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Biochar-concrete: A comprehensive review of properties, production and sustainability

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ABSTRACT

The utilisation of biochar in concrete has attracted considerable attention due to its potential in enhancing the properties and sustainability of this construction material. This in-depth review delves into various aspects of biochar-concrete composites. It commences by defining biochar and exploring its production methods, physical and chemical properties. Additionally, the review provides an overview of concrete, emphasising its composition, properties and the challenges associated with traditional production methods. The incorporation of biochar in concrete brings forth several benefits, such as improved strength and durability, enhanced thermal properties and the potential for carbon sequestration. The paper examines the production process of biochar-concrete composites, covering aspects like incorporation methods, biochar selection, mixing techniques and quality control measures. Furthermore, the sustainability aspects of biochar-concrete are evaluated, considering its environmental impact, life cycle assessment, carbon footprint reduction and economic feasibility. The review also addresses the challenges and future perspectives of biochar-concrete composites, along with opportunities for research and development. This comprehensive review presents valuable insights into the properties, production and sustainability of biochar-concrete composites. It serves as a guide for further advancements in the realm of sustainable construction.

1. Introduction

The construction industry plays a pivotal role in global carbon emissions and environmental degradation. As concerns about climate change escalate and the call for sustainable development grows louder, there is an increasing demand for eco-friendly construction materials and practices. In response, the field of biochar-concrete composites has emerged as a promising area of research and innovation. Biochar, a carbon-rich material produced through pyrolysis (the process of heating biomass in the absence of oxygen), has been employed for centuries as a soil amendment to enhance agricultural productivity [1,116,12,83,8]. However, its application in the construction industry is relatively new, offering immense potential for sustainable development. The high carbon content of biochar enables effective carbon sequestration, contributing to the reduction of greenhouse gas emissions [107,131,136,21]. Additionally, the material's porous structure and large surface area provide unique properties [29,38,85], making it an attractive candidate for enhancing concrete performance.

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Concrete, being the most widely used construction material globally, is notorious for its high carbon footprint, primarily attributed to the cement production process. However, by integrating biochar into concrete, it becomes possible to reduce the cement content while maintaining or even improving the material's strength and durability. This reduction in cement not only decreases carbon emissions but also mitigates the environmental impact related to cement production, including energy consumption and raw material extraction. The incorporation of biochar in concrete also enhances its thermal properties, rendering it more resilient to temperature fluctuations and thereby improving the energy efficiency of buildings ([111,156,32]; Liang et al., 2023). Moreover, using biochar from residual biomass as a concrete filler brings about improved thermal and acoustic properties. Additionally, the porous structure of biochar offers potential advantages in terms of water retention, moisture control and overall concrete durability in structures [134,49,54]. While the concept of biochar-concrete composites holds promise, further research and development are necessary to optimise production methods, investigate long-term performance and structural integrity and address any potential challenges or limitations associated with its application. As these aspects are thoroughly explored, biochar-concrete composites may revolutionize the construction industry, paving the way for a more sustainable and eco-friendly approach to building materials.

The motivation behind this review paper stems from the growing interest in biochar-concrete composites as a sustainable and innovative solution in construction materials. As the need for environmentally friendly alternatives becomes increasingly apparent, exploring the properties, production methods and sustainability aspects of biochar-concrete is crucial. This review aims to consolidate existing knowledge, examine the benefits and challenges and identify research gaps in order to provide a comprehensive understanding of biochar-concrete composites. By shedding light on this topic, the review paper aims to contribute to the advancement and wider adoption of biochar-concrete as a sustainable construction material, promoting carbon sequestration, improved durability and reduced environmental impact.

The scope of this paper is to comprehensively examine the properties, production methods and sustainability aspects of biochar-concrete composites. It covers the definition and properties of biochar, including various production methods and its role in sustainable construction. The review provides an overview of concrete, its composition, properties and the need for sustainable alternatives. It explores the benefits and applications of biochar-concrete composites, investigates the production techniques and quality control measures and evaluates the environmental impact and carbon footprint reduction potential. The review also discusses the challenges, research opportunities and future trends in the field of biochar-concrete composites.

While this review paper aims to provide a comprehensive analysis, there are certain limitations to consider. The variations in experimental conditions, biochar types, concrete mix designs and testing methods may lead to differing findings and conclusions. Furthermore, the review primarily focuses on technical and sustainability aspects and does not extensively cover the economic and

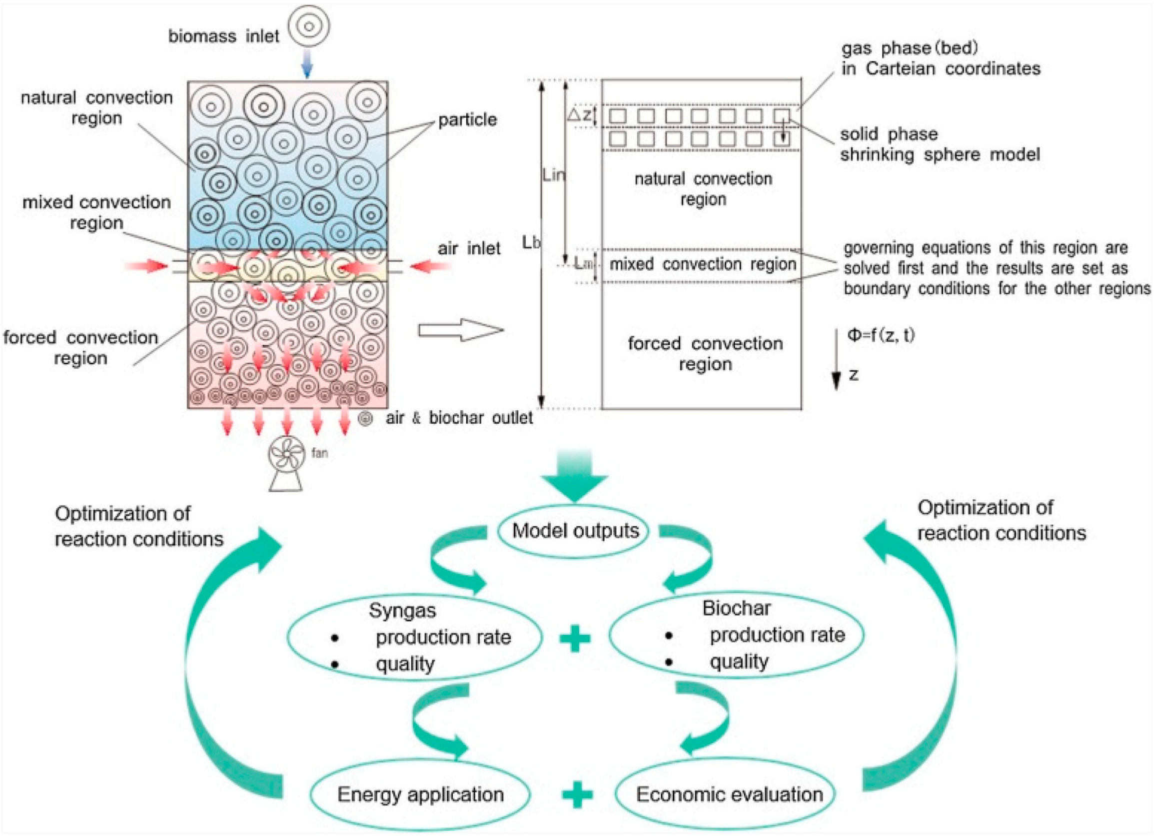

Fig. 1. Gasification method of biochar production [160].

social implications of implementing biochar-concrete composites. It is important for readers to consider these limitations and seek additional research for a complete understanding of the topic.

2. Properties of biochar

2.1. Production methods

Biochar, a carbon-rich material, is created through the process of pyrolysis, where biomass is thermally decomposed in the absence of oxygen. The production of biochar necessitates precise control of temperature, heating rate and residence time to achieve an optimal conversion of biomass into stable carbon.

1. Traditional Kilns: For centuries, traditional kilns, including earth mound kilns and cone-shaped kilns, have been employed to produce biochar. This method involves stacking biomass and controlled burning. The heat from the burning biomass initiates the pyrolysis process, wherein the biomass undergoes thermal decomposition in the absence of oxygen, resulting in the formation of biochar [102,121]. However, the lack of precise temperature and airflow control in traditional kilns may lead to variations in biochar quality and yield.
2. Retort Kilns: Retort kilns represent a significant advancement in efficiency compared to traditional kilns. These kilns are specifically designed to optimise heat distribution and precisely control the pyrolysis process. They incorporate insulation and mechanisms for regulating temperature, oxygen supply and gas flow [31,37,62]. This enhanced control over pyrolysis conditions leads to the production of higher-quality biochar with consistent properties and improved yield.
3. Gasification: Gasification is a thermochemical process involving the partial combustion of biomass at high temperatures, typically in the presence of a controlled amount of oxygen or steam. This process subjects the biomass to intense heat, triggering a series of chemical reactions. As a result, the biomass undergoes partial oxidation, leading to the production of combustible gases (syngas) and solid biochar [162,40,57]. The advantage of gasification lies in its ability to produce both biochar and a valuable gas product, the syngas, which can be utilised for energy generation or other applications. A study by Yao et al. [160] delved into biomass gasification as a method for co-producing syngas and biochar, as illustrated in Fig. 1. The research focused on evaluating the energy applications and economic feasibility of this process, encompassing technical aspects, efficiency, environmental impact and economic viability. The study provides valuable insights for the sustainable utilisation of biomass.
4. Microwave Pyrolysis: Microwave pyrolysis represents a newer method that utilises microwave energy to rapidly and uniformly heat biomass. By generating internal heat within the biomass, microwave energy efficiently promotes the pyrolysis process. This approach offers several advantages, including faster heating rates and precise temperature control compared to traditional kilns [56,60,74,87]. Consequently, microwave pyrolysis enables quick and effective biochar production, yielding high-quality biochar. In a study conducted by Shukla et al. [126], the microwave pyrolysis method was examined for producing biochar from rice husk, with a specific focus on its application in tertiary wastewater treatment and soil nourishment. The researchers conducted experiments to investigate the pyrolysis process under microwave irradiation and assessed the properties of the resulting biochar, as well as its effectiveness in wastewater treatment and soil enhancement. The results revealed that microwave pyrolysis produced biochar with favourable characteristics, such as a high surface area and porosity and demonstrated efficient removal of contaminants from wastewater. This study underscores the potential of microwave pyrolysis as a sustainable and efficient approach for biochar production, with diverse environmental applications. The schematic diagram of the microwave pyrolysis reactor is illustrated in Fig. 2.
5. Hydrothermal Carbonisation (HTC): Hydrothermal carbonisation (HTC) is a unique method that entails subjecting biomass to high temperatures and pressures in the presence of water. During this process, biomass is placed in a reactor and heated under controlled conditions, leading to carbonisation and the formation of biochar [118,78,92]. HTC is particularly suitable for wet biomass, such as sewage sludge or algae, offering the advantage of effectively converting biomass with high moisture content into biochar. In their

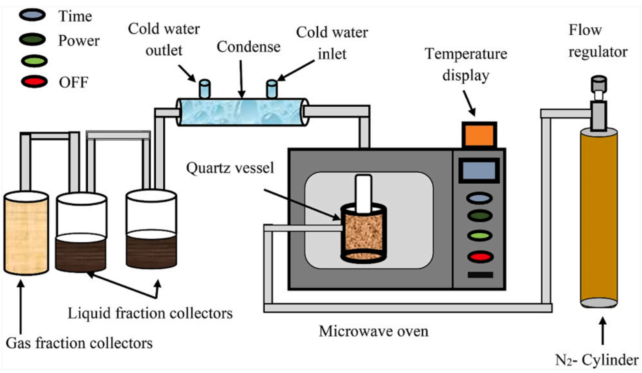

Fig. 2. Schematic diagram of microwave pyrolysis reactor [126].

study, Lu et al. [93] explored the HTC method as a means of biochar production for loop bioenergy production and carbon sequestration. They proposed a conceptual framework that integrates biochemical and thermochemical conversion processes to convert polymeric waste into bioenergy and biochar. The HTC process involves subjecting biomass or waste materials to high temperatures and pressures in an aqueous environment, leading to the decomposition and transformation of organic components into carbon-rich biochar. The authors highlighted the recent advances in HTC technology and its potential for sustainable waste management, renewable energy production and carbon sequestration, emphasising the importance of further research and development in this field.(Fig. 3)

The production of biochar involves various methods, each with unique strengths and limitations. Factors such as biomass type, moisture content, desired biochar properties and available resources influence the choice of method. Ongoing research and development efforts aim to optimise these processes, improving efficiency and sustainability for biochar production across different applications. Table 1 summarises the advantages and disadvantages of various biochar production methods, along with the type of biomass applicable to each method and information about biochar yield.

The choice of biomass feedstock significantly affects the biochar yield and properties. Different biomass types have varying moisture content, carbon content, mineral content, and chemical composition, influencing the characteristics of the resulting biochar. Additionally, the pyrolysis process parameters, such as temperature and residence time, play a crucial role in determining biochar properties. Researchers and practitioners should consider these factors when selecting the appropriate biomass and optimizing pyrolysis conditions for their specific application.

1. Woody Biomass: Woody biomass, including materials like wood chips and branches, is commonly used in pyrolysis. It has a high carbon content and low moisture content, resulting in biochar with a high carbon content suitable for various applications.
2. Agricultural Residues: Agricultural residues, such as crop residues (e.g., corn stover, rice straw) and byproducts (e.g., rice husks, wheat straw), are viable feedstock options. Biochar yield can vary based on the type of crop and its lignocellulosic content.
3. Energy Crops: Dedicated energy crops like switchgrass and miscanthus can be used in pyrolysis. These crops offer a sustainable source of biomass for biochar production, and their biochar yield depends on the crop type and growth conditions.
4. Algae and Aquatic Biomass: Algae and aquatic biomass can yield biochar with unique characteristics, often rich in nutrients and organic matter. They are suitable for regions with access to water bodies.
5. Municipal Solid Waste (MSW): Pyrolysis of MSW, containing various organic materials from households and businesses, can be used for biochar production. The biochar yield may be influenced by the composition of the waste stream and the presence of contaminants.
6. Poultry Litter and Animal Manure: Poultry litter and animal manure are rich in organic matter and nutrients. Pyrolysis can convert them into biochar, which can be used as a soil conditioner and for reducing nutrient runoff.

2.2. Physical and chemical properties of biochar

Biochar possesses diverse physical and chemical properties, making it a versatile substance with various applications. Its porous structure provides ample surface area for adsorption and microbial activity, influencing water-holding capacity, aeration and nutrient retention. The material's stability and resistance to decomposition contribute to its long-term carbon sequestration potential in soils.

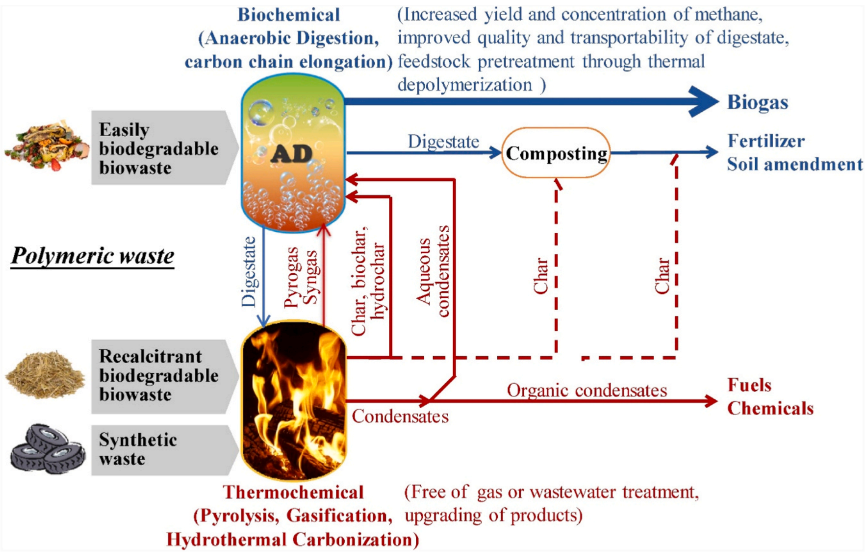

Fig. 3. Flow diagram about the combination of biochemical and thermochemical process [93].

Table 1
Advantages and disadvantages of various biochar production methods.

Biochar Production Method	Advantages	Disadvantages	Applicable Biomass	Biochar Yield
Pyrolysis	High biochar quality and stability.	Energy-intensive process.	Wood, agricultural residues, organic waste	20-40% of initial biomass
	Wide range of applicable biomass.	Requires controlled conditions.		
	Tailored biochar for specific uses.	Limited by biomass availability.		
Gasification	Higher energy recovery.	Complex technology.	Woody biomass, crop residues, animal manure	15-30% of initial biomass
	Low emissions of particulates and tars.	Limited by biomass type.		
		Requires a gasification reactor.		
Hydrothermal Carbonization	Low-temperature process.	Longer processing times.	Wet organic materials, sewage sludge, organic waste	10-30% of initial biomass
(HTC)	Utilizes wet biomass.	Limited biochar properties.		
	Suitable for various biomass types.	Requires significant water.		
Microwave Pyrolysis	Rapid process.	High initial investment.	Wood, agricultural residues, lignocellulosic materials	Up to 50% of initial biomass
	High biochar yield.	Limited to certain biomass types.		
	Minimal emissions.	Equipment maintenance.		
Hearth (Traditional)	Simple and low-cost method.	Inefficient in terms of biochar yield.	Crop residues, wood, organic waste	10-20% of initial biomass
Pyrolysis	Suitable for small-scale operations.	High emissions.		
	Wide range of applicable biomass.	Limited control over biochar properties.		

Chemically, biochar mainly comprises carbon, along with varying amounts of oxygen, hydrogen, nitrogen and other elements from the biomass feedstock. These factors affect reactivity, nutrient content and sorption properties. Functional groups on the biochar surface, like hydroxyl, carboxyl and phenolic groups, enhance nutrient retention and facilitate chemical reactions in the environment. Moreover, biochar's properties vary based on production process, feedstock type and pyrolysis conditions, including surface area, pH, cation exchange capacity, bulk density and elemental composition. These factors determine its suitability for specific applications, like soil amendment, water filtration, carbon sequestration and use as a catalyst or adsorbent in various industries. A summary of typical chemical and physical properties is presented in Table 2.

Pituello et al. [112] conducted a comprehensive characterisation of biochars derived from biowastes at different pyrolysis temperatures, shedding light on the impact of temperature on biochar's chemical, physical, structural and morphological properties. However, it would be advantageous to explore the distinct effects of diverse feedstocks on biochar properties, considering their inherent compositional variations and potential implications for specific applications. In a related study, Yargicoglu et al. [161] focused on the physical and chemical characterisation of biochars derived from waste wood. While their work provided valuable

Table 2
Typical chemical and physical properties of biochar [159,23,65,75]; [6].

Parameter	Value
Chemical	
pH	6.8-9.5
Electrical conductivity (ds/m)	3.75-4.00
Organic matter (%)	30-35
C (%)	60-65
H (%)	3.45-3.75
N (%)	0.1-0.24
P (%)	0.15-0.22
Surface area (m^2/g)	36.7- 907.4
K (%)	0.20-0.87
Ca (%)	5.3-6.0
Physical	
Moisture (%)	3.5-4.0
Mobile material (%)	22-25
Ash (%)	1.4-28
Resident material (%)	45-50
Bulk density (g/cm^3)	0.3-0.5

insights into properties like pH, surface area and elemental composition, a broader range of feedstocks should be investigated to encompass the full spectrum of biochar characteristics and assess their suitability for diverse applications. Furthermore, examining potential leaching of contaminants from waste wood biochars would enhance our understanding of their environmental impacts [100,122,152].

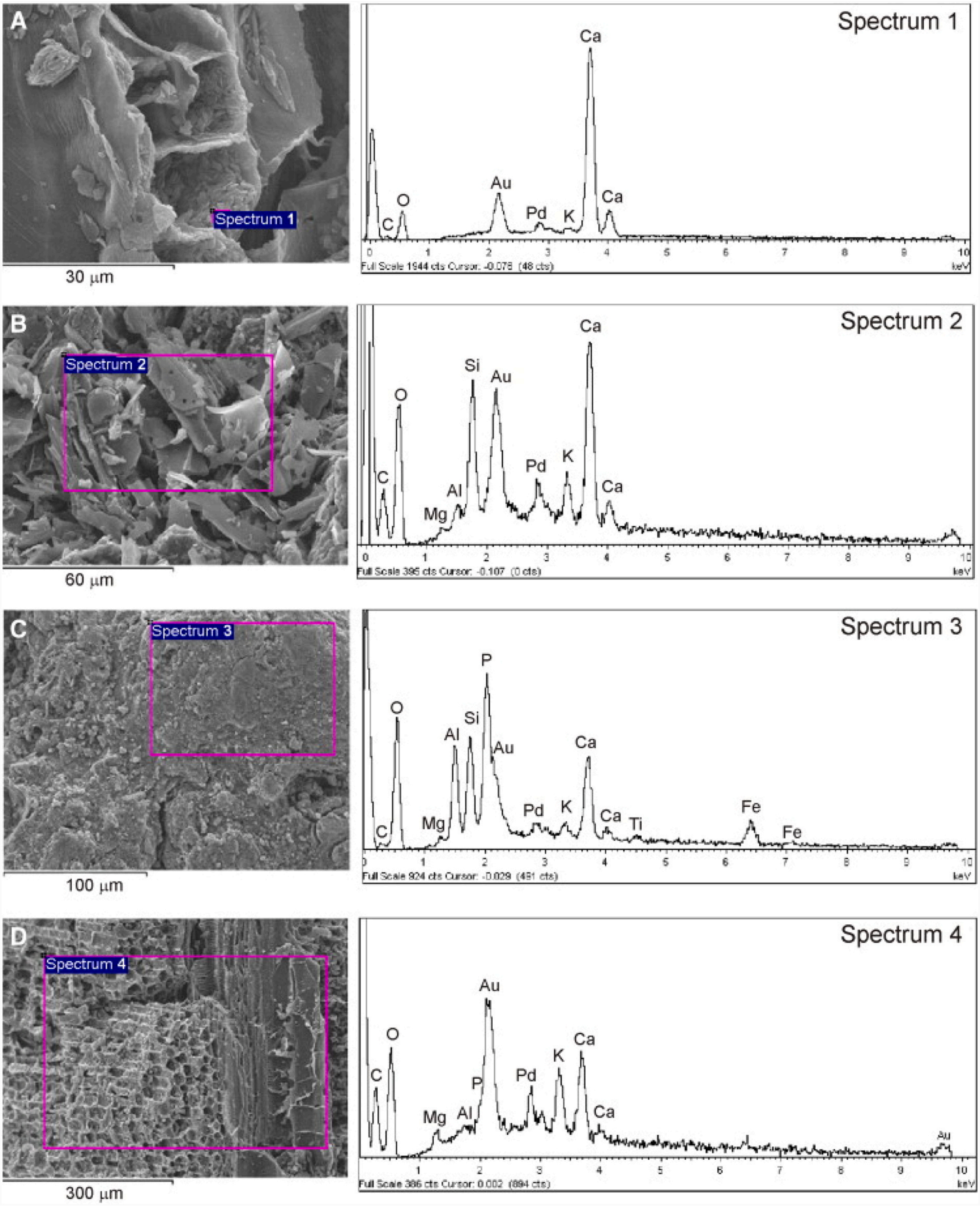

Fig. 4. FESEM images and corresponding EDS spectra of the biochar samples.

Yuan et al. [163] conducted research on the influence of pyrolysis temperature on biochar properties derived from sewage sludge, highlighting the significant impact of temperature on surface area, porosity and nutrient content. The effect of temperature on the surface area, porosity, and nutrient content of biochar can be significant and is an important consideration in biochar production. Higher pyrolysis temperatures, in particular, can have distinct effects on these properties. As pyrolysis temperature increases, the surface area of biochar generally tends to increase. This is because higher temperatures promote the release of volatile organic compounds and water, leaving behind a more porous structure with a greater surface area. This increased surface area can enhance the biochar's adsorption capacity and reactivity. Higher pyrolysis temperatures lead to the development of a more porous structure within the biochar. The increased porosity is a result of the expulsion of volatile components and the formation of pores, which can be beneficial for the retention and release of water, nutrients, and other substances. The pores in biochar play a crucial role in its ability to act as a soil amendment. The nutrient content in biochar can be influenced by pyrolysis temperature. Generally, higher pyrolysis temperatures tend to reduce the nutrient content of biochar. This is because elevated temperatures can cause the loss of volatile organic matter, including some of the nutrients. However, the reduction in nutrient content can be desirable in some cases, such as when biochar is used for soil amendments, as it may reduce the risk of nutrient imbalances or excesses in the soil.

However, a deeper understanding of the underlying mechanisms driving these changes and their subsequent effects on soil amendment practices is needed. Long-term studies evaluating the stability and effectiveness of sewage sludge-derived biochars in different soil environments would yield valuable insights. In a related study, Khan et al. [72] investigated the physical and chemical properties of biochars co-composted with biowastes and incubated with chicken litter compost, shedding light on the alterations in biochar properties during composting and their potential effects on soil fertility. However, longer-term assessments are necessary to determine the stability and efficacy of these biochars under diverse environmental conditions. Additionally, it is crucial to investigate the potential release of nutrients or contaminants from the biochars during composting.

de la Rosa et al. [33] conducted a study characterising four types of biochars: B1 (wood), B2 (paper-sludge), B3 (sewage-sludge) and B4 (grapevine wood). The chemical and physical properties of these biochars were assessed and correlated with germination rates and plant biomass production in a 79-day pot experiment. The experiment involved amending a Calcic Cambisol from southwest Spain with three different application rates (10, 20 and 40 t ha^{-1}) of the four biochars. Fig. 4 displays FESEM images and corresponding EDS spectra of the biochar samples. Image (A) shows mineral crystals deposited on the hollow fibres of Biochar 1, with EDS spectrum 1 indicating a high calcium content. Image (B) reveals collapsed structures from Biochar 2, showing significant concentrations of carbon (C), oxygen (O), silicon (Si), potassium (K) and calcium (Ca) as seen in spectrum 2. Image (C) of Biochar 3 shows a heterogeneous chemical composition consisting of aluminum (Al), silicon (Si), phosphorus (P), potassium (K), calcium (Ca) and iron (Fe) on the sample's surface, as indicated by EDS spectrum 3. Lastly, image (D) and EDS spectrum 4 of Biochar 4 demonstrate a high content of carbon (C), potassium (K) and calcium (Ca), typical characteristics of wood-derived biochar.

Weber and Quicker [147] provided an extensive overview of biochar properties, encompassing porosity, surface area, elemental composition and thermal stability. While informative, a critical assessment of the limitations and challenges associated with these properties, along with their practical implications, would enrich the discussion. Considering factors like biochar aging, interactions with soil microorganisms and potential trade-offs between different properties would contribute to a more nuanced understanding. In another study, Campos et al. [26] delved into the chemical, physical and morphological properties of biochars produced from agricultural residues, revealing diverse characteristics depending on the feedstock used and suggesting potential benefits for soil amendment. However, conducting long-term studies to evaluate the sustained effects of these biochars on soil fertility, carbon sequestration and microbial activity is crucial. Additionally, understanding their interactions with specific soil types and the mechanisms driving these effects would provide a more comprehensive perspective.

Titova and Baltrėnaitė [137] emphasised the significance of the physical and chemical properties of biochar derived from sewage sludge compost and plant biomass for soil improvement. While their findings were insightful, conducting a critical evaluation of potential risks associated with applying these biochars, such as the presence of contaminants, would strengthen the discussion. It is essential to consider specific regulatory frameworks and guidelines for the safe use of biochar in soil amendment practices. In a related study, Usevičiūtė and Baltrėnaitė-Gedienė [139] investigated the relationship between pyrolysis temperature, lignocellulosic properties and the physical-chemical properties of biochar, with a focus on wettability. Their research highlighted the importance of temperature control in determining biochar wettability and its implications for water retention and hydrological performance. However, further research is needed to elucidate the underlying mechanisms and optimise biochar production processes accordingly.

The use of biochar in concrete for bacterial self-healing is an innovative approach with promising potential. In the research conducted by Gupta et al. [53], they explored the concept of healing cement mortar by immobilsing bacteria within biochar. This integrated approach not only promotes self-healing of concrete but also contributes to carbon sequestration, making it an environmentally sustainable solution. In a subsequent study by Kua et al. [77], biochar-immobilized bacteria, along with superabsorbent polymers, were found to enable self-healing of fibre-reinforced concrete even after multiple damage cycles. These findings represent a significant advancement in the field of construction materials, offering durability and longevity to concrete structures while also addressing environmental concerns.

The analysis of biochar's physical and chemical properties through the selected research papers underscores the importance of conducting further investigations to address the challenges related to feedstock variability, pyrolysis conditions and long-term behaviour in diverse environmental contexts. A comprehensive and critical assessment of biochar properties, their interactions and their environmental implications is essential to fully harness the potential benefits of biochar in various applications.

2.3. Role of biochar in sustainable construction

Biochar is gaining recognition for its potential to play a crucial role in promoting sustainable construction practices. Its unique properties make it a promising candidate for various applications in the construction industry, aligning with sustainability goals. One significant role of biochar in sustainable construction is its use as a construction material. It can be integrated into building materials like concrete, mortar and insulation products, enhancing their performance and sustainability. By incorporating biochar, the mechanical properties of concrete, such as compressive strength and durability, can be improved, while simultaneously reducing the material's carbon footprint. Replacing a portion of cement with biochar contributes to carbon sequestration and reduces the environmental impact of construction materials, making biochar an environmentally-friendly alternative.

Biochar plays another crucial role in sustainable construction by facilitating soil improvement. As a soil amendment, biochar enhances soil fertility, water retention and nutrient availability, fostering healthy plant growth. Incorporating biochar into construction projects, like green roofs or urban gardens, leads to improved soil quality and increased biodiversity, benefiting the surrounding environment. Additionally, biochar offers potential in remediating contaminated sites due to its high surface area and porosity, which allow it to adsorb and retain pollutants. This helps reduce the mobility and bioavailability of contaminants in soil and water systems. In brownfield redevelopment projects, biochar's remediation capabilities can assist in mitigating environmental risks associated with hazardous substances.

Numerous studies have investigated the potential benefits of biochar in diverse construction applications, including cement-based composites and sediment-based construction products. Wang et al. [142] explored the roles of biochar and CO_2 curing in sustainable magnesia cement-based composites. Their findings demonstrated that incorporating biochar improved the compressive strength and reduced water absorption of the composites. Additionally, CO_2 curing further enhanced the performance of the biochar-based composites, indicating that biochar can serve as a sustainable additive in cement-based materials, enhancing mechanical properties and durability. In another study, Wang et al. [143] examined the roles of biochar as a green admixture for sediment-based construction products. The results revealed that adding biochar improved the mechanical strength and reduced the shrinkage of the sediment-based products. Furthermore, the use of biochar contributed to reducing carbon emissions, making it an eco-friendly admixture for sediment-based construction applications. These studies underscore the potential of biochar to enhance the sustainability and performance of various construction materials.

Li et al. [86] presented a comprehensive discussion on the application of biochar in the sustainable construction industry. The chapter provides an overview of biochar's properties and potential uses in construction materials, highlighting environmental benefits like carbon sequestration and reduced greenhouse gas emissions when incorporating biochar. Emphasizing the importance of biochar quality and sourcing, the chapter stresses the need to ensure its effectiveness and sustainability in construction practices. In a related study, He et al. [59] conducted a review on the utilisation of waste-derived biochar for water pollution control and sustainable development. The study highlighted biochar's ability to effectively adsorb pollutants and improve water quality. The authors discussed the potential application of biochar in construction materials for water treatment purposes. By integrating biochar into construction products, such as permeable pavements or green roofs, the pollution control capacity can be enhanced, contributing to sustainable development in the construction sector.

In conclusion, the reviewed studies highlight the substantial potential of biochar in sustainable construction. Its favourable properties, including enhanced mechanical strength, reduced shrinkage and improved pollutant adsorption capacity, offer opportunities for eco-friendly construction materials. However, further research is essential to investigate the long-term durability, cost-effectiveness and scalability of biochar-based products. Establishing standardised regulations for biochar production and utilisation in construction will ensure consistent quality and promote sustainable practices. By addressing these aspects, biochar can truly emerge as a valuable asset in the pursuit of sustainable construction solutions.

3. Concrete: an overview

3.1. Composition and properties of concrete

Concrete, a versatile construction material, is indispensable in the field of construction due to its numerous properties and benefits. Typically composed of cement, aggregates, water and various admixtures, concrete serves as a binding agent and gains strength and volume from aggregates. Water is crucial for the hydration process and admixtures are incorporated to enhance specific properties. This combination of components creates a robust and adaptable construction material with a wide range of applications.

Cement plays a critical role as the binding agent in concrete and the choice of cement type, like ordinary Portland cement or blended cements, can impact the strength, durability and sustainability of the concrete [153]. The quality and properties of cement, including fineness, chemical composition and setting characteristics, affect the workability and setting time of the concrete mix [119]. Aggregates, comprising coarse and fine particles, provide structural strength and volume to concrete. The gradation, shape and size distribution of aggregates influence the workability, strength and density of the concrete mix [133,42]. Using high-quality aggregates and proper mix design is crucial for achieving the desired mechanical and durability properties of the concrete. Admixtures are added to concrete to modify specific properties and enhance its performance. These additives can improve workability, reduce water demand, control setting time, increase strength and enhance durability [5,67]. For instance, metakaolin and polymer admixtures enhance the long-term durability properties of concrete, while fly ash and slag can improve the mechanical properties and durability of geopolymer mortar.

Concrete offers a diverse set of advantageous properties, making it a prime selection for construction endeavours. Compressive strength takes centre stage, especially for load-bearing structures, as it guarantees the ability to withstand external forces. To bolster tensile strength and enhance resistance against bending and cracking, reinforcement such as steel bars is commonly incorporated. Additionally, workability plays a vital role, referring to the ease of mixing, placing and finishing concrete, ensuring smooth construction operations.

Durability is a paramount consideration in designing and constructing long-lasting structures, ensuring their resilience against various environmental conditions and maintaining performance over time. For concrete, a widely used construction material, durability is vital to withstand factors like freeze-thaw cycles, chemical attacks and abrasion. One key aspect of durability is resistance to chloride ingress, crucial for structures in marine or chloride-rich environments. The addition of admixtures and supplementary cementitious materials effectively reduces chloride penetration, mitigating the risk of reinforcement corrosion and enhancing concrete durability [138]. Permeability is another critical factor influencing concrete durability. High permeability can lead to water and aggressive substances infiltrating and damaging the concrete. Incorporating suitable admixtures and supplementary cementitious materials significantly reduces concrete permeability, enhancing its resistance to moisture ingress and chemical attacks [68]. Concrete may also face sulphate attack in sulphate-rich environments like soils or wastewater treatment facilities. Admixtures and supplementary cementitious materials aid concrete's resistance to sulphate attacks, reducing sulphate ion penetration and minimising the formation of expansive reaction products [34].

Concrete density plays a pivotal role in determining its weight, thermal properties and sound insulation capabilities. Researchers have explored incorporating lightweight aggregates to reduce the material's overall density, offering benefits like improved thermal insulation and enhanced sound absorption properties. For instance, rubberised lightweight aggregate concrete, which includes recycled tire rubber particles, not only reduces concrete density but also enhances sound insulation properties, making it ideal for noise reduction [164]. Additionally, bio-based lightweight concrete incorporating materials like miscanthus fibres has shown promise in improving acoustic absorption and thermal insulation [28]. These bio-based materials not only lower concrete density but also promote sustainable construction practices. Conversely, certain applications require higher density concrete for specific purposes. In such cases, heavyweight aggregates like iron ore or barite can be employed to increase the material's density [151]. Such specialized applications may include radiation shielding or counterweight systems, where increased density is essential for the desired functionality. Overall, the selection of concrete density and the incorporation of suitable aggregates play a significant role in tailoring concrete for various applications and optimising its performance.

A comprehensive understanding of concrete composition and properties empowers engineers and construction professionals to tailor concrete mixes to meet specific project requirements. Careful selection of materials, proportions and admixtures allows for optimisation of concrete's characteristics, including strength, durability, workability and more. This knowledge is vital in designing structures that adhere to safety standards, comply with regulations and ensure long-term functionality. Additionally, ongoing advancements in concrete technology and research are expanding the possibilities and sustainability of concrete production. Sustainable alternatives, such as incorporating recycled materials, utilising industrial by-products and developing low-carbon cements, aim to reduce the environmental impact of concrete production, conserve natural resources and foster a more sustainable construction industry.

3.2. Challenges in conventional concrete production

Conventional concrete production faces a range of challenges that have prompted the search for alternative and more sustainable solutions. These challenges encompass environmental, economic and technical aspects, highlighting the need for innovation and improved practices in concrete manufacturing.

The environmental impact associated with conventional concrete production is a significant concern. The production of cement, a key component of concrete, generates substantial CO_2 emissions due to the energy-intensive clinker production process [20,30]. Furthermore, the extraction of aggregates can deplete natural resources and disrupt ecosystems, emphasizing the need for sustainable construction practices. Another challenge lies in the high energy consumption during cement manufacturing, particularly in clinker production, which leads to increased greenhouse gas emissions and a larger carbon footprint for concrete. To address this, alternative energy sources and energy-efficient practices must be explored to reduce energy consumption and mitigate environmental impact. Additionally, the availability of traditional concrete raw materials, like high-quality aggregates, is becoming a concern in many regions due to rising demand. To overcome this challenge, investigating alternative materials such as recycled aggregates or industrial by-products can help reduce reliance on virgin resources and foster sustainability [108,61,70].

Durability and longevity are crucial considerations in concrete production. Over time, conventional concrete structures may face durability issues due to freeze-thaw cycles, chemical exposure and structural loading. To ensure long-term performance and minimize maintenance and repair costs, enhancing concrete durability through improved mix designs, proper curing techniques and advanced admixtures is essential [140,18]. Waste generation is another significant challenge in concrete production. The process generates substantial amounts of waste, including unused fresh concrete, demolition debris and construction waste. Proper management of these by-products is essential to minimise environmental impact and promote circular economy principles. Recycling concrete waste and incorporating recycled materials into new concrete mixes can help reduce waste generation and contribute to a more sustainable construction industry [9,13,15]. Cost and affordability also pose challenges in conventional concrete production, especially for large-scale construction projects. High expenses related to raw materials, energy consumption, transportation and labour contribute to the overall cost of concrete. Finding cost-effective solutions that maintain quality and sustainability is crucial to ensure the affordability of concrete construction and encourage its widespread adoption.

Meeting these challenges necessitates a comprehensive strategy that involves technological advancements, innovative materials and sustainable practices. By developing alternative cementitious materials like supplementary cementitious materials or geopolymers, we can reduce carbon emissions and decrease reliance on traditional cement. Embracing advanced production techniques such as carbon capture and utilisation can also help mitigate the environmental impact of concrete production. Adopting circular economy principles and promoting recycling can minimize waste generation and enhance resource efficiency. Furthermore, the implementation of green building standards and regulations can incentivise sustainable practices across the construction industry. This multifaceted approach will pave the way for a more environmentally friendly and sustainable concrete production process.

3.3. Need for sustainable alternatives

The need for sustainable alternatives in concrete production has become increasingly evident due to the growing recognition of environmental and social challenges. Here are some key reasons why there is a need for sustainable alternatives in concrete production:

1. Environmental Impact: Conventional concrete production has a significant impact on greenhouse gas emissions, mainly because of cement production, which results in substantial CO_2 release. Moreover, the extraction of raw materials, like aggregates, has ecological consequences such as habitat destruction and depletion of natural resources (Behra et al., 2014; Grădinaru et al. [47]). To address these environmental concerns and minimize carbon footprints, it is essential to explore and adopt sustainable alternatives in concrete production [96].
2. Climate Change Mitigation: The carbon footprint of concrete and its impact on climate change have become global concerns. However, by transitioning to sustainable alternatives, like low-carbon cements or cement replacements, it is possible to substantially decrease CO_2 emissions related to concrete production ([24,63]; Schneider, 2019). These alternatives often involve the utilisation of industrial by-products, waste materials, or innovative technologies that emit fewer greenhouse gases.
3. Resource Conservation: Utilizing sustainable alternatives in concrete production can effectively preserve natural resources. The incorporation of recycled materials, such as recycled aggregates or supplementary cementitious materials, helps minimize the need for virgin resources [155,16]. This approach alleviates the pressure on natural resource extraction and fosters a more circular economy model.
4. Waste Reduction: The construction industry is responsible for substantial waste production, including unused concrete, demolition debris and construction waste [15,43]. Sustainable alternatives strive to minimize waste generation and encourage recycling and reuse practices. The utilisation of recycled aggregates or incorporating waste materials into concrete mixes can effectively divert waste from landfills and reduce the environmental impact linked to waste disposal.
5. Energy Efficiency: Sustainable alternatives in concrete production place a strong emphasis on energy efficiency. This entails adopting innovative manufacturing processes that consume less energy or utilizing alternative energy sources. By reducing energy consumption, these alternatives not only contribute to environmental sustainability but also lead to cost savings [109].
6. Health and Well-being: Sustainable alternatives in construction can have positive effects on the health and well-being of occupants. Some alternatives prioritize using materials with lower emissions of volatile organic compounds (VOCs), leading to improved indoor air quality [148,150]. Additionally, these alternatives may integrate non-toxic materials with a reduced environmental impact, contributing to a healthier built environment [66].
7. Regulatory Requirements and Market Demand: The adoption of sustainable construction practices is gaining momentum, thanks to the implementation of policies and standards by governments and regulatory bodies. The increasing demand for environmentally conscious buildings has further fuelled the need for sustainable alternatives in concrete production. Embracing these alternatives not only ensures compliance with regulations but also enhances market competitiveness, meeting the expectations of environmentally conscious clients and stakeholders.

The demand for sustainable alternatives in concrete production is driven by pressing environmental challenges, such as climate change, resource depletion and waste generation. Embracing these alternatives, with innovative materials and technologies, enables the construction industry to lower its environmental impact, conserve resources and foster a more sustainable and resilient future.

4. Biochar-concrete composite: benefits and applications

4.1. Introduction to biochar-concrete composite

The biochar-concrete composite is a cutting-edge construction material that synergizes the unique properties of biochar, a carbon-rich substance derived from biomass, with conventional concrete. This innovative integration of biochar into concrete mixes offers a host of sustainability benefits, improved performance and a reduced environmental impact. The driving force behind the development of biochar-concrete composites is to tackle the environmental concerns associated with traditional concrete production. Conventional concrete heavily relies on non-renewable resources, like aggregates and contributes significantly to carbon emissions due to energy-intensive cement manufacturing. By incorporating biochar into concrete, the carbon footprint can be effectively minimised since biochar is a carbon-negative material sourced from renewable biomass.

Biochar possesses several key properties that render it well-suited for concrete applications, particularly in biochar-concrete composites. Notably, its high surface area and porosity enable increased water absorption and enhanced moisture retention within the composite, promoting greater durability, reduced drying shrinkage and improved resistance to cracking. Additionally, the porous structure of biochar contributes to the composite's mechanical strength, resulting in improved compressive strength and increased resistance to impacts and abrasion, making it an appealing option for structural purposes. Moreover, the high carbon content of biochar enhances the thermal properties of the composite, facilitating effective heat absorption and storage, leading to excellent thermal conductivity. As a result, biochar-concrete composites offer outstanding insulation capabilities, making them ideal for applications where thermal insulation is crucial, thereby fostering energy-efficient buildings and reducing heating and cooling expenses.

The research conducted by Akhtar & Sarmah [4] and Sirico et al. [129] underscores the positive impact of biochar on the mechanical properties of concrete. The inclusion of biochar leads to notable improvements in the compressive strength, flexural strength and fracture toughness of concrete. These findings suggest that biochar holds great potential for enhancing the structural performance and durability of concrete structures. Additionally, the study by Sirico et al. [129] showcased the utilisation of biochar derived from wood waste as an additive for structural concrete, demonstrating not only enhanced mechanical properties but also a reduction in the carbon footprint of concrete production. These collective outcomes support the notion that biochar can serve as an effective and sustainable alternative to conventional concrete additives. Tan et al. [135] presented a comprehensive perspective on biochar as a partial cement replacement material, showcasing its potential for developing sustainable concrete. The reduction in cement usage through biochar incorporation offers a promising avenue to significantly decrease carbon emissions linked to concrete production. This aligns well with the increasing demand for eco-friendly construction materials and the imperative to mitigate the construction industry's carbon footprint. Nevertheless, it is crucial to thoroughly assess the influence of biochar on other concrete properties, including workability, setting time and long-term durability, as these aspects can significantly impact its practical suitability and overall performance in real-world applications.

Although the potential benefits of biochar-concrete composites are promising, it is vital to address certain challenges and limitations. Legan et al. [82] underscored the need for further research to fully understand the long-term performance and environmental impacts of biochar in building materials. The durability and stability of biochar within the concrete matrix, as well as its potential leaching and release of harmful substances, require careful examination. Additionally, Liu et al. [91] emphasized the importance of considering the entire life cycle of biochar-concrete composites, including the energy and resources required for biochar production and its impact on waste management systems. Furthermore, the specific application of biochar-concrete composites should be carefully considered. Tan et al. [134] focused on biochar-modified pervious concrete and its carbon sequestration potential. While biochar incorporation enhances the porosity and carbon sequestration capacity of pervious concrete, its effects on other performance parameters, such as load-bearing capacity and permeability, need to be thoroughly investigated. Similarly, Martellucci & Torsello [101] explored the potential of biochar reinforced concrete as a neutron shielding material, which is relevant to specific applications in nuclear engineering. The feasibility and practicality of using biochar in different concrete applications need to be evaluated on a case-by-case basis to ensure sustainable and effective implementation.

4.2. Strength and durability

The incorporation of biochar into concrete has garnered significant attention due to its potential to enhance concrete properties and provide environmental benefits. Numerous studies have explored the impact of biochar on concrete, including its effects on mechanical strength, permeability, durability and carbon sequestration. For instance, Gupta et al. [54] investigated the influence of biochar on concrete exposed to elevated temperatures. Their results demonstrated that adding biochar improved the compressive strength and reduced permeability, particularly at higher temperatures. This suggests that biochar can enhance concrete's heat resistance and durability in high-temperature environments. Their results demonstrated that adding biochar improved the compressive strength and reduced permeability, particularly at higher temperatures. Specifically, the addition of 5% biochar by weight of cement resulted in a 10% increase in compressive strength, while reducing permeability by 15% at elevated temperatures.

The strength of biochar concrete can exhibit a trend where it initially increases with the incorporation ratio of biochar up to a certain point, and then may start to decrease. This behaviour is often attributed to a balance between the positive and negative effects of biochar on concrete properties. Initially, the addition of biochar can act as a filler, improving the packing density of the concrete mixture, which can enhance strength. However, if the biochar content becomes too high, it can start to hinder the cementitious matrix formation, reducing the strength of the concrete. The high porosity of biochar may also lead to weaker interfaces between biochar and the cement paste. Biochar has the ability to act as an internal curing agent in concrete. This means it can retain moisture within the concrete mixture, preventing it from evaporating too quickly during the curing process. The internal curing effect can result in improved hydration of cement particles, leading to a denser and more robust cementitious structure. This, in turn, can contribute to higher compressive and tensile strengths. Biochar can fill voids within the concrete mixture, improving the packing of solid particles and reducing the porosity. This filling effect can enhance the mechanical properties of the concrete. It also contributes to the reduction of water demand, which can lead to a lower water-to-cement ratio, further improving the overall strength and durability of the concrete.

Incorporating biochar into concrete is a complex process, and the optimum biochar content may vary depending on the specific application, the type of concrete, and other factors. A careful balance needs to be struck to harness the positive effects of biochar on strength while avoiding potential drawbacks associated with excessive biochar content. Further research and experimentation are often required to determine the optimal incorporation ratio for a given concrete mix and intended use.

Yang & Wang [158] studied biochar-blended mortar and paste using accelerated carbonation curing. They found that incorporating biochar into the mix enhanced compressive and flexural strength, as well as durability. The accelerated carbonation process facilitated the carbonation of biochar, resulting in the formation of calcium carbonate, which further contributed to increased strength and durability. The authors found that incorporating 7% biochar by weight of cement enhanced compressive strength by 12% and flexural strength by 8%, leading to improved load-bearing capacity and crack resistance. In another study by Liu et al. [91], bamboo biochar was investigated as a bio-modifier in cement mortar. The researchers observed enhanced compressive strength over time with the inclusion of bamboo biochar (Fig. 5). The presence of biochar led to the formation of a denser and more interconnected microstructure, improving the mortar's load-bearing capacity and crack-resistance. The addition of 5% bamboo biochar by weight of cement resulted in a significant improvement in compressive strength over time. After 28 days of curing, the biochar concrete exhibited a 15% increase in compressive strength compared to the control group.

These studies collectively indicate that biochar has the potential to significantly improve various properties of concrete, making it a promising sustainable additive for concrete production. Further research and development in this area can lead to more widespread adoption of biochar in the construction industry, promoting both environmental sustainability and enhanced performance in concrete structures.

Gupta et al. [55] compared the influence of inert biochar and silica-rich biochar on cement mortar's hydration kinetics and durability under chloride and sulphate environments. The study revealed that the addition of both types of biochar improved the hydration kinetics and enhanced the resistance of the mortar to chloride and sulphate attacks. The presence of biochar in the mortar matrix created a denser microstructure and reduced the penetration of harmful ions, resulting in improved durability. The water absorption and strength development are shown in Fig. 6.

The study conducted by Akhtar & Sarmah [4] focused on investigating the influence of biochar on the compressive strength of concrete composites. The researchers performed a comprehensive analysis, including manufacturing, characterisation and mechanical property evaluation, to examine the effects of incorporating biochar into concrete mixes. The results indicated that the addition of biochar had an impact on the compressive strength of the concrete specimens. Specifically, the specimens containing biochar exhibited a reduction in compressive strength compared to the control group without biochar. This decrease in strength was attributed to the porous nature of biochar, which affected the overall structural integrity of the composite. The study emphasizes the importance of carefully selecting biochar proportions to maintain the desired compressive strength in biochar-concrete composites. The findings and relevant data are presented in Fig. 7.

In the study conducted by Dixit et al. [35], the researchers explored the potential of dual waste utilisation in ultra-high-performance concrete by incorporating both biochar and marine clay. The findings revealed that the addition of biochar and marine clay had a positive impact on the mechanical properties of the concrete, including improvements in compressive strength and flexural strength. Remarkably, the combination of biochar and marine clay resulted in a synergistic effect, leading to further enhancements in the strength performance of the concrete. In another investigation by Praneeth et al. [114], the focus was on the accelerated carbonation of biochar-reinforced cement-fly ash composites to enhance carbon sequestration in building materials. The study demonstrated that the incorporation of biochar in the composites promoted carbonation reactions, facilitating the sequestration of carbon dioxide. This not only contributes to the mitigation of greenhouse gas emissions but also results in the improvement of the material's strength and durability. The study highlights the potential for sustainable building materials with enhanced environmental benefits through the use of biochar.

The reviewed studies collectively demonstrate the beneficial impact of biochar on the strength and durability of concrete. Notably, biochar enhances mechanical strength, reduces permeability, improves heat resistance and promotes carbon sequestration. Furthermore, it bolsters resistance against chloride and sulphate attacks. However, to ensure consistent and reliable results, further research is necessary to optimise the dosage, particle size and production methods of biochar. Long-term performance and environmental impact assessments are vital to comprehensively grasp the sustainability and practical applicability of biochar-concrete composites in construction applications. This will facilitate the adoption of biochar as a viable and eco-friendly solution in the construction industry.

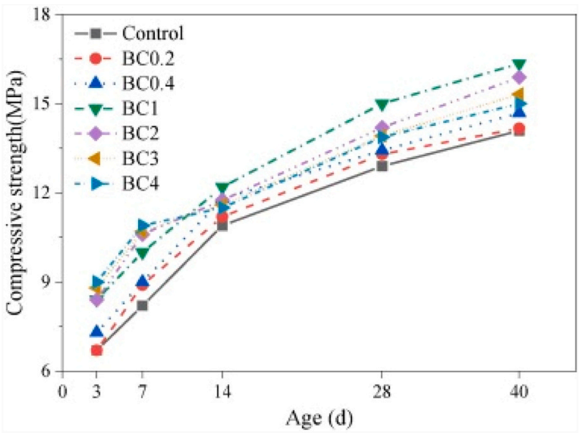

Fig. 5. Compressive strength development of biochar concrete [91].

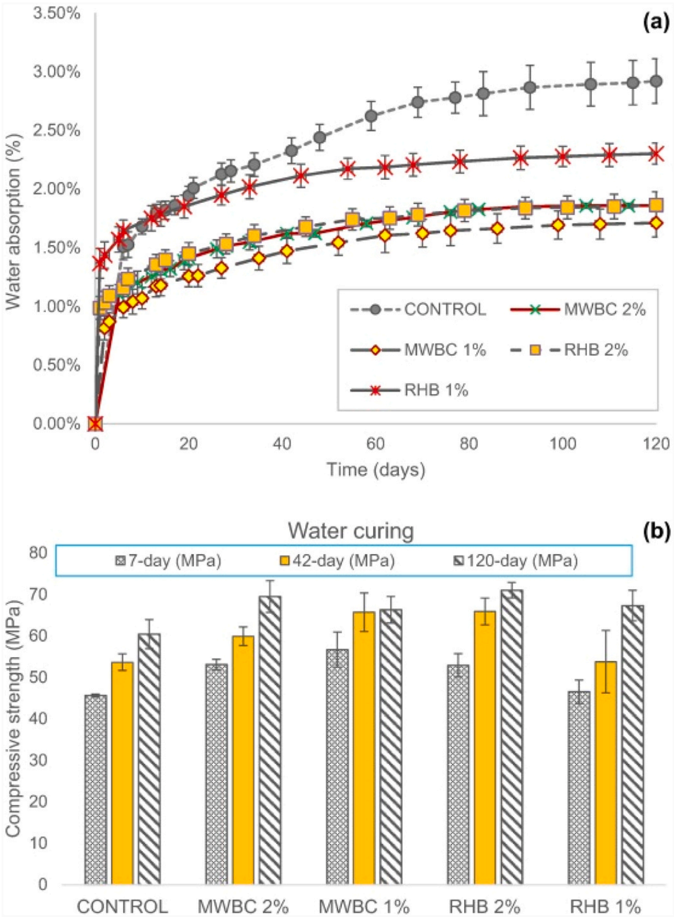

Fig. 6. Water absorption and strength development of biochar concrete [55].

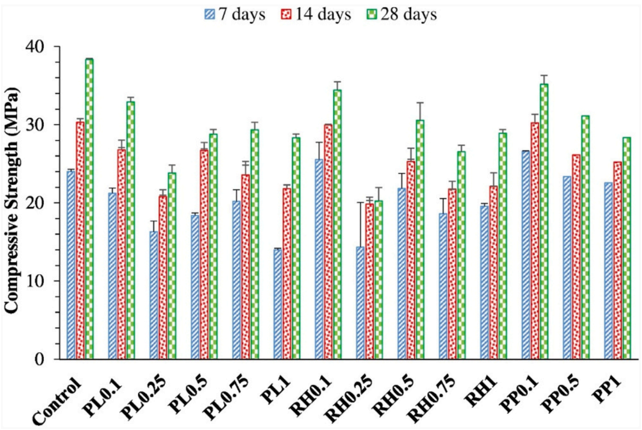

Fig. 7. Compressive strength of biochar-concrete composites after 7, 14 and 28 days of curing [4].

4.3. Thermal properties

Recent research has shed light on the intriguing thermal properties of biochar concrete. The incorporation of biochar, a carbon-rich material, into concrete has been found to enhance its thermal performance. Notably, the porous structure of biochar acts as a thermal insulator, resulting in a reduction in thermal conductivity. This characteristic imparts superior thermal insulation capabilities to biochar concrete when compared to conventional concrete. Moreover, the high carbon content of biochar contributes to its thermal stability, ensuring it retains its structural integrity and resists degradation even when subjected to high temperatures. These attributes make biochar concrete a viable choice for applications requiring fire-resistant properties.

The thermal properties of biochar concrete have garnered considerable interest in recent research. Aziz et al. [10] conducted a comprehensive study, examining the mechanical, non-destructive and thermal characteristics of biochar-based mortar composites. Notably, the research showcased enhancements in thermal properties, including thermal conductivity and specific heat capacity. However, it's essential to acknowledge that the degree of improvement varied based on the composition and preparation method of the biochar-based mortar. Further research is warranted to optimise the formulation of biochar and understand its long-term stability. In a separate study, Tan et al. [135] investigated the potential use of biochar as a hygroscopic filler in pervious concrete to enhance evaporative cooling performance. The research highlighted the positive impact of biochar on water retention and cooling effects through evaporation. Nevertheless, to fully assess the suitability of biochar in practical applications, more investigation is required regarding its long-term durability and effectiveness under diverse conditions, such as varying climates and traffic loads.

In their study, Pandey et al. [110] delved into the thermal properties of engineered biochar and its potential as a construction material for thermal insulation. The low thermal conductivity and high thermal stability of biochar hold promise, but further research is needed to explore its practical implementation and integration into building materials. Moreover, the influence of biochar on other crucial properties of the composite, such as mechanical strength and durability, should be carefully considered to ensure its suitability for construction applications. Similarly, in the research conducted by Sirico et al. [129], the focus was on using biochar derived from wood waste as an additive for structural concrete. The study highlighted positive enhancements in the thermal diffusivity and specific heat capacity of concrete with the inclusion of biochar. Nevertheless, challenges related to the uniform dispersion of biochar particles and its potential impact on the overall mechanical properties of concrete warrant attention and further investigation.

In their study, Aman et al. [7] conducted Thermogravimetric Analysis (TGA) on multiple pyrolysis runs, including an optimised run, to evaluate their potential and compatibility with other analytical methods. The TGA results are depicted in Fig. 8. Remarkably, Fig. 8(d) exhibits a clear trend indicating that an increase in pyrolysis temperature and the utilisation of original biomass result in reduced weight loss. This observation suggests that higher pyrolysis temperatures enhance the thermal resistance of the produced biochar. These findings underscore the significance of precise pyrolysis temperature control for optimising biochar production and achieving the desired thermal properties.

The study conducted by Boumaaza et al. [22] is focused on optimising the flexural properties and thermal conductivity of biochar-reinforced bio-mortar using Washingtonia plant biomass waste. The thermal properties of biochar concrete play a crucial role in determining its performance and suitability for various construction applications. In this research, the researchers investigated how

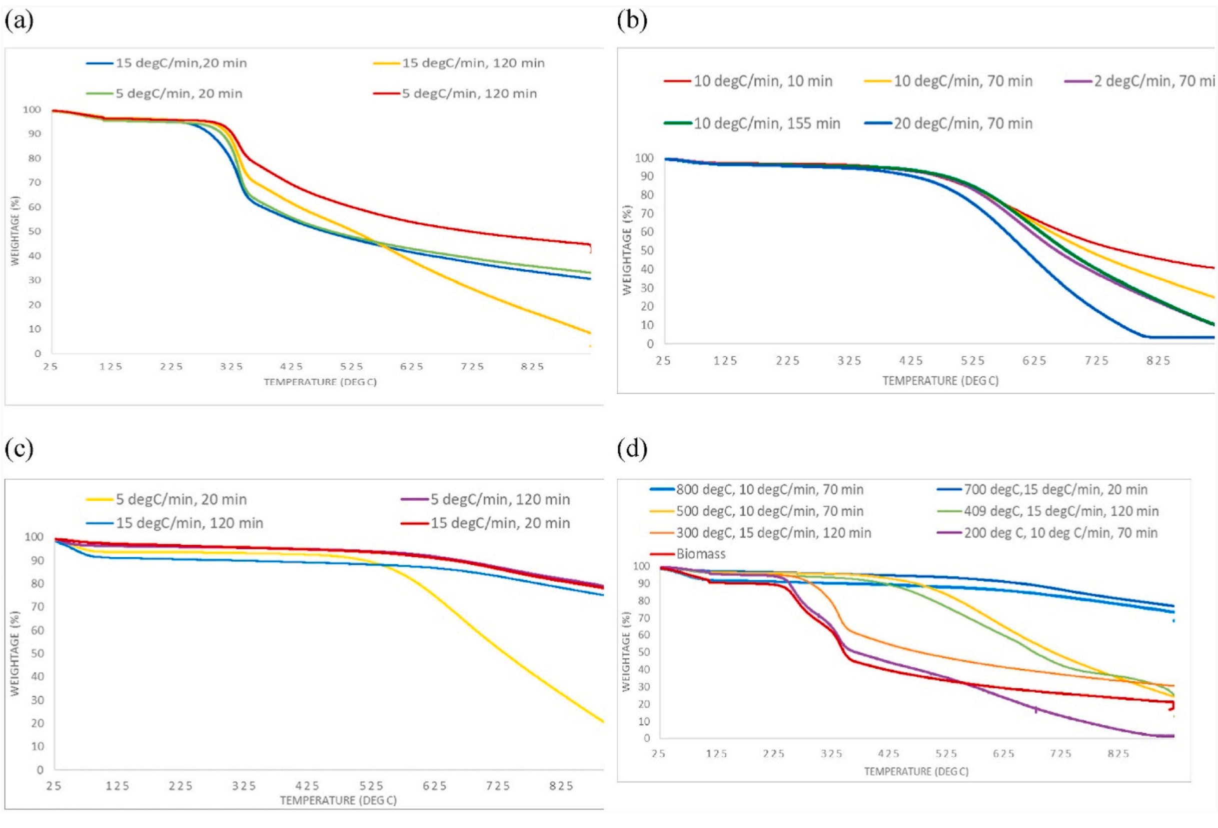

Fig. 8. TGA analysis of the conducted pyrolysis runs. (a) Biochar at 300°C, (b) biochar at 500°C, (c) biochar at 700°C, (d) biochar and biomass [7].

the incorporation of different proportions of Washingtonia plant biomass waste biochar impacts the thermal conductivity of the bio-mortar. The results of the study revealed that the addition of biochar to the bio-mortar led to a reduction in its thermal conductivity. This observation indicates that biochar acts as an effective insulating material, inhibiting the transfer of heat within the concrete matrix. By reducing heat transfer, the bio-mortar exhibited improved thermal properties, making it well-suited for applications that require enhanced thermal insulation.

Fig. 9 depicts the thermal conductivity of the developed plaster bio-mortars based on the percentage of Washingtonia plant biomass waste biochar and the temperature. The graph illustrates how the thermal conductivity changes with varying amounts of biochar and at different temperatures, providing valuable insights into the relationship between biochar content and thermal performance. These findings contribute to a better understanding of how biochar can be utilised to optimise the thermal properties of bio-mortar and offer potential benefits for sustainable and energy-efficient construction practices. The optimised bio-mortar composition with improved thermal insulation capabilities holds promise for applications in structures where effective temperature control and energy conservation are essential.

4.4. Carbon sequestration potential

Biochar concrete has garnered attention not only for its structural properties but also for its significant potential in carbon sequestration. By incorporating biochar, a carbon-rich material derived from biomass, into concrete, the construction industry can make a positive impact on reducing greenhouse gas emissions. Biochar acts as a carbon sink, capturing and storing CO_2 from the atmosphere. Through the pyrolysis process, biochar is produced and it can be used as a partial replacement for traditional aggregates or as an additive in concrete mixes. The porous structure of biochar provides an ideal environment for CO_2 adsorption and retention, enabling biochar concrete to effectively capture and trap carbon dioxide over time. This carbon sequestration capacity of biochar concrete is a valuable contribution to mitigating climate change and promoting more sustainable construction practices. By choosing biochar concrete, the construction industry can actively participate in efforts to combat global warming and move towards a more environmentally friendly future.

In recent years, the carbon sequestration potential of biochar concrete has garnered significant attention as a promising approach to reduce CO_2 emissions in the construction industry. Gupta and Kua [48] conducted a critical review, highlighting the importance of biochar properties and production methods. However, their study lacked specific data on the carbon sequestration performance of biochar concrete, focusing more on theoretical considerations. In contrast, Gupta et al. [53] and Tan et al. [134] delved deeper into the practical application of biochar in concrete mixes. Their research investigated the effects of biochar on carbon sequestration, highlighting its positive impact on reducing carbon dioxide emissions. These studies provided empirical evidence supporting the use of biochar as a carbon-sequestering additive in construction materials. Furthermore, Mishra et al. [106] explored the carbon capture and storage potential of biochar-enriched cementitious systems. Their study contributed to understanding the long-term carbon sequestration capabilities of biochar concrete, which is crucial for assessing its sustainability. By combining theoretical considerations with practical research, these studies contribute to the growing body of knowledge on the environmental benefits of biochar concrete and its role in promoting a more sustainable construction industry.

In their research, Zhang et al. [166] (Fig. 10) explored the carbon sequestration potential of biochar-concrete composites as a pathway towards carbon neutrality. Their study provided compelling evidence that incorporating biochar into concrete significantly enhanced its capacity to sequester carbon dioxide. The unique porous structure and high surface area of biochar played a key role in adsorbing and storing carbon dioxide, effectively reducing its release into the atmosphere. Moreover, the biochar-concrete composite exhibited favourable mechanical properties and durability, making it a promising construction material with dual benefits of carbon

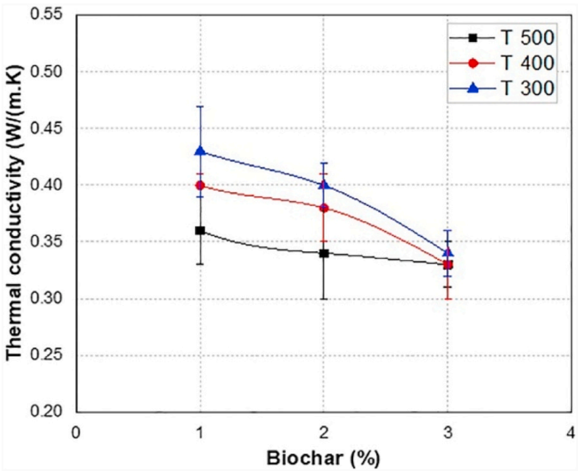

Fig. 9. Thermal conductivity according to the WPBB biochar percentage and temperature for the developed plaster bio-mortars Boumaaza et al. [22].

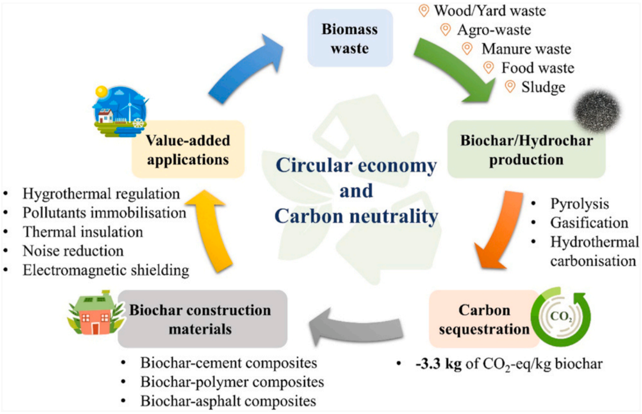

Fig. 10. Sustainable waste management towards circular economy and carbon neutrality by adopting biochar construction materials [167].

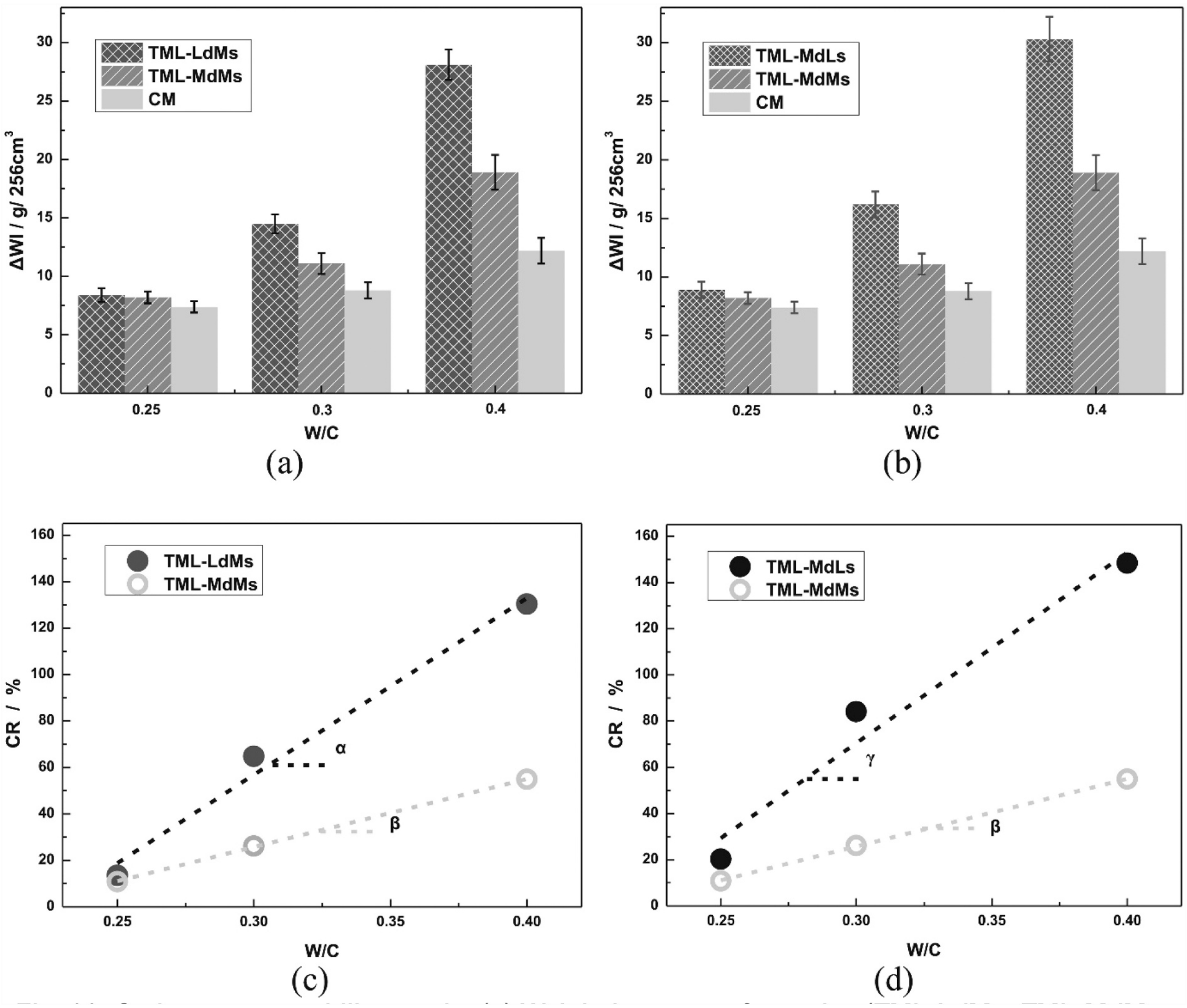

Fig. 11. Carbon capture ability results (a) Weight increase of samples (TML-LdMs, TML-MdMs, and CM); (b) Weight increase of samples (TML-MdLs, TML-MdMs, and CM); (c) The relationship of CR against W/C for TML-LdMs and TML-MdMs; and (d) The relationship of CR against W/C for TML-MdLs and TML-MdMs. Liu et al., [90].

sequestration and enhanced structural performance. This research sheds light on the potential of biochar as a valuable tool in mitigating greenhouse gas emissions and promoting sustainability in the construction industry. By harnessing the carbon sequestration potential of biochar, concrete production can play a vital role in combating climate change and advancing towards a more sustainable future.

In the research conducted by Liu et al. [90], the focus was on exploring the carbon sequestration potential of biochar concrete. The study aimed to investigate various technologies and methods to effectively incorporate biochar into building materials, thus enhancing their capacity to capture carbon dioxide. The results revealed that the addition of biochar to concrete significantly increased its ability to sequester carbon. Biochar, being rich in carbon content, possesses a unique ability to capture and store carbon dioxide. The incorporation of biochar into concrete, a sustainable construction material, offers a promising approach to reducing the carbon footprint of the built environment. By using biochar concrete in construction projects, the construction industry can play a vital role in mitigating carbon emissions and advancing environmental sustainability. The study also presented the findings in Fig. 11, where Fig. 11(a) demonstrated that the samples with added biochar (TML-LdMs and TML-MdMs) exhibited higher weight increase (ΔWI) compared to the control samples (CM). Moreover, the samples with higher biochar dosages (TML-LdMs) showed a greater capacity for CO2 capture than those with medium biochar dosages (TML-MdMs). These results indicate that the addition of biochar enhances the CO2 capture ability of building materials and increasing the biochar dosage further improves the capacity to capture carbon dioxide. This research underscores the potential of biochar concrete as a promising approach to mitigating carbon emissions and promoting sustainability in the construction industry.

Recent studies by Yang & Wang [157] and Kua & Tan [76] have showcased the potential of biochar as a game-changer in concrete construction for both enhancing strength and durability and capturing carbon. By incorporating biochar into mortar and utilizing accelerated carbonation curing, Yang &Wang's research demonstrated a significant improvement in compressive strength and durability. Kua and Tan's novel approach using dry and pre-soaked biochar further hones the balance between carbon capture and mechanical properties in cementitious mortar. These findings highlight the dual advantage of biochar, making it a promising tool for creating more sustainable and resilient concrete structures that combat climate change while ensuring structural integrity.

Although the studies conducted on biochar concrete have provided valuable insights, certain limitations must be addressed to ensure its practical applicability. Most of the research conducted thus far has been limited to laboratory-scale experiments and it is essential to conduct field studies to validate the real-world carbon sequestration potential of biochar concrete. Furthermore, the long-term durability and performance of biochar concrete necessitate extensive investigation. This includes assessing its resistance to degradation over time and understanding its impact on the structural properties of the material. Comprehensive studies are required to determine the long-term effectiveness of biochar concrete as a sustainable construction material. While the reviewed studies have highlighted the promising carbon sequestration potential of biochar concrete, more research is needed to fully comprehend its performance under real-world conditions. By addressing these gaps in knowledge, the construction industry can potentially harness the benefits of biochar concrete as a viable and sustainable solution for reducing carbon emissions and combating climate change. By striving for a deeper understanding of biochar concrete's capabilities, the construction sector can take significant strides towards adopting greener and more environmentally-friendly practices.

4.5. *Negative effects of the addition of biochar on the performance of concrete*

The addition of biochar can lead to a reduction in the workability of concrete, making it more challenging to mix and place. Biochar particles can absorb water and may lead to a drier, stiffer mix. Biochar is porous, and excessive incorporation can increase the overall porosity of the concrete. This may result in increased permeability, reducing the concrete's ability to resist the ingress of water and aggressive chemicals. As mentioned earlier, if the incorporation of biochar is excessive, it can negatively impact the compressive strength of concrete. The high porosity and weaker interfaces between biochar and the cementitious matrix may lead to reduced strength.

Biochar may extend the setting time of concrete due to its absorption of water. This can affect construction schedules and may require adjustments to the concrete mix to ensure proper setting and curing. Biochar can darken the colour of concrete. While this may not be a critical issue for structural applications, it could impact the aesthetic appearance of concrete surfaces. Achieving a uniform dispersion of biochar within the concrete mixture can be challenging. Uneven distribution can lead to variations in concrete properties and performance. It is essential to carefully balance the benefits and drawbacks of biochar addition to concrete and conduct thorough testing to optimize the mix for a specific application. Additionally, considering the intended use and environmental conditions (e.g., exposure to harsh weather or chemicals) is crucial in determining whether the addition of biochar is appropriate and how to best mitigate potential negative effects.

4.6. *Applications and case studies*

Biochar concrete has emerged as a promising and versatile material in sustainable construction practices, garnering significant attention in recent studies. Researchers have explored various aspects of biochar production, activation methods and its application in diverse sectors. Sakhiya et al. [120] provided a comprehensive overview of biochar's potential in soil improvement, waste management and carbon sequestration, showcasing its versatility and wide-ranging benefits. In a case study conducted by Golla et al. [44], the structural performance of an exterior beam-column joint was thoroughly examined using biochar impregnated pond ash concrete. The findings revealed substantial improvements in both the strength and durability of the joint, highlighting the remarkable potential of biochar concrete in enhancing the overall performance of concrete structures. These studies collectively demonstrate the promising role of biochar concrete in sustainable construction and open up exciting possibilities for its future applications in the industry.

In their comprehensive review, Bolan et al. [21] delved into the multifunctional applications of biochar, going beyond its well-known role in carbon storage. The study explored the diverse uses of biochar in various sectors, shedding light on its potential in water and soil remediation, agricultural practices and energy production. By showcasing the versatility of biochar, the researchers highlighted its crucial role in promoting sustainable development across different fields, making it a promising candidate for eco-friendly solutions in the face of pressing environmental challenges.

He et al. [59] provided a fascinating case study on the integrated applications of water hyacinth biochar, demonstrating its potential in the circular economy. The research showcased the successful utilisation of water hyacinth biochar in different practical applications, including its efficacy in adsorbing heavy metals and retaining nutrients. By highlighting its role in sustainable resource management, the study emphasized the significance of water hyacinth biochar in mitigating pollution, managing waste and promoting a more circular and environmentally responsible approach to resource utilisation. In their life cycle assessment study, Azzi et al. [11] meticulously evaluated the urban uses of biochar with a specific case study in Uppsala, Sweden. By comprehensively analysing the environmental impact of biochar application in urban settings, the researchers provided valuable insights into the potential benefits of incorporating biochar into urban infrastructure. With a particular focus on carbon sequestration and waste management, the study underscored the importance of considering biochar as a sustainable and eco-friendly solution for urban planning and development.

Khan et al. [71] conducted an insightful SWOT analysis and techno-economic assessment of biochar produced from Saudi agricultural waste as a cement additive. The research meticulously evaluated the mechanical and durability properties of biochar-modified cement composites, revealing its potential as a viable additive for enhancing the performance of concrete. By highlighting the strengths, weaknesses, opportunities and threats associated with this approach, the study provided a comprehensive outlook on the feasibility and implications of incorporating biochar into cement production, paving the way for more sustainable and environmentally conscious construction practices. In a thorough review, Singhal [128] thoroughly explored the potential of biochar as a cost-effective and eco-friendly substitute for binders in concrete. By delving into the feasibility of replacing traditional binders with biochar, the study shed light on the environmental benefits and carbon reduction potential of this approach. With an emphasis on sustainable concrete production, the research showcased biochar as a promising solution for lowering carbon emissions and fostering more sustainable practices in the construction industry.

In summary, the array of studies and case studies reviewed here significantly advances our comprehension of the diverse applications and advantages of biochar concrete in sustainable construction. The research showcased the vast potential of biochar concrete in enhancing structural performance, while also contributing to the reduction of environmental impacts. Additionally, the studies highlighted its role in promoting circular economy principles by effectively utilizing biochar, a renewable resource, in construction materials. Collectively, these findings underscore the promising role of biochar concrete as a pivotal component in sustainable construction practices, offering a greener and more resilient future for the construction industry.

5. Production of biochar-concrete composite

5.1. Incorporation methods

Biochar incorporation methods in concrete play a crucial role in achieving effective dispersion and integration of biochar particles within the concrete matrix. Each method offers unique advantages and considerations based on the desired outcome and the characteristics of biochar and concrete.

1. Dry Mixing: In this approach, biochar is incorporated directly into the dry mix of aggregates and cement. This method ensures the even dispersion of biochar particles throughout the concrete mix [49]. However, to prevent particle agglomeration and achieve optimal dispersion, thorough mixing is required. It is crucial to use suitable mixing equipment and techniques to attain a uniform distribution of biochar within the concrete, ensuring the effectiveness of the biochar-concrete composite.
2. Wet Mixing: Wet mixing is a technique that involves pre-wetting biochar particles before adding them to the concrete mix. This pre-wetting process is crucial as it enhances the compatibility of biochar with the other components of concrete and fosters better bonding between the materials [95]. The wetted biochar is then mixed with other wet ingredients, such as water and cement, to create a homogeneous blend. By incorporating wetted biochar, the dispersion throughout the concrete mix is improved, leading to enhanced overall performance. The pre-wetting of biochar ensures that it is well-saturated with water, allowing for better interaction and adhesion with other concrete components during the mixing process. This thorough integration is vital for achieving a consistent and uniform distribution of biochar within the concrete matrix. Through wet mixing, the biochar particles are better dispersed throughout the concrete, which has a positive impact on the material's mechanical strength, durability and other properties. A more uniform distribution of biochar in the concrete results in a composite material that exhibits improved performance characteristics.
3. Slurry Mixing: Slurry mixing involves the preparation of a biochar-water slurry, which is then added to the concrete mix. The process begins by creating a mix of biochar and water, forming a uniform slurry. This slurry is then combined with other concrete ingredients, such as aggregates and cement, ensuring that the biochar particles are uniformly dispersed throughout the entire mix. The incorporation of the biochar-water slurry facilitates better distribution of biochar within the concrete matrix. This uniform dispersion of biochar enhances the overall properties and performance of the concrete [165]. By ensuring that biochar is evenly distributed, the concrete benefits from improved mechanical strength, durability and other desired characteristics. Slurry mixing is an effective method to optimise the use of biochar in concrete. It allows for a well-distributed and homogenous blending of biochar

particles with the other concrete components. This results in a biochar-concrete composite that exhibits enhanced properties and performance, making it a valuable approach in sustainable construction practices.

4. Surface Coating: Surface coating is a technique that involves applying a thin layer of cementitious materials or polymers onto the surface of biochar particles. This coating process serves to enhance the bonding between the biochar and the surrounding concrete matrix ([97]; Menash et al., 2021). By modifying the surface of the biochar, this method improves its compatibility with other concrete constituents, resulting in a more integrated and cohesive composite. The application of the cementitious or polymer coating creates a stronger interface between the biochar and the surrounding concrete, leading to improved mechanical properties and enhanced durability. The surface modification process helps to ensure that the biochar is effectively incorporated into the concrete mix, contributing to the overall strength and performance of the material. Surface coating is an effective approach to maximize the benefits of biochar in concrete applications. By enhancing the bond between biochar and the concrete matrix, it optimises the utilisation of biochar and its potential contributions to the strength and durability of the concrete. This method plays a significant role in advancing sustainable construction practices and promoting the use of biochar as a valuable additive in concrete mixes.
5. Pelletisation: Pelletisation is a process that involves compressing biochar particles into uniform pellets or granules of specific sizes. This method ensures a consistent and controlled particle size distribution, which facilitates their uniform dispersion within the concrete mix [14]. The creation of well-defined pellets enhances the efficiency of the mixing process, resulting in a more homogenous distribution of biochar in the concrete. By achieving a standardised pellet size, the biochar can be optimally integrated into the concrete mix, leading to improved mechanical properties and overall performance of the biochar concrete. The uniform dispersion of biochar pellets enhances the bonding between biochar and other concrete components, contributing to the strength, durability and structural integrity of the material. Pelletisation is an efficient and effective technique to enhance the utilisation of biochar in concrete applications. It allows for better control of the particle size, ensuring consistent and predictable results. Through this method, biochar can be seamlessly incorporated into the concrete mix, unlocking its full potential and contributing to the sustainable development of construction materials.
6. Pre-activation: Pre-activation is a process that involves treating biochar before its incorporation into concrete. This treatment can take various forms, such as chemical activation or subjecting biochar to high temperatures. The main purpose of pre-activation is to modify the surface properties of biochar, enhancing its reactivity and adsorption capacity [3,124]. Chemical activation can involve the use of specific chemicals that react with the biochar surface, creating more active sites for adsorption and interaction with concrete constituents. High-temperature treatment, on the other hand, can open up the porous structure of biochar, increasing its surface area and making it more receptive to bonding with other materials in the concrete. By pre-activating biochar, its performance and effectiveness as an additive in concrete are significantly improved. The treated biochar exhibits enhanced properties and interactions when incorporated into the concrete mix. This can lead to improved mechanical strength, durability and other desirable characteristics of the resulting biochar concrete. Pre-activation is a valuable technique that optimises the potential of biochar, making it a versatile and valuable sustainable solution in the construction industry.

The method of incorporating biochar into concrete is a critical consideration, influenced by factors such as the intended application, desired properties and the characteristics of both biochar and concrete. Choosing the most appropriate method is essential to ensure uniform dispersion and effective utilisation of biochar in the concrete mix. Proper mixing techniques and suitable equipment play a pivotal role in achieving consistent and high-quality biochar concrete. By selecting the optimal incorporation method, the concrete can fully harness the carbon capture potential and other advantageous properties of biochar, leading to sustainable and environmentally friendly construction practices.

5.2. Selection of biochar

The selection of biochar for use in concrete involves considering various factors to ensure its compatibility with the cementitious matrix and to optimise the desired properties of the resulting biochar concrete. Here are some key considerations when choosing biochar for concrete applications:

1. Feedstock Selection: Selecting the right feedstock for biochar production holds significant importance, as different biomass sources possess distinct chemical compositions and properties. The choice of feedstock should prioritize abundance, easy availability and sustainability. Factors such as moisture content, lignin content and ash content of the chosen biomass can directly impact the properties of the resulting biochar and its compatibility with the concrete matrix. Careful consideration of the feedstock is essential to produce biochar that optimally complements the concrete mix, ensuring enhanced performance and sustainability [21].
2. Production Method: The biochar production method, whether through pyrolysis or gasification, plays a pivotal role in determining its physical and chemical properties. Factors such as temperature, heating rate and residence time during the pyrolysis process significantly influence the biochar's porosity, surface area and chemical composition. In-depth knowledge of the production method and its effects on biochar characteristics is crucial in selecting biochar that aligns with the desired specifications for concrete applications. Being cognizant of these factors ensures the optimal utilisation of biochar in concrete, resulting in enhanced performance and sustainable construction practices [85,84]
3. Particle Size and Distribution: The size and distribution of biochar particles are critical factors that influence the workability and uniformity of the concrete mix. Ensuring the compatibility of biochar particles with the size distribution of aggregates and other cementitious materials is essential for achieving a well-blended mix. Optimal particle size distribution of biochar enhances the

packing density, flowability and mechanical properties of the resulting biochar concrete, contributing to its overall performance and quality [98]. By carefully considering particle size and distribution, engineers and construction professionals can create biochar concrete with improved characteristics and better construction outcomes.

4. Surface Chemistry and Reactivity: The surface chemistry of biochar is a crucial factor that influences its interaction with cementitious materials in biochar concrete. Biochar with a high surface area and a diverse range of functional groups exhibits improved adsorption and binding properties, fostering better compatibility with cement and other components of the concrete [135,39]. The reactivity of biochar is a significant determinant of its impact on the strength and durability of the resulting biochar concrete, making it an essential consideration in selecting the most suitable biochar for specific construction applications. By understanding the surface chemistry of biochar, engineers can optimise its contribution to the overall performance of biochar concrete, ensuring long-lasting and robust construction materials.
5. Carbon Content and Sequestration Potential: The carbon sequestration potential of biochar is a highly valued characteristic, as it directly impacts its ability to reduce greenhouse gas emissions [132,19]. Biochar derived from biomass with high carbon content and low volatile matter can contribute significantly to the carbon-neutral or even carbon-negative properties of biochar concrete. Assessing the carbon content and sequestration potential of biochar is essential in the context of sustainable concrete applications. By understanding and optimising these factors, biochar concrete can play a pivotal role in mitigating climate change and promoting environmentally-friendly construction practices.
6. Compatibility with Cementitious Matrix: Biochar should be compatible with cement and other cementitious materials to ensure proper hydration, setting and long-term durability of the concrete. The chemical and physical properties of biochar should align with the cementitious matrix to avoid any negative effects on the strength, workability, or durability of the biochar concrete. Compatibility testing, such as heat of hydration tests and strength development tests, can help evaluate the interaction between biochar and cementitious materials.
7. Testing and Evaluation: Laboratory testing and evaluation are essential to assess the performance of biochar in concrete comprehensively. A range of tests, including compressive strength, water absorption, porosity analysis and durability assessments such as freeze-thaw resistance and chloride ion penetration, offer valuable insights into the behaviour and suitability of biochar in concrete mixes. These tests help verify the desired properties and performance of biochar concrete, ensuring its effectiveness as a sustainable construction material. Through rigorous testing and analysis, construction professionals can confidently incorporate biochar into concrete and make informed decisions to enhance the overall quality and environmental impact of their projects.

Careful consideration of these factors, combined with thorough testing and evaluation, allows for the optimal selection of biochar for concrete applications. This approach ensures that desired outcomes, such as improved mechanical properties, enhanced sustainability and carbon sequestration potential, are effectively achieved. By making informed choices and leveraging the unique properties of biochar, the construction industry can contribute to more eco-friendly and resilient building practices, reducing environmental impact and promoting a greener future.

5.3. Quality control and testing

Quality control and testing are essential aspects of ensuring the performance and reliability of biochar concrete. Here are some key considerations for quality control and testing in biochar concrete:

1. Raw Material Testing: Before incorporating biochar into concrete, thorough testing of its quality and characteristics is crucial [134,45,58]. This involves analysing parameters like particle size distribution, moisture content, pH, bulk density, elemental composition, surface area and porosity. These tests play a vital role in ensuring that the biochar meets the desired specifications and is well-suited for use in concrete applications. By conducting these assessments, construction professionals can confidently integrate biochar into concrete mixes, harnessing its beneficial properties for sustainable and high-performance construction projects.
2. Mix Design Optimisation: To achieve the desired strength, workability and durability, the mix design of biochar concrete requires careful optimisation. This entails determining the appropriate proportions of cement, water, aggregate and biochar based on the specific project requirements [106,114,22]. Laboratory testing, such as slump tests, compressive strength tests and durability tests, plays a crucial role in achieving mix design optimisation. By conducting these tests and fine-tuning the mix proportions, construction professionals can ensure that the biochar concrete meets the necessary performance criteria and delivers sustainable and resilient structures.
3. Performance Testing: To assess the properties and behaviour of biochar concrete, a range of performance tests should be conducted. These tests encompass compressive strength testing, flexural strength testing, modulus of elasticity testing, water absorption testing, permeability testing and shrinkage testing. Performance testing provides valuable insights into the structural integrity, durability and long-term performance of biochar concrete [128,154]. By thoroughly evaluating its performance through these tests, we can ensure that biochar concrete meets the required standards for sustainable and resilient construction applications.
4. Thermal Properties Testing: Biochar can significantly impact the thermal properties of concrete. Evaluating its heat transfer characteristics can be achieved through thermal conductivity and thermal diffusivity tests [10,32,73]. These tests provide valuable information about the energy efficiency and thermal performance of biochar concrete, making them particularly relevant for applications where excellent insulation properties are desired. By understanding the thermal behaviour of biochar concrete, we can effectively harness its potential to enhance energy efficiency and promote sustainable construction practices.

5. Durability Testing: To ensure the durability of biochar concrete, it is essential to conduct a series of tests evaluating its resistance to environmental factors like freeze-thaw cycles, chemical attack, abrasion and carbonation. Tests such as the chloride ion penetration test, sulphate resistance test and accelerated weathering tests are instrumental in providing valuable insights into the durability performance of biochar concrete [158,55,54]. By subjecting the material to rigorous testing, we can ascertain its ability to withstand harsh conditions and ensure its long-lasting performance in various construction applications.
6. Long-Term Monitoring: Continuous monitoring of biochar concrete over an extended period is crucial to evaluate its long-term behaviour and durability [129,130]. This can be accomplished through either field monitoring or laboratory-based accelerated aging tests. By conducting long-term assessments, we can validate the effectiveness of biochar as a sustainable and durable additive in concrete, ensuring its reliability and performance throughout its service life in real-world construction applications.
7. Quality Assurance/Quality Control (QA/QC) Procedures: Quality assurance and quality control (QA/QC) procedures are essential throughout the production and construction processes of biochar concrete. This involves regular inspection and testing of raw materials to ensure their suitability and consistency [125,144]. Adherence to standardised mixing procedures and proper curing techniques is vital to achieve uniformity in the concrete mix. On-site testing during construction helps verify the quality of the final product and ensures that the biochar concrete meets the desired specifications and performance requirements. Implementing robust QA/QC measures is critical to producing durable and reliable biochar concrete for sustainable construction applications.

Through the rigorous implementation of quality control measures and thorough testing, the quality, performance and durability of biochar concrete can be effectively assessed and ensured. These practices play a crucial role in harnessing the full potential of biochar as a sustainable construction material while upholding the highest standards of safety and reliability. By prioritizing quality control, the construction industry can confidently embrace biochar concrete as a viable and environmentally-friendly solution for building a more sustainable future.

6. Sustainability aspects of biochar-concrete

6.1. Environmental impact

The incorporation of biochar in concrete holds both positive and negative environmental implications. On the positive side, biochar serves as a valuable tool in sequestering CO_2 from the atmosphere, acting as a carbon sink and aiding in the fight against climate change. Moreover, by utilising biochar derived from organic waste materials, such as agricultural residues or forestry by-products, the concrete industry can actively contribute to waste management efforts and reduce the burden on landfills. However, it is essential to prudently manage the environmental impact of both biochar production and its usage. The pyrolysis process employed to create biochar demands energy, potentially leading to carbon emissions that contribute to greenhouse gas levels [99,123,41]. To mitigate such emissions, prioritising the use of renewable energy sources during biochar production becomes paramount. By doing so, the concrete industry can achieve a more sustainable approach and positively influence its environmental footprint. A comprehensive evaluation of the life cycle of biochar, from production to incorporation in concrete, is essential to ensure that its environmental benefits outweigh any potential drawbacks [27,64].

The responsible sourcing of raw materials for biochar production is of utmost importance to uphold environmental integrity. Ensuring that the feedstock used in biochar production comes from sustainable sources is critical to avoid contributing to deforestation or habitat destruction. Adherence to stringent environmental regulations and guidelines is necessary to effectively control emissions during the production process and uphold excellent air quality standards [104,113,38]. By prioritising environmental responsibility in the selection and handling of raw materials, the biochar industry can make a positive impact on sustainable practices and contribute to a greener future.

The integration of biochar into concrete requires rigorous quality control and testing to safeguard the structural integrity and durability of the final product. A range of tests, including compressive strength, water absorption and durability assessments, should be conducted to thoroughly assess the performance of biochar concrete. This ensures that the desired properties of the concrete are maintained even with the incorporation of biochar. Additionally, it is essential to consider the potential impact of biochar concrete on water and soil quality [146,80,81]. Monitoring and characterising leachate from biochar concrete can help identify any potential leaching of contaminants, ensuring that water and soil remain unaffected. Implementing appropriate measures, such as using protective barriers or encapsulating the biochar, can effectively mitigate environmental risks and promote sustainable practices in the concrete industry.

6.2. Life cycle assessment

A Life Cycle Assessment (LCA) of biochar concrete is a comprehensive approach that evaluates the environmental impacts associated with its entire life cycle, from raw material extraction to end-of-life disposal. This assessment provides valuable insights into the environmental performance of biochar concrete and helps identify areas for improvement and optimisation.

The LCA of biochar concrete encompasses various stages, starting with the extraction and processing of raw materials required for concrete production, including aggregates, cement and water. The environmental impacts, such as energy consumption, emissions and resource depletion associated with these processes, are thoroughly evaluated. The LCA also includes an assessment of the production of biochar, encompassing activities like feedstock collection, pyrolysis and activation processes. Factors such as the energy sources utilised, emissions generated and the overall efficiency of the biochar production process are taken into account [69,94]. During the construction phase, the transportation of materials to the construction site, energy consumption during the mixing and casting of concrete and any waste generated are meticulously analysed to gauge their environmental implications. Subsequently, the use phase of biochar concrete involves evaluating its environmental impacts in terms of structural performance, encompassing aspects like durability, energy efficiency and maintenance requirements [145,89]. Moreover, special attention is given to potential leaching of contaminants from the biochar concrete into the surrounding environment to ensure environmental safety.

The end-of-life phase completes the LCA, addressing the potential disposal or recycling options for biochar concrete [105,11]. If the concrete is recycled, the environmental impacts associated with the recycling process are thoroughly examined. On the other hand, if the concrete is disposed of, the implications of landfilling or incineration are assessed in detail. This comprehensive life cycle assessment of biochar concrete provides invaluable insights into its environmental footprint and helps promote sustainable decision-making in construction practices.

The life-cycle greenhouse gas (GHG) emission results for the proposed biochar applications are depicted in Fig. 12, with a functional unit (FU) of 1 tonne of wood-based biochar (WH biochar) as assessed by He et al. [59]. For the augmented concrete application, a life-cycle GHG emission of − 567.8 kg CO_2-eq/FU was observed (Fig. 12a). The avoided concrete production, which included the production of Portland cement (PC) and the use of recycled aggregate, contributed to a reduction of 349.9 kg CO_2-eq/FU. Similar to the agricultural soil application, the WH biochar preparation and the carbon content sequestration contributed 263.5 and − 481.3 kg CO_2-eq/FU, respectively. The life-cycle GHG emission associated with WH biochar preparation is presented in Fig. 12b. These results highlight the potential of biochar applications to mitigate GHG emissions, especially in AC and concrete production scenarios, where significant reductions were observed.

The LCA of biochar concrete comprehensively considers various environmental impact categories, encompassing greenhouse gas emissions, energy consumption, water usage, air pollution and waste generation. This holistic evaluation provides a comprehensive understanding of the environmental performance of biochar concrete in comparison to conventional concrete. The LCA results serve as valuable guidance for decision-making processes and help identify areas where improvements can be made in the production and utilisation of biochar concrete. For instance, if the LCA indicates that a significant portion of the environmental impact is attributed to energy consumption during biochar production, strategies can be developed to optimise energy sources or enhance the efficiency of the production process. Similarly, if transportation emerges as a notable contributor to the environmental impact, steps can be taken to minimise transportation distances or adopt more sustainable transportation methods. Through the diligent conduct of LCA for biochar concrete, stakeholders gain crucial insights that empower them to make informed decisions focused on promoting environmental sustainability and minimising the overall ecological footprint of this innovative construction material. By continually refining and optimising the production and application of biochar concrete based on LCA findings, the construction industry can contribute positively to environmental preservation and sustainable development.

6.3. Carbon footprint reduction

The use of biochar in concrete offers significant potential for reducing carbon footprints associated with construction materials. By incorporating biochar, which is derived from biomass waste through pyrolysis, into concrete mixes, several carbon footprint reduction benefits can be realised.

Firstly, biochar serves as a carbon sink, making it a powerful tool for mitigating climate change [115,117,46]. Instead of allowing biomass waste to decompose and release CO_2 into the atmosphere, converting it into stable and carbon-rich biochar effectively sequesters the carbon within the material. By incorporating biochar into concrete mixes, the construction industry can harness this carbon sequestration potential, offsetting the carbon emissions associated with traditional cement production. Secondly, biochar offers an eco-friendly alternative to cement, a major contributor to greenhouse gas emissions in the construction sector. The production of cement involves the energy-intensive calcination of limestone, leading to significant CO_2 emissions. By partially replacing cement with

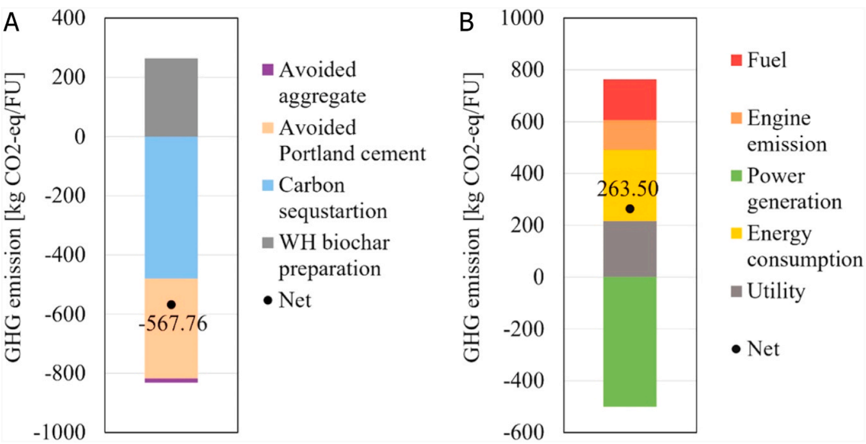

Fig. 12. LCA results of biochar applications: (a) Augmented concrete application (b) WH biochar preparation [59].

biochar in concrete mixes, the carbon footprint of the resulting material is substantially reduced [149,27,36,71]. This eco-friendly substitution can be achieved without compromising the structural integrity and performance of the concrete, providing a sustainable solution for the construction industry.

The sustainable production of biochar, utilising renewable energy sources like biomass-derived heat or solar energy, minimises emissions during pyrolysis ([79,88]; Chen et al., 2021). This eco-conscious approach not only enhances biochar's environmental advantages but also reduces the carbon footprint associated with construction materials. By adopting clean energy practices, the construction industry can contribute to a greener future while benefiting from biochar's potential applications in enhancing material properties, acting as a carbon sink, improving thermal performance, and enhancing water and nutrient retention in construction materials. Such initiatives align with the objectives of sustainability and environmental responsibility.

When assessing the carbon footprint reduction potential of biochar concrete, it is essential to consider the complete life cycle of the material. LCA studies provide a comprehensive analysis of the environmental impacts associated with biochar concrete, taking into account various stages from raw material extraction to production, transportation, use and disposal. Numerous LCA studies have consistently demonstrated that the incorporation of biochar in concrete substantially lowers carbon footprints compared to traditional concrete mixes [141,149]. This scientific evidence reinforces the viability and sustainability of using biochar in concrete applications, making it a promising solution to address climate change and promote eco-friendly construction practices.

In conclusion, incorporating biochar in concrete presents a promising and innovative strategy to reduce the carbon footprint in the construction industry. Through carbon sequestration, cement substitution and the adoption of renewable energy sources in biochar production, this approach plays a significant role in combating climate change and fostering sustainability within the construction sector. By embracing the potential of biochar concrete, we can pave the way for a greener and more environmentally conscious future in construction practices.

6.4. *Economic feasibility*

The economic feasibility of using biochar in concrete is a crucial aspect to consider when evaluating its potential adoption in the construction industry. While biochar offers several environmental benefits, it is essential to assess its economic viability to ensure its practical application. Here are some key points to consider regarding the economic feasibility of using biochar in concrete:

1. Cost of Biochar Production: Biochar production costs depend on several factors, such as the type of biomass, pyrolysis technology, production scale, and energy requirements [25,2]. To ensure competitiveness with other construction materials, cost-effectiveness is crucial. Efficient production processes, economies of scale, and access to affordable biomass sources play a vital role in reducing biochar production costs. Lowering these costs can make biochar a more attractive option for the construction industry, promoting sustainable practices and mitigating the environmental impact of conventional materials. By aligning economic viability with environmental benefits, the adoption of biochar in construction can pave the way for a more sustainable and greener future.
2. Availability and Cost of Biomass Feedstock: The economic viability of biochar production heavily relies on the availability and cost of biomass feedstock. Biomass sources like agricultural residues, forestry waste, or energy crops are key factors determining the feasibility of biochar as a concrete additive [28,48,53]. Utilising low-cost and abundant biomass feedstock is essential for making biochar production cost-effective. The proximity of biomass sources to the production facility is also a critical consideration. Closer proximity can reduce transportation costs and logistics, positively impacting the overall economics of the project. Efficient handling and sourcing of biomass materials can further contribute to cost optimisation and ensure the competitiveness of biochar as a sustainable construction material. By strategically evaluating and managing the availability and cost of biomass feedstock, biochar producers can enhance the economic feasibility of their operations. This, in turn, promotes the wider adoption of biochar in the construction industry, driving forward sustainable and eco-friendly practices in concrete production.
3. Cement Replacement Ratio: The economic feasibility of biochar in concrete is closely tied to the extent of its substitution for cement in the mixes. Greater substitution levels can lead to significant cost savings by reducing cement consumption. However, it is essential to strike a balance between cost reduction and maintaining the desired properties of the concrete, such as strength, durability and workability. Optimising the biochar-cement ratio is a critical step in achieving this balance [103,51,50]. Careful consideration of the concrete's intended application and performance requirements is necessary to determine the most suitable biochar-cement proportion. This ensures that cost-effectiveness is achieved without compromising the structural integrity and functionality of the final concrete product. By finding the optimal biochar-cement mix ratio, construction projects can harness the economic benefits of using biochar while delivering high-quality, sustainable concrete solutions. Such efficient utilisation of biochar in concrete not only supports cost savings but also contributes to eco-friendly construction practices that align with the growing demand for environmentally responsible building materials.
4. Performance and Durability Considerations: Thoroughly evaluating the long-term performance and durability of concrete structures incorporating biochar is of utmost importance. This assessment should encompass an examination of its effects on critical aspects such as strength, shrinkage, creep and other mechanical properties. By doing so, we can accurately gauge the economic feasibility of biochar concrete. It is imperative to ensure that biochar concrete meets or surpasses the required performance standards, offering a comparable or even superior service life when compared to traditional concrete [129,130,17]. Demonstrating its durability and reliability over time is essential for gaining wider acceptance and adoption of biochar concrete in construction practices. By conducting comprehensive evaluations and addressing any potential concerns related to long-term performance, we can confidently promote the economic viability of biochar concrete. This will pave the way for its increased use in sustainable and

cost-effective construction, aligning with the industry's growing demand for eco-friendly solutions that deliver enduring and high-quality results.

5. Market Acceptance and Demand: The economic feasibility of biochar concrete is closely tied to its market acceptance and demand. Evaluating the potential demand from construction companies, developers and infrastructure projects is crucial to understanding the market opportunity for biochar concrete. If there is a substantial demand and willingness among stakeholders to invest in sustainable construction materials, it can significantly enhance the economic viability of biochar concrete. The willingness of the market to pay a premium for eco-friendly and sustainable solutions plays a key role in driving the adoption of biochar concrete. As environmental consciousness grows within the construction industry, there is a rising interest in materials that offer both superior performance and a reduced carbon footprint. Biochar concrete, with its potential for carbon sequestration and environmental benefits, has the opportunity to capitalise on this trend and become a sought-after choice for sustainable construction projects [127,134,91]. Market acceptance and demand can create a positive feedback loop, leading to increased production volumes and economies of scale, further contributing to the economic feasibility of biochar concrete. As more construction projects embrace sustainable practices and the advantages of biochar concrete become apparent, its position in the market will strengthen, making it an attractive and viable option for environmentally conscious stakeholders.
6. Government Policies and Incentives: Government policies, regulations and incentives play a pivotal role in shaping the economic feasibility of biochar concrete. Supportive policies that encourage sustainable construction practices, carbon reduction and the adoption of alternative materials can have a profound impact on the market dynamics for biochar concrete. One of the most influential factors is the presence of incentives and financial support offered by governments. Tax incentives, grants and subsidies that promote the use of eco-friendly construction materials, like biochar concrete, can effectively lower the overall cost of adopting this innovative technology (Lehmann & Joseph, 2012; [27]). Such incentives make it more economically viable for construction companies and developers to embrace biochar concrete, making it a financially attractive option compared to traditional concrete. Additionally, green building certifications and sustainability standards set by regulatory bodies can further drive the demand for biochar concrete. When projects seek to achieve green building certifications, the use of environmentally friendly materials, like biochar concrete, becomes an essential consideration. Meeting these standards not only aligns with sustainability goals but also provides potential access to new markets and clientele who prioritize eco-conscious construction practices. Furthermore, supportive government policies can create a more level playing field for sustainable materials, ensuring that biochar concrete competes fairly with conventional concrete in the market. This can lead to increased adoption rates, further driving down costs through economies of scale and technological advancements.

Overall, The economic feasibility of biochar concrete hinges on several factors: production costs, biomass availability, cement replacement ratio, performance impact, market demand and supportive policies. A thorough cost-benefit analysis is crucial, considering short-term expenses and long-term benefits. Access to affordable biomass feedstock and optimising cement substitution contribute to cost-effectiveness. Meeting performance standards ensures durability. Market acceptance and government incentives also play key roles. By evaluating these factors, stakeholders can determine if biochar concrete is an economically viable and sustainable option for construction, fostering a greener future and reducing carbon footprints.

7. Challenges and future perspectives

7.1. Limitations and challenges

The use of biochar in concrete presents several limitations and challenges that need to be considered. Several studies have explored the potential benefits of incorporating biochar as a supplementary cementitious material in concrete, including improved strength, reduced carbon emissions and enhanced durability. However, certain limitations and challenges should be taken into account:

1. Variability in biochar properties: The wide range of properties in biochar due to different feedstock and pyrolysis conditions presents challenges in establishing standardised guidelines for its use in concrete. These variations can significantly influence its performance and effectiveness, making it essential to carefully assess and tailor biochar for specific concrete applications to achieve optimal results.
2. Compatibility with cement: The incorporation of biochar in concrete has the potential to impact cement hydration, potentially affecting setting time and early strength development. The chemical composition and surface properties of biochar can influence the hydration process, necessitating careful consideration to ensure compatibility with cement and avoid any adverse effects on the concrete's overall performance. It is crucial to conduct thorough testing and evaluation to assess the interaction between biochar and cementitious materials, ensuring that the desired properties of the concrete are maintained and optimised.
3. Influence on workability: The addition of biochar to concrete mixes can influence the workability, posing challenges in achieving the desired consistency. Biochar's high surface area and porous nature may absorb water, resulting in a reduction of the water-cement ratio and potentially affecting the workability and handling properties of fresh concrete. Proper mix design and testing are essential to ensure that biochar inclusion does not compromise the workability and overall performance of the concrete during construction.
4. Lack of standardisation and guidelines: The incorporation of biochar in concrete is an emerging area and standardised testing methods and guidelines are still in the early stages of development. This lack of uniformity makes it difficult to compare findings from various studies and establish definitive recommendations for its application in concrete mixes. As research in this field

progresses, efforts to establish standardised testing protocols will be crucial in providing consistent and reliable data, enabling better understanding and wider adoption of biochar in concrete construction.

5. Long-term performance and durability: The long-term performance and durability of biochar-incorporated concrete remain an area that requires more investigation. Although initial studies have indicated promising results concerning strength and durability properties, a comprehensive understanding of its performance over extended periods is still lacking. Key factors such as carbonation, leaching and degradation need to be thoroughly evaluated to determine the concrete's stability and reliability over time. Continued research and monitoring of biochar concrete's behaviour will be essential in ensuring its viability as a sustainable construction material with lasting benefits. The long-term performance and durability of biochar in concrete for bacterial self-healing, as evidenced by the research of Gupta et al. [52], has shown remarkable promise. In their study, the integration of bacteria immobilization within biochar not only enables self-healing but also contributes to carbon sequestration in cement mortar. This dual functionality enhances the material's sustainability and long-term resilience. The study by Kua et al. [77] further emphasises biochar's potential by incorporating superabsorbent polymers, enabling self-healing in fibre-reinforced concrete even after enduring multiple damage cycles. These findings collectively underscore the capacity of biochar to significantly improve concrete durability over time, reducing maintenance costs and extending the lifespan of concrete structures.
6. Cost and availability: The widespread availability and cost-effectiveness of biochar are crucial factors in determining its practical applicability in concrete on a larger scale. The regional variations in biochar availability and cost, as well as the choice of feedstock for production, play pivotal roles in ensuring its viability as a sustainable construction material. By addressing these considerations, the successful integration of biochar into concrete can be fostered, contributing to the reduction of carbon footprints and advancing sustainable construction practices.

To overcome the limitations and challenges associated with biochar in concrete, a concerted effort is needed through continued research, standardised testing methodologies and collaborative endeavours among researchers, industry stakeholders and policymakers. By fostering this collaboration and addressing these hurdles, the promising advantages of biochar in concrete, including environmental sustainability and enhanced performance, can be fully harnessed and realized. This collective effort will pave the way for a greener and more sustainable future in the construction industry.

7.2. Research and development opportunities

The use of biochar in concrete presents promising research and development opportunities to further explore its potential benefits and address the existing limitations. Some key areas of focus for future studies include:

1. Optimisation of biochar properties: Additional research is required to comprehensively explore the diverse effects of various feedstock materials, pyrolysis conditions and post-treatment processes on biochar properties. This entails delving into factors such as particle size, surface area, chemical composition and surface modification techniques to understand their influence on biochar's behaviour within concrete. By fine-tuning these properties, researchers can bolster the compatibility, workability and long-term durability of biochar-concrete composites, thereby maximising their potential as a sustainable construction material.
2. Performance characterisation: In-depth research is essential to thoroughly evaluate the mechanical properties, durability and long-term performance of biochar-concrete composites. This necessitates conducting standardised tests to gauge compressive strength, flexural strength, tensile strength and resistance to degradation mechanisms like freeze-thaw cycles, chemical attacks and abrasion. Furthermore, assessing the carbon sequestration potential and conducting life cycle assessments of biochar-concrete mixes will provide valuable insights into their environmental benefits. By gathering such comprehensive data, we can confidently understand and harness the advantages of biochar-concrete composites in sustainable construction practices.
3. Admixture compatibility and optimisation: Conducting research on the interaction between biochar and various types of cementitious materials, admixtures and supplementary cementitious materials is of utmost importance. By comprehending the impact of biochar on the hydration kinetics, setting time and early-age strength development of concrete, we can formulate suitable admixture combinations and fine-tune the mix design to achieve superior performance. This investigation is pivotal in harnessing the full potential of biochar as a beneficial additive in concrete applications, promoting its effective utilisation for sustainable and high-performing construction practices.
4. Standardisation and guidelines: Creating uniform testing methods, guidelines and specifications for integrating biochar into concrete is vital to promote its widespread use. This initiative encompasses establishing consistent protocols for material characterisation, mix proportioning and performance evaluation. Standardisation efforts will enhance information exchange, encourage quality control and serve as a foundation for regulatory frameworks pertaining to biochar-concrete applications. By achieving standardisation, the construction industry can confidently embrace biochar concrete, ensuring its seamless integration into sustainable construction practices.
5. Durability under specific environmental conditions: Conducting research on the behaviour of biochar-concrete composites under specific environmental conditions, such as high temperatures, aggressive chemical environments, or extreme weather conditions, can offer valuable insights into their applicability for various purposes. This involves studying their resistance to critical factors like alkali-silica reaction (ASR), sulphate attack, chloride ingress and carbonation. Understanding how biochar-concrete performs in these challenging scenarios can inform its suitability for diverse construction applications and ensure the material's reliability and durability in real-world conditions.

6. Cost-effectiveness and scalability: Research efforts should prioritize the development of cost-effective and scalable methods for biochar production, with careful consideration of feedstock availability and sustainability. Exploring innovative production techniques, such as integrating biochar production with other industrial processes or utilising agricultural and forestry residues, can offer opportunities for cost reduction and promote a circular economy approach. By optimising the biochar production process, we can enhance the economic viability of biochar as a sustainable construction material while minimising its environmental impact.

Collaboration between researchers, industry partners and policymakers are essential to address these research and development opportunities. By conducting comprehensive studies, sharing knowledge and fostering innovation, the use of biochar in concrete can be further optimised, leading to more sustainable and environmentally friendly construction practices. Working together, we can unlock the full potential of biochar as a valuable construction material, contributing to a greener and more sustainable future for the construction industry.

8. Concluding remarks

In conclusion, the use of biochar in concrete presents a promising avenue for sustainable construction practices. Biochar, as a carbon-rich material derived from biomass, offers several potential benefits such as reduced environmental impact, improved material properties and the opportunity to contribute to the circular economy. Throughout this discussion, we have explored the limitations, challenges, research and development opportunities, as well as future trends associated with the use of biochar in concrete.

While there are still challenges to overcome, such as standardisation, cost-effectiveness and scalability, research and development efforts are actively addressing these issues. The ongoing advancements in understanding the mechanisms, customisation of biochar formulations, synergistic use with other materials and real-world implementation are paving the way for the wider adoption of biochar in concrete. Moreover, the use of biochar aligns with the growing demand for sustainable construction practices and the reduction of carbon emissions. By utilising biochar, the construction industry can make significant strides in reducing its environmental footprint and moving towards a more sustainable future.

It is crucial for researchers, industry stakeholders and policymakers to collaborate and continue their efforts in further exploring the potential of biochar in concrete. This includes conducting rigorous studies, promoting knowledge sharing and establishing guidelines and standards to ensure the quality and performance of biochar-concrete composites. Ultimately, the use of biochar in concrete holds great promise for transforming the construction industry towards a more sustainable and environmentally friendly direction. By harnessing the benefits of biochar, we can contribute to the creation of durable, high-performance concrete structures while mitigating the environmental impacts associated with traditional construction materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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