CO_2 sequestration, contributing to carbon mitigation efforts across both the waste and construction sectors. When integrated into non-structural applications, such as insulating panels, renders, or architectural coatings, biochar further enhances building envelope performance, extending material lifespans and reducing operational energy demands [124].

To quantify and validate these sustainability benefits, future studies should incorporate tools such as life cycle assessment (LCA), carbon footprint modeling, and techno-economic analysis. These instruments are essential for evaluating trade-offs across the full biochar value chain, from biomass sourcing and conversion processes to construction performance and end-of-life scenarios. Moreover, harmonized LCA methodologies and economic evaluation frameworks are crucial for guiding policy development and incentivizing industrial uptake.

In summary, the use of biochar and hydrochar in construction materials offers a viable pathway to close resource loops, reduce environmental burdens, and accelerate the transition to circular and low-carbon material systems, in line with global sustainability and climate goals.

4. Conclusions

Biochar has emerged as a promising material for climate-resilient and resource-efficient construction. Derived from the thermochemical conversion of agricultural and urban biomass, it combines high porosity, stable carbon content, and chemical tunability, enabling its use as a multifunctional additive in both cementitious and non-cementitious systems. When properly engineered and dosed, biochar can enhance mechanical strength, reduce water absorption, improve thermal insulation, and extend material service life.

Its incorporation into construction materials aligns directly with the principles of the circular economy by valorizing biomass waste, reducing dependency on virgin materials such as Portland cement and natural aggregates, and enabling long-term CO_2 sequestration. Applications in non-structural components, such as insulation panels, mortars, and multifunctional coatings, further reduce embodied carbon and operational energy consumption, while supporting industrial symbiosis across sectors. These roles position biochar as a key enabler for closed-loop material cycles and decarbonization of the built environment.

Hydrochar, while comparatively less studied, has also demonstrated potential in asphalt modification, thermal insulation, and lightweight composites. Its production via hydrothermal carbonization (HTC) allows for the use of wet organic waste without drying, offering an energy-efficient route for waste valorization. Although it tends to reduce mechanical strength when compared to biochar, hydrochar shows promising properties such as improved electrical resistivity, setting control, and thermal conductivity reduction, features that merit further exploration.

Despite these advances, significant challenges remain. Variability in feedstock type, pyrolysis or HTC conditions, and biochar properties results in inconsistent performance across studies. Scalability, energy consumption, and the absence of standardized production and testing protocols further hinder widespread implementation. Additionally, most published findings are based on laboratory-scale experiments, with limited real-world validation.

To unlock the full potential of biochar and hydrochar in sustainable construction, future research and policy development should focus on several key areas:

- Establishing harmonized quality standards for production, characterization, and application in construction materials;
- Investigating nano-biochar and biochar aggregates for multifunctional performance;
- Expanding durability assessments under diverse and aggressive environmental conditions;
- Integrating life cycle assessments (LCA), carbon footprint modeling, and cost-benefit analyses to quantify net sustainability gains;
- Promoting technical guidelines, regulatory incentives, and carbon credit schemes to encourage adoption at scale.

In conclusion, biochar and hydrochar represent transformative solutions to reduce the environmental footprint of the construction industry. By converting residual biomass into performance-enhancing additives, they support the transition to climate-smart, resource-efficient, and circular construction systems. Their successful integration will directly contribute to the objectives of the European Green Deal, the UN Sustainable Development Goals, and other global sustainability frameworks.

Nevertheless, this review acknowledges certain limitations. The analysis predominantly draws on peer-reviewed literature in English, primarily from laboratory-scale research. The diversity in production processes and testing methodologies limits comparability across studies. Future work should aim to consolidate industrial-scale performance data, promote harmonized testing frameworks, and include cross-regional assessments to better understand the scalability and applicability of biochar and hydrochar across varied construction contexts.

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Conflicts of Interest

The author declares no conflict of interest.

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