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# Impact of biochar on strength, durability, and carbon sequestration in cement based materials

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## Abstract

This study investigates the influence of biochar, derived from biomass waste through pyrolysis, on the performance of cementitious composites. Biochar was incorporated as a partial replacement for cement in varying proportions up to 5wt% to evaluate its effects on mechanical properties, durability, and microstructure. Experimental results demonstrated that the inclusion of biochar improved compressive, tensile, and flexural strength, primarily due to enhanced hydration, refined pore structure, and better interfacial bonding. Durability was also improved, as evidenced by reduced water absorption and shrinkage. These findings highlight the potential of biochar as a sustainable supplementary cementitious material that contributes to reducing the carbon footprint of concrete. While a brief bibliometric overview is included to contextualize global research interest in this area, the primary focus of this paper is on the experimental validation of biochar's material benefits in advancing sustainable construction practices.

**Keywords** Biochar, Carbon sequence, Construction materials, Pyrolysis, Climate change mitigation, Biochar concrete

## 1 Introduction

The current rise in global temperatures is a definitive indication of climate change like it shows something that clearly proves the Earth's climate is changing, like rising temperatures, melting glaciers, or more extreme weather, with carbon dioxide emissions playing a significant role in this occurrence. The construction sector, driven by rising population demands and the necessity for improved infrastructure, is anticipated to contribute to a further increase in greenhouse gas emissions [1–3]. The swift rise in CO<sub>2</sub> emissions is approaching a crucial limit, potentially resulting in irreversible impacts on the climate. The entire construction process, starting from the extraction of raw materials to the production of Cement, plays a crucial role in the emission of greenhouse gases, with ordinary Portland cement (OPC) being a major factor [4–8]. The production of Cement contributes significantly to global CO<sub>2</sub> emissions, mainly as a result of fuel combustion and the chemical processes involved in its creation. Typically, the creation of 1000 kg of



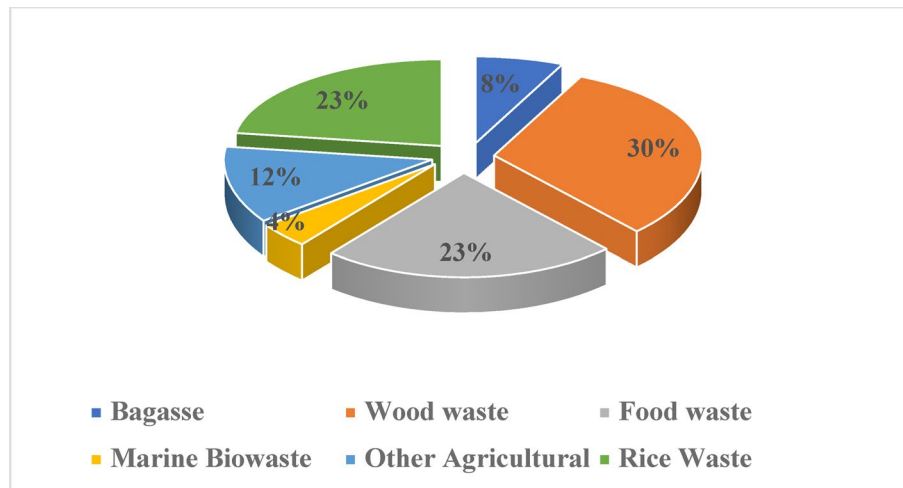
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OPC results in the emission of around 900 kg of CO<sub>2</sub>, intensifying environmental issues like global warming and the depletion of the ozone layer [9–11].

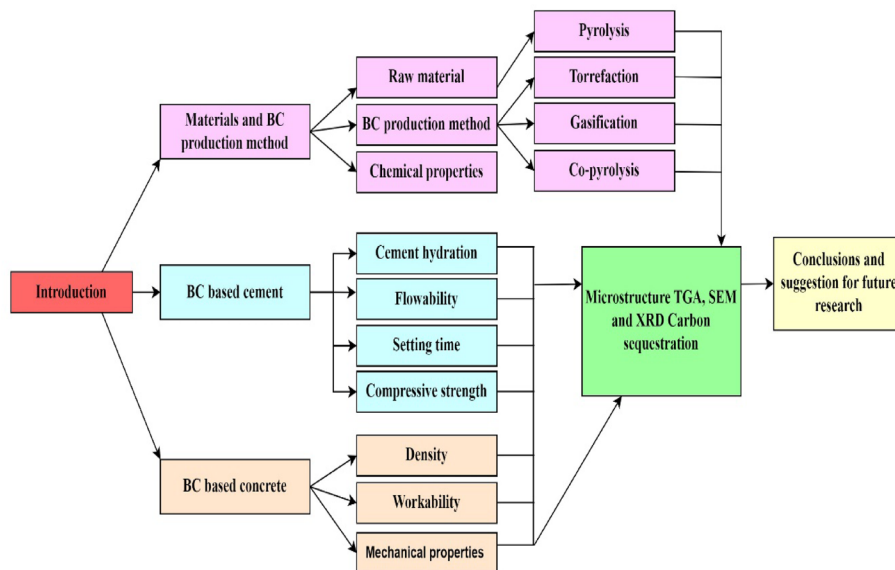
On other hand, A combination of the increase in the global population, there is an anticipated escalation in CO<sub>2</sub> emissions, highlighting the need to investigate alternative construction materials that offer lower carbon footprints [12–15]. Studies emphasise the possibility of integrating recycled materials and industrial by-products into Cement to improve its sustainability. Initiatives aimed at lessening the environmental footprint of the cement sector are progressively centred on embracing sustainable materials and decreasing dependence on conventional OPC. In this context, the incorporation of biochar in construction has surfaced as a compelling approach to diminish carbon emissions and aid in the pursuit of carbon neutrality within the sector [13, 16–19]. The impact of climate change linked to the use of natural materials highlights evident indicators that the incorporation of substances such as cement, sand, gravel, and limestone in construction is detrimental to the environment. This occurs due to their production and extraction processes, which result in elevated CO<sub>2</sub> emissions, depletion of resources, and harm to ecosystems, all of which play a role in global warming and climate change.

Comparative analysis between studies has been added to highlight variations in performance based on biochar type, dosage, and production method. For instance, several studies reported optimal mechanical performance at 1–5 wt% biochar replacement, while higher proportions tend to compromise workability and increase porosity [20]. In terms of durability, biochar was found to significantly reduce water absorption and shrinkage under specific conditions. Moreover, biochar's potential in carbon sequestration was discussed, emphasizing its role in climate change mitigation through CO<sub>2</sub> entrapment and waste valorization. Research gaps have also been identified, particularly the need for long-term durability studies, microstructural interaction analysis, and the synergistic use of biochar with other supplementary cementitious materials. To enhance clarity and accessibility, we have included relevant tables summarizing the physical and chemical properties of biochar, as well as keyword co-occurrence data. Additionally, figures depicting trends in strength, durability, and global research activities provide visual support for the discussed themes. Overall, these improvements offer a more structured, critical, and informative review of the existing literature, aligning well with the study's objectives [21].

Figure 1 shows biochar from various sources the ability of soil to handle heightened stress can create environmental issues, resulting in an increase in waste biomass production. Conventional approaches to waste management, including incineration, land-filling, and field dumping, lead to harm to the environment [22, 23]. Comprehensive analyses have been conducted to identify strategies that can effectively minimize the carbon footprint associated with these processes. A promising approach entails substituting Cement in concrete with alternative materials derived from industrial waste or recycling processes, which not only reduces environmental waste but also improves the use of available resources [24, 25]. Biochar, derived from waste biomass, has surfaced as an economical approach for capturing CO<sub>2</sub>. The use of this material in construction, especially as a partial replacement for Portland cement, has shown remarkable effectiveness. Recent investigations highlight the promise of biochar as a sustainable additive, responding to the demand for more eco-friendly construction materials [26, 27]. Biochar's capacity to sequester atmospheric CO<sub>2</sub> makes it a promising and sustainable



**Fig. 1** Biomass categories used as supplementary cementitious materials



**Fig. 2** Process of BC

adsorbent for use in cementitious applications. Generated via oxygen-restricted thermo-chemical methods such as pyrolysis, biochar effectively transforms organic waste into a useful construction resource. The cost-effectiveness, financial advantages, and eco-friendly production techniques have attracted considerable attention in the construction sector, establishing biochar as an essential component in minimising the industry's ecological footprint [27–29] (Fig. 2).

## 2 Methodology

Innovative methods in the production of biochar-based fertilisers emphasise the integration of nutrient-dense materials into the biochar. A prevalent method, direct treatment, utilises nutrient-rich feedstock to create biochar fertilisers, capitalising on the natural minerals present in the feedstock while reducing the need for extra processing steps. This approach involves combining the feedstock with nutrient-dense materials during

the pre-treatment phase. When this mixture undergoes pyrolysis—a thermal decomposition process that occurs without oxygen the nutrients become incorporated into the biochar structure. This guarantees that the nutrients are completely integrated within the biochar throughout its creation.

Alternatively, post-treatment methods incorporate nutrients into the biochar following pyrolysis, providing enhanced adaptability in modifying the nutrient composition. This approach entails combining nutrient-rich substances with the biochar after its creation, and in certain instances, a subsequent pyrolysis cycle is employed to further enhance nutrient incorporation and improve the characteristics of the biochar. The various processes, occurring at different stages of pyrolysis, provide adaptable methods for producing biochar-based fertilisers that are rich in nutrients.

This study adopts a systematic methodology to evaluate biochar’s role in cementitious materials, focusing on its effects on mechanical strength, durability, and microstructural properties. Biochar is incorporated as a partial cement replacement in varying proportions, and its impact is assessed through compressive strength, water absorption, and thermal performance tests. Advanced analytical techniques, including SEM and XRD, are used to examine microstructural modifications and hydration behaviour. The findings contribute to optimizing biochar-enhanced concrete for sustainable and high-performance construction applications (Fig. 3).

### 3 Discussion

#### 3.1 Quantity analysis

Biochar is currently generating a lot of interest. This study explores the global research that has been performed on the subjects of “biochar concrete” and “biochar cement.” The analysis considers the author’s location and the year of publication. The data is obtained from ScienceDirect. Multiple studies have been carried out to confirm the possible application of biochar in the production of carbon-negative or zero-carbon concrete. The results showed a significant improvement in the cement hydration of the

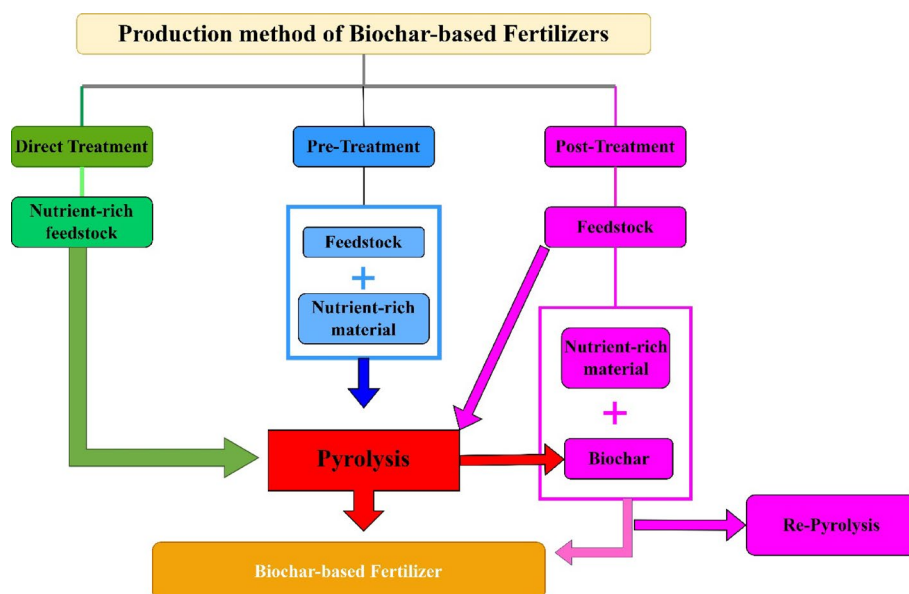


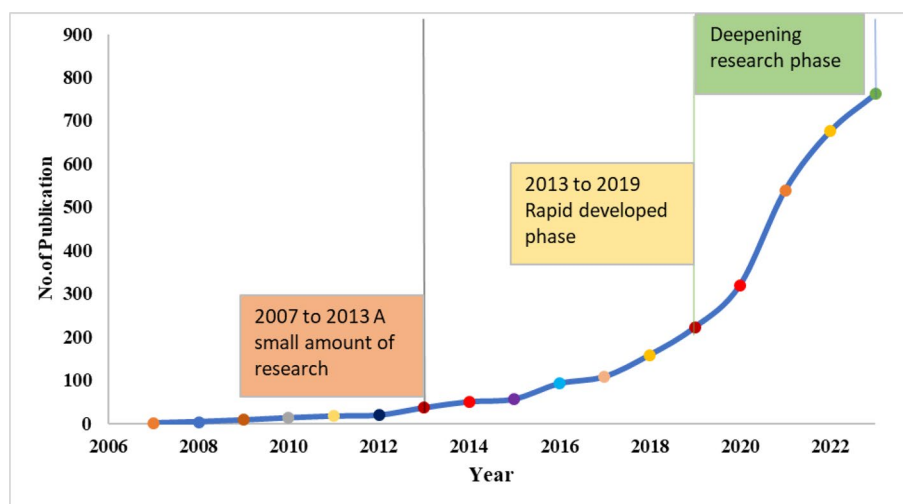
Fig. 3 Methodology

cementitious composites. Furthermore, experts have noted that the cementitious product's inner structure can become denser and its compressive strength can improve as the water absorbed by the biochar is gradually utilized for curing. Introducing biochar into concrete has the potential to improve its capacity to sequester carbon. The graph illustrates the trend in the publication of articles on the subject of "Biochar in cement" over the period from 2006 to 2023. The data is visually represented by a blue line and nodes. It's evident that the investigation of a particular topic has undergone significant expansion over time. From 2007 to 2013, there was a steady rise in the number of publications, with an average of approximately 36 papers being published per year and less than one hundred papers in total each year. Nevertheless, there was a notable rise in the quantity of publications and a sudden upswing in research activity beginning in 2013. Beginning in 2014, there was a clear uptick in the embrace of environmentally conscious practices and a stronger focus on constructing buildings in a sustainable manner and repurposing waste materials found in the surroundings. The increasing trajectory of this data clearly demonstrates a heightened dedication to environmental awareness (Fig. 4).

By 2023, a significant number of publications had emerged, with a particular emphasis on cement-related studies. Highlighting the difficulties of recycling and the importance of cement materials in construction. It is evident that due to advancements in recycling technologies and the implementation of stricter regulations to promote sustainability in the construction sector, there is a growing awareness among individuals about the benefits of recycling natural waste for both the economy and the environment. There has been a noticeable shift in the building industry towards recognizing and valuing sustainable techniques, as demonstrated by the significant rise in publications on the subject.

### 3.1.1 Literature

Recent studies have shown that incorporating biochar into cementitious materials can significantly improve mechanical properties when used at optimal dosages [30]. For instance, Gupta et al. [30] and Gupta and Kua [49] demonstrated that partial cement replacement with biochar (1–5 wt%) enhances compressive and flexural strength due to internal curing, refined pore structure, and improved hydration. Biochar's porous morphology acts as a filler and promotes bonding at the interfacial transition zone, leading



**Fig. 4** Number of papers on Biochar waste recycled materials research in the last 17 years

to higher tensile resistance and reduced micro-cracking. However, excessive biochar content can negatively affect strength by increasing porosity and reducing workability, highlighting the importance of dosage optimization.

In terms of durability and sustainability, biochar has been reported to lower permeability, mitigate drying shrinkage, and improve resistance to aggressive environmental conditions. Researchers such as Murali and Wong [20] and Praneeth et al. [31] observed reduced water absorption and enhanced fire resistance in biochar-modified mortars. From a sustainability perspective, biochar offers substantial environmental advantages by sequestering atmospheric CO<sub>2</sub> and repurposing biomass waste. Life cycle assessments, as discussed by Zaid et al. [27], reveal that biochar-concrete composites can significantly reduce the carbon footprint of construction materials, contributing to the circular economy and climate change mitigation goals.

### 3.2 Properties of biochar for application in concrete

#### 3.2.1 Physical properties

Table 1 shows the biochar is recognised for its unique physical properties, which are significantly affected by the type of feedstock utilised and the specific conditions during its production via pyrolysis. A key feature is its significant porosity, which provides a vast surface area, making biochar an outstanding medium for retaining water and nutrients [32]. This porous structure facilitates microbial activity and aids in the long-term trapping of carbon, contributing to carbon sequestration. Another significant characteristic is its surface area, which can vary from moderate to very high, influenced by the pyrolysis temperature, thereby improving its ability to adsorb pollutants [33, 34]. The thermal stability of biochar ensures its persistence in environmental conditions, rendering it resistant to degradation and suitable for prolonged use across diverse applications.

#### 3.2.2 Chemical properties

Additionally, to its diverse range of chemical properties, biochar is useful for a number of agricultural and environmental applications. Depending on the feedstock and pyrolysis conditions, it contains significant amounts of oxygen, hydrogen, and trace elements in addition to its primary composition of carbon [35–38]. Because of its high carbon content, biochar can function as a carbon sink because it is stable. With an average pH of 6.5–10, biochar's alkaline properties aid in neutralising enhancing nutrient availability [39, 40]. It also retains important nutrients like calcium, magnesium, and potassium, enhancing concrete strength. Furthermore, because of its reactive surface chemistry, biochar can immobilise pollutants and heavy metals, lowering their mobility and bio-availability [41].

**Table 1** Physical properties of biochar

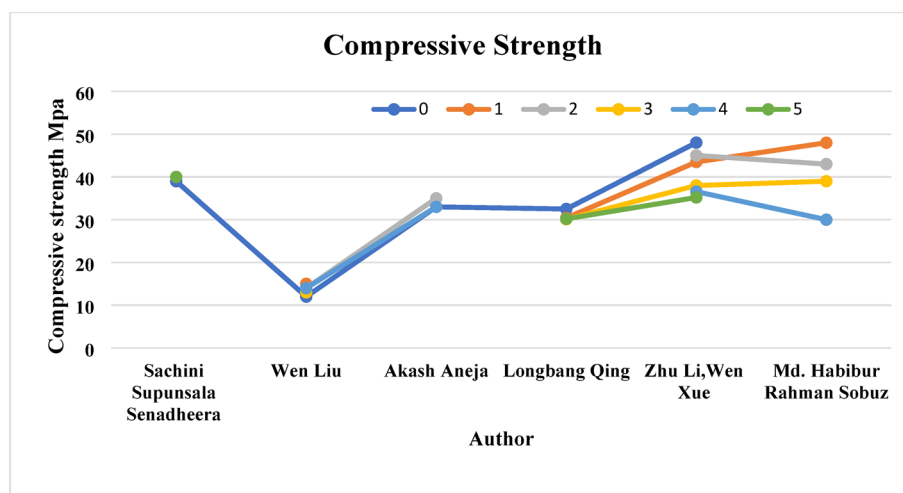
Property	Range	Units	Description
Porosity	40–70%	Percentage (%)	The volume of pore space relative to the total volume
Surface area	200–500 m <sup>2</sup> /g	Square meters/gram	Area available for adsorption and interaction with nutrients
Bulk density	0.2–0.6 g/cm <sup>3</sup>	Grams per cm <sup>3</sup>	The mass per unit volume of biochar
Thermal stability	High	–	Resistance to thermal decomposition under environmental conditions
Water retention	2–6 times its own weight	–	Ability to retain water due to its porous structure

## 4 Hardening properties

### 4.1 Compressive strength

A number of studies have investigated the application of biochar as a partial substitute for Cement in concrete, revealing diverse effects on compressive strength. For instance, Gupta et al. [30] noted that substituting Cement with biochar at lower levels (up to 5%) led to a minor reduction in compressive strength, yet remained within acceptable limits for structural applications [30, 42]. Conversely, Gupta and Kua [49] observed that increasing the biochar replacement percentages (10–15%) resulted in more pronounced reductions in strength, indicating a compromise between ecological advantages and structural integrity [43, 44]. In a similar vein, Restuccia and Ferro [78] noted that although biochar has the potential to improve the durability and sustainability of concrete, an increase in biochar content often resulted in a decrease in compressive strength, underscoring the necessity for optimised replacement levels for effective use. Figure 5 shows the different compressive strengths [20, 45].

Explored the potential of repurposing hardwood materials as biomass and discovered a notable 32.9% increase in strength in pervious biochar concrete by substituting 6.5% of the cement weight. Understanding the unique features of pervious concrete, incorporating finer-particle-size biochar led to a denser biochar-cement matrix [49]. Understand to this improvement, the compressive strength has been boosted and water permeability has been significantly reduced. The concrete mix with a 2% Biochar content as a cement substitute demonstrated the highest compressive strength after 28 days [20, 50]. The researchers conducted an experiment where they substituted a certain percentage of Cement in mortar with biochar derived from switchgrass and hardwood. Through careful investigation, it was discovered that by incorporating biochar as a substitute for 5% of the Cement, a notable enhancement of around 10% in compressive strength was observed after 28 days [51]. Furthermore, the 7-day compressive strength of BC increases by 18, 13, and 10% when 0.50, 1, and 2% of the mass of Cement is replaced with biochar derived from mixed wood sawdust pyrolyzed at 500 °C. According to the study, there were notable increases in strength observed at different levels of biochar replacement after 28 days [20, 52].



**Fig. 5** Compressive strength [46–48]

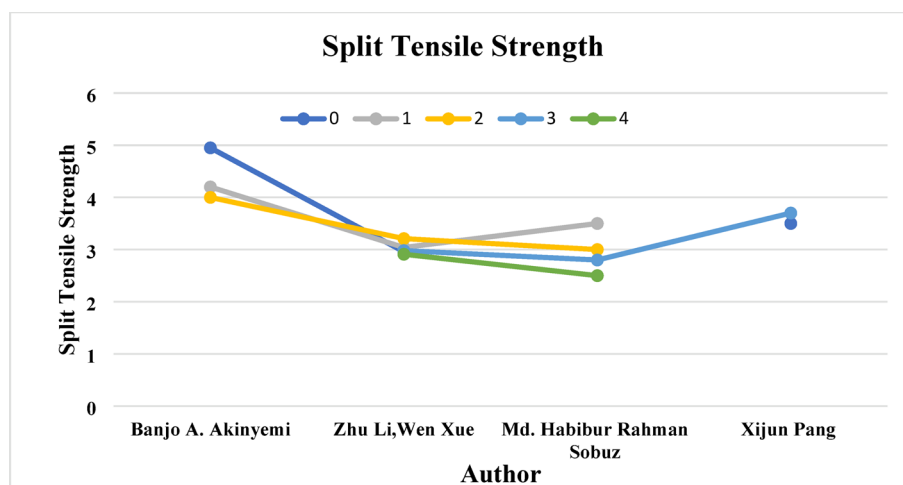
#### 4.2 Split tensile strength

Recent studies have indicated that biochar, a carbon-rich substance derived from the thermal decomposition of biomass, could potentially be used as a substitute for Cement in concrete composites. Figure 6 represented when properly utilized, biochar has the potential to improve the split tensile strength of the composite material [27, 53–56]. Studies have shown that adding biochar in small amounts usually 5–10% of the weight of Cement can enhance the split tensile strength of the material. This is because the fine particles of biochar fill in the gaps, reducing porosity and improving the bonding within the material [57]. In addition, the exterior chemical reactions of biochar can enhance hydration responses which ultimately enhances the strength of the composite material. It is important to carefully fine-tune the content of biochar to avoid any negative effects on strength caused by inadequate dispersion and weak interfacial bonding. In general, biochar-cement materials provide a sustainable option with desirable mechanical properties, such as improved split tensile strength, as long as the amount of biochar is properly regulated [27, 58, 59].

Studies have shown that using biochar derived from wood wastes can significantly improve the split tensile strength of concrete, with optimal results observed at a dosage of 0.5%. In the study of C40 concrete, it was found that the addition of 2% of BC resulted in a significant improvement of 10.6% in the splitting tensile strength [20]. There is a noticeable decline in the tensile strength when more than 2% of BC is used as an alternative for Cement. Discovered that incorporating a 2.5% inclusion of BC derived from wood waste significantly enhanced compressive strength, while further additions of BC had minimal impact on tensile strength when compared to the control group [62]. The replacements for splitting tensile strength demonstrated substantial enhancements of 8.5% and 10.6%, respectively, at percentages of 3% and 2%. The BC 0.50%, BC 1%, and BC 2% mixes experienced a decrease in split-tensile strength under normal conditions at 28 days. The recorded losses were 19%, 11%, and 12% respectively [20, 30, 63].

#### 4.3 Flexural strength

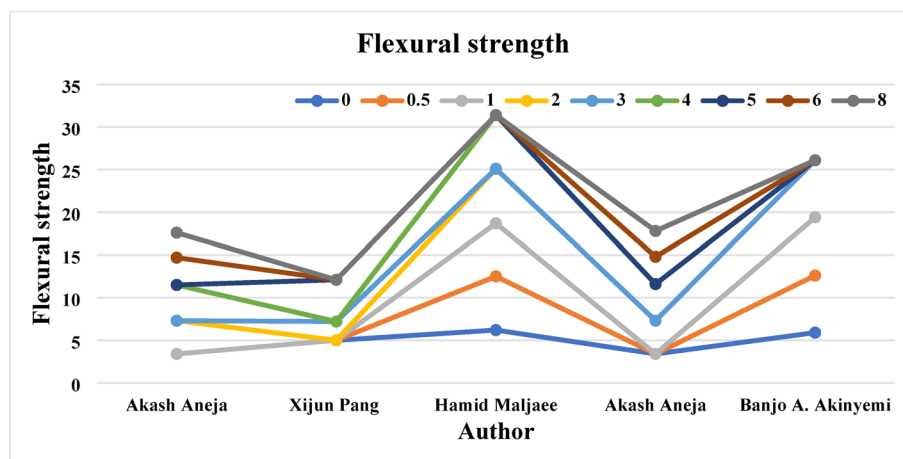
Integrating biochar into cementitious composites can greatly improve the flexural strength of the substrate. Biochar enhances the interfacial bonding within the cement



**Fig. 6** Split tensile strength [60, 61]

matrix due to its large surface area and porosity. Nevertheless, the specific characteristics and amount of biochar play a crucial role when considering how it affects flexural strength. Research has indicated that incorporating a specific amount of biochar, usually between five and ten percent of the Cement's weight, can enhance the flexural strength [51]. Figure 7 shows, larger amounts might lead to a decrease in strength because of greater porosity and lower composite density. Continued investigation and the establishment of uniform assessments are crucial for gaining a comprehensive understanding and maximising the benefits of biochar in cementitious materials, guaranteeing in accordance enhancements in achievement [64].

The results of comparing flexural strength were obtained from various sources in the literature. By substituting the Cement with BC, the flexural strength is enhanced. Recent research found that incorporating hazelnut-derived biochar as a partial replacement for Cement resulted in a significant 30% increase in flexural strength [66]. This improvement was observed in both 7-day and 28-day tests. Noticed a significant decrease in crack propagation in cementitious composites with the addition of 1% biochar (made from peanut shell and hazelnut shell). This resulted in an enhancement of their flexural strength and toughness. When 5% biochar derived from food and rice wastes was added, there was a noticeable decrease in flexural strength. Specifically, the flexural strength was reduced by 14% and 18% respectively. The decrease in compressive strength is likely due to the dilution effect on the Cement and the build-up of biochar particles [46]. The increase in flexural strength seen when biochar is added to the concrete is due to the way the biochar fills the pores, connecting the different components and making the composite more flexible. Previous studies have reported comparable results, suggesting that a significant amount of BC can cause air to become trapped in the solidified concrete [67, 68]. This leads to the creation of empty spaces, ultimately affecting the concrete's ability to withstand bending forces. It was found that the flexural strength showed better results when 1% of the Cement was substituted with BC, compared to other replacement percentages. At 28 days of age, there was a significant increase of 7.34% in flexural strength when 1% was substituted, as compared to the control group. Using a particular feedstock in the biochar processing, it was observed that samples with a 1 wt% cement replacement showed a notable 5% increase in flexural strength [20].



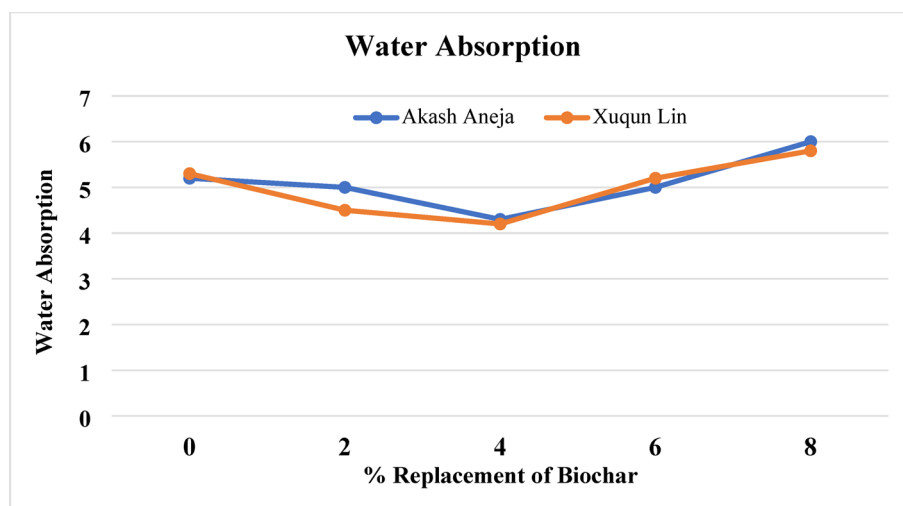
**Fig. 7** Flexural strength [60, 65]

## 5 Durability properties

### 5.1 Water absorption

The presence of biochar as a partial replacement for Cement has an enormous effect on the water absorption properties of the composite material. The natural pores of biochar enhance the overall pores of the cementitious matrix, resulting in higher rates of water absorption. Figure 8 represented the extent of this impact differs depending on the amount of biochar used [69, 70]. Using lower amounts around from five to ten of the Cement's weight may lead to a slight rise in water absorption, while higher amounts can significantly increase pores and the amount of water absorbed. It is crucial to carefully consider the impact of biochar on water absorption in order to preserve its long-lasting qualities and lifespan, while still benefiting from its mechanical property enhancements [71–73].

The mortar mixtures that include wood wastes at 1% and 2% replacement of Portland cement have a WA depth that is significantly lower compared to the control mixture, which only contains Portland cement as the binder. Based on the findings, it was discovered that adding 5 wt% coconut, promotional wood, and Singapore wood biochar to the mix resulted in a decrease in WA by 12–17% compared to the control mix. Interestingly, the different types of biochar exhibited similar WA behaviour. The inclusion of 1 wt% regular biochar and 0.25–2 wt% ground biochar in the mixture resulted in a decrease in WA by 30% and 16–19%, respectively, in comparison with the control mix [75]. The addition of biochar to mortar has been found to significantly decrease water absorption. This is primarily due to the filling effect of biochar, which reduces the passage of water through capillary pores. Additionally, biochar also helps to promote hydration in the mortar [31]. Research findings indicate that incorporating woody biochar as a replacement for 3% fly ash and 20% silica fume can effectively decrease the permeability pore space by approximately 2–3%. By incorporating just 1% of woody biochar, the water absorption of mortar was reduced by a significant 9% [60]. The inclusion of 1–3 wt% wood saw dust biochar greatly enhanced the water resistance, with up to a 35% decrease in water penetration. Additionally, the addition of 5 wt% resulted in a slight reduction in water permeation, by around 5–8% [51]. Using biochar as a substitute for Cement at a weight percentage of up to 5% can result in decreased permeability. Additionally,



**Fig. 8** Water absorption [74]

biochar-cement mortars maintain similar mechanical strength when compared to samples without biochar [31].

## 5.2 Shrinkage

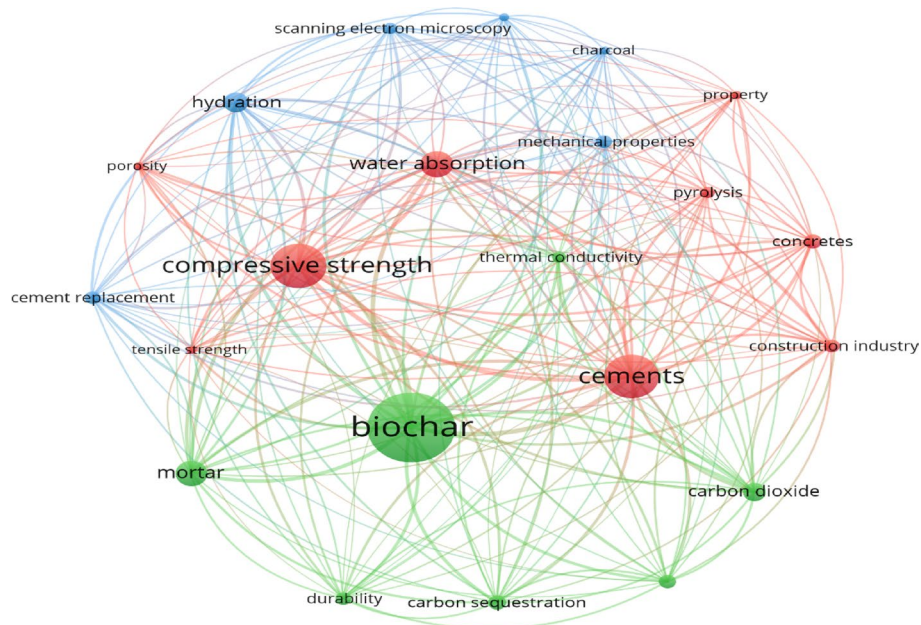
Studying the use of trees as biomass to examine the reduction in size of biochar-cement composites. Through the incorporation of 2 wt% weed tree biochar, scientists observed a 5.5% increase in internal moisture content and a 16.3% decrease in autogenous shrinkage after 180 h of drying [27]. Utilised sawdust biochar as a replacement for Cement at a weight percentage of 2–5% in high-performance concrete applications. Researchers found that there was a significant decrease in shrinkage in biochar mortars when 5 wt% of Cement was substituted. When 1 wt% sawdust biochar was added, there was a slight decrease in drying shrinkage. However, when 2 wt% sawdust biochar was incorporated, drying shrinkage increased [42]. Using a higher dosage of wood waste biochar resulted in consistent findings, with increased drying shrinkage observed at an early age (7 days) and decreased drying shrinkage over a longer period (232 days)[76]. Through experimentation, it was discovered that adding 1% biochar to mortar can decrease its drying shrinkage. However, when the mortar contains 2% biochar, the drying shrinkage is actually higher compared to the control. These findings align with previous studies that have observed an increase in early age drying shrinkage and a decrease in elderly shrinkage when using wood ash [77].

## 6 Keyword analysis

Quantity evaluation has proven to be effective in identifying both present investigation structures and potential future trends. By considering keyword co-occurrence analysis, valuable insights can be gained. Analysing the research involved utilising VOS viewer, an open-source software known for its flexible visualisation capabilities. Figure 9 and Table 2 shows; after examining numerous articles, we found a grand total of 21 keywords. The results of the analysis on co-occurrence are displayed in the illustration. The network is composed of three distinct colours, each representing one of the primary masses identified in the study. When it comes to cement substitutes, hydration, scanning electron microscopy mechanical properties, charcoal, the blue masses are focused on these matters. On the other hand, the red masses prioritise Cement, compressive strength, water absorption, pyrolysis, concretes, construction industry, tensile strength, and porosity. The main areas that the green masses are interested in include biochar, carbon dioxide, carbon sequestration, durability, mortar, and thermal conductivity. The thickness of the line reflects the strength of co-occurrence between masses. Understanding the geographical behaviour of the selected topic is essential as it encompasses extensive research conducted over the past 23 years. The VOS viewer provides a way to visualise the distribution of publications based on their average publication year. The graph still displays the mass size and line width from the previous clarification, indicating the average publishing year for each keyword.

### 6.1 Country analysis

If utilised VOS viewer to evaluate the achievements of every country to the global research belonging. Co-country analysis can provide a quantitative summary of the geographic distribution of the articles. Figure 10 and Table 3 shows, during each time slice,

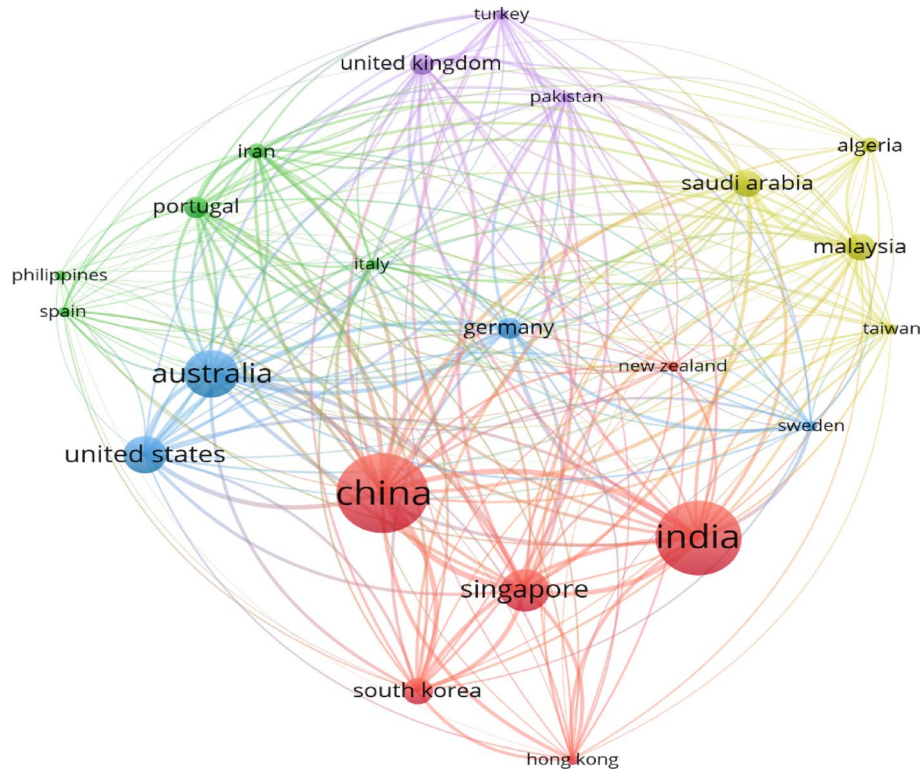


**Fig. 9** Keyword analysis

**Table 2** Keyword data

Label	Occurrences	Avg. pub. year	Avg. citations	Avg. norm. citations
Biochar	65	2021.8923	23.8154	1.153
Carbon dioxide	17	2022.2941	22.2941	1.7146
Carbon sequestration	14	2021.7857	26.2143	1.564
Cement replacement	12	2021.5833	38.4167	1.1968
Cements	41	2021.7073	31.2927	1.3906
Charcoal	8	2021.5	20.375	1.1357
Compressive strength	42	2021.8333	24.7619	1.064
Concretes	14	2021.9286	32.2143	1.234
Construction industry	12	2022.5	22.8333	1.8595
Durability	12	2021.9167	27.3333	1.5121
Environmental impact	8	2021.875	16.625	1.0333
Hydration	19	2021.4737	33.5789	1.5387
Mechanical properties	12	2022.25	26.8333	0.9537
Mortar	24	2021.3333	30.9167	1.2148
Porosity	8	2021.875	27.625	1.2036
Property	8	2022.125	19.375	1.2652
Pyrolysis	11	2022.3636	17.1818	1.4575
Scanning electron microscopy	11	2021.9091	27.3636	1.4193
Sustainable development	13	2022.2308	12	1.3968
Tensile strength	8	2021.625	36.875	0.8771
Thermal conductivity	11	2022.2727	20.0909	1.4007
Water absorption	25	2021.36	36.52	1.2891

a careful selection is made of the top 22 nations. There is a wealth of information available from countries that have conducted research on information technology for biochar waste management. The publications contain data from 22 different countries. The quantity of investigations published by a country is influenced by its size. When it comes to this matter, India, China, and Singapore have made significant achievements that set them apart from other countries. In addition, significant studies have been conducted



**Fig. 10** Country analysis

**Table 3** Country data

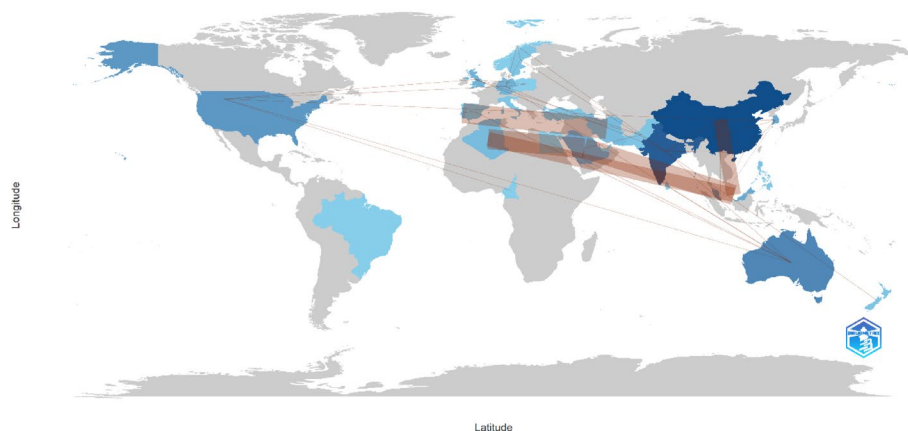
Label	Documents	Citations	Norm. citations	Avg. pub. year	Avg. citations	Avg. norm. citations
Algeria	3	17	3	2023	6	1
Australia	9	173	13	2022	19	1
China	15	276	17	2022	18	1
Germany	4	75	5	2022	19	1
Hong Kong	2	14	2	2022	7	1
India	14	196	12	2022	14	1
Iran	3	128	4	2021	43	1
Italy	2	60	2	2022	30	1
Malaysia	5	30	4	2023	6	1
New Zealand	2	258	3	2020	129	1
Pakistan	2	64	8	2023	32	4
Philippines	2	7	0	2022	4	0
Portugal	4	134	5	2022	34	1
Saudi Arabia	5	25	9	2023	5	2
Singapore	8	480	14	2020	60	2
South Korea	5	82	6	2022	16	1
Spain	2	6	1	2024	3	1
Sweden	2	44	1	2023	22	1
Taiwan	2	18	2	2023	9	1
Turkey	2	59	3	2023	30	1
United Kingdom	4	80	4	2022	20	1
United States	7	114	6	2021	16	1

in the remaining countries in recent times. Consequently, there has been a noticeable rise in ecological consciousness as they acknowledge the importance of waste management in relation to wood and its impact on the ecosystem. The thickness of the link lines reflects the frequency of coordination between countries. Technological innovations have gained significant attention in these countries to handle wood waste. There are five different colour combinations to choose from, each representing a unique nation. For example, the colour orange is associated with countries like India, China, Singapore, South Korea, Hong Kong, and New Zealand. Australia, the United States, Germany, and Sweden all share the colour blue. Green is commonly associated with the countries Philippines, Spain, Portugal, Iran, and Italy. Purple is associated with Turkey, Pakistan, and the United Kingdom. Every individual in this country plays a role in the recycling process, helping to transform waste into new materials that can be used in construction, including biochar for agricultural purposes (Fig. 11).

## 6.2 Trend topics

The trend topics chart offers a thorough overview of the frequency and development of different important terms in the field of building materials research between 2019 and 2023. The terms that have been emphasized are related to various aspects of a specific subject. These terms cover a range of topics such as the properties of materials, their behaviour under certain conditions, and their potential applications. Figure 12 represented by exploring these terms further, one can gain a deeper understanding of the subject at hand. The size of the circles represents the term frequency, with larger circles indicating more frequent usage. Based on the chart, it is clear that “biochar” has attracted a lot of interest, especially in recent years. This is probably because of its potential to benefit the environment and improve material properties. Similarly, there has been a noticeable increase in the importance of “thermal conductivity,” which indicates a rising concern for energy efficiency and thermal management in construction materials. Words such as “carbon,” “compressive strength,” and “cements” have consistently remained relevant, highlighting their crucial significance in materials research. Interestingly, the initial stages of the chart saw a higher usage of “water absorption” and “bio chars,” but these topics have seen a decline in recent mentions. This could suggest a shift in research focus or the maturation of these areas. There has been a consistent

Country Collaboration Map



**Fig. 11** Connection of country collaboration map

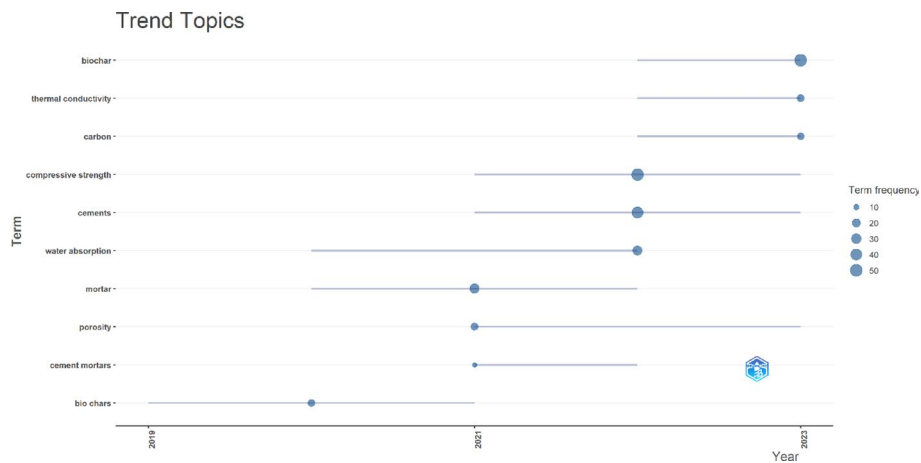


Fig. 12 Trend topic

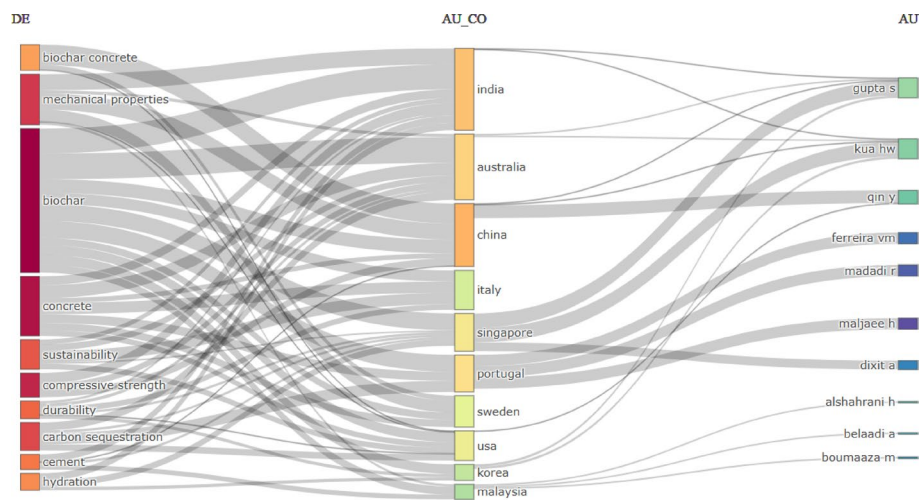


Fig. 13 Three-field plot

focus on studying “mortar,” “porosity,” and “cement mortars,” indicating a continued interest in understanding the fundamental properties and performance of cement-based materials. In general, the chart effectively portrays the ever-changing nature of trends in research, showcasing both new areas of interest and ongoing focus in the field of building materials.

### 6.3 Three-field plot

The three-field plot illustrates the interconnections among countries (AU\_CO), research domains (DE), and authors (AU) in the realm of construction supplies research. Several countries have made significant contributions to the research, including China, India, Sweden, Malaysia, Australia, Singapore, Korea, Italy, the USA, and Portugal. Figure 13 shows, these countries have strong connections to a wide range of research areas. These include studying the properties of materials like biochar and concrete, exploring the mechanical aspects of these materials, investigating their sustainability and carbon sequestration potential, and examining the specific properties of biochar concrete such as compressive strength, durability, hydration, and Cement. Notable authors in these

fields include Surdeep Gupta, Harn Wei Kua, Victor M. Ferreira, Rozita Madai, Yinhong Qin, Ananya Dixit, Kennel Roy, Nhassan Alcalá, Assaad Khaled, and Mess Aouda Boumas. This plot showcases the global cooperation and wide range of research interests within the building materials industry.

## 7 Recommendations

To maximize the benefits of biochar in cementitious composites, the following practical and research-oriented strategies are recommended:

- *Material selection* Choose appropriate biomass feedstocks and optimize pyrolysis conditions to enhance the physical and chemical properties of biochar for cement applications.
- *Replacement ratio* Limit cement replacement levels to 5–10% in structural applications to maintain mechanical integrity, while higher percentages may be explored for non-structural or insulating components.
- *Mix design adjustments* Modify water-to-cement ratios and incorporate plasticizers if needed, as biochar can affect workability due to its porous nature.
- *Standardization* Develop standardized testing procedures for biochar-concrete to ensure reproducibility and quality control in large-scale implementations.
- *Life Cycle Assessment (LCA)* Conduct full LCA studies to evaluate the long-term environmental and economic impacts of using biochar in construction.
- *Future research* Investigate the long-term durability, microstructural interactions, and synergy of biochar with other industrial by-products in cementitious matrices.

## 8 Conclusion

This investigation demonstrates that biochar, when used as a partial cement substitute (1–5 wt%), enhances the mechanical strength, durability, and water resistance of cementitious composites. Microstructural analyses confirmed improved pore structure and hydration behaviour. Moreover, biochar contributes to carbon sequestration, aligning with global sustainability goals. Complementing the experimental findings, a bibliometric analysis revealed increasing global interest in biochar-based cement technologies, with notable research contributions from Asia and Europe. The integrated insights from both experimental and trend analyses affirm biochar's role as a viable, eco-friendly alternative in sustainable construction practices.

The future of biochar in concrete is focused on optimising production techniques and feedstock selection to improve material qualities such as mechanical strength and durability. The study also wants to know how biochar affects the microstructure of concrete, such as porosity and the interfacial transition zone. Furthermore, environmental advantages, notably carbon sequestration and overall sustainability, are important areas of research.

### Author contributions

GUK: Conceptualization, Methodology, Investigation, Formal Analysis, Validation, Writing—Original draft. NG: Conceptualization, Methodology, Investigation, Software, Data curation, Formal analysis, Visualization, Writing—Original draft. DR: Conceptualization, Methodology, Investigation, Software, Data curation, Supervision, Writing—Original draft. GUA: Conceptualization, Methodology, Investigation, Formal Analysis, Validation, Writing—Original draft.

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**Data availability**

The datasets used and/or analyses during the current study are available from the corresponding author on reasonable request.

**Declarations****Ethics approval and consent to participate**

Not applicable.

**Consent for publication**

Not applicable.

**Competing interests**

The authors declare no competing interests.

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