Biochar-Enhanced Carbon-Negative and Sustainable Cement Composites: A Scientometric Review

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Review

Biochar-Enhanced Carbon-Negative and Sustainable Cement Composites: A Scientometric Review

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Abstract: The increasing demand for cement, which is being driven by global urbanization and infrastructure expansion, necessitates sustainable alternatives to be used as construction materials. Cement-based composites, a prevalent construction material, are known for their high carbon footprint. Consequently, exploring sustainable alternatives is urgently needed to curb the environmental impact of the construction sector by capturing carbon dioxide (CO_2). Thus, utilizing biochar (BC) in cement-based composites, either as additive or cement, and in aggregate replacement could be a green approach, by producing enhanced composites with the capabilities of CO_2 sequestration. This review investigates the BC-modified cement composites by performing a scientometric assessment of the Scopus database and a thorough manual review. A scientometric assessment of Scopus-indexed publications retrieved from 2010–2024 was conducted to highlight key research trends, including influential authors, frequently cited works, countries, and institutions. The findings provide a comprehensive overview of the current situation of BC research and applications in cement-based composites for sustainable construction. The assessment revealed that the Construction and Building Materials journal was the most prolific source of publications ($n = 34$), followed by Gupta, with S as the most prolific author ($n = 11$), and China as the leading country in the field ($n = 56$). It also highlights the emerging areas for the use of BC in the construction sector for sequestering CO_2 and potential future directions. Additionally, the review discusses BC sources and BC production technologies and characteristics. It also discusses the influence of BC inclusion on the fresh properties, its mechanical properties, durability characteristics, carbon capture capabilities, and the environmental impacts of modified cement-based composites. It has been noted that BC addition to cement-based composites from 1% to 2% can increase its mechanical performance, whereas, beyond a 5% to 6% replacement, they experienced a decline compared to non-modified composites. BC addition has reduced the flow characteristics of the modified composites due to its porous morphology and hydrophobic nature but has shown improved internal curing and reduced shrinkage. It also improved the microstructure of the cement-based composite through pore refinement, due to the filling ability of the BC particles attributed to its specific surface area and size. Additionally, the carbon sequestration potential of BC can be exploited in cement-based composites to create low carbon or carbon-negative building materials with improved mechanical and durability characteristics. The study also highlights the future directions for further studies and implementation strategies of BC as a sustainable construction material at a large scale.

Keywords: biochar; biochar-based composites; scientometric analysis; mechanical properties; durability; carbon sequestration; sustainability

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1. Overview

Cement composites are the most widely used construction material in the world due to their properties and the ease of their material availability, construction, mouldability and diverse applications [1–8]. Concrete application can be found in almost all types of civil engineering structures [9]. The diverse applications of concrete make it the second most used material in the world after water, and it is top of the list of man-made materials [10]. Cement-based concrete is primarily made up of three constituents, which are water, aggregates and cement [11–14]. Among them, cement is the most expensive and energy-consuming product and has a significant carbon footprint [10,15–17], posing a threat to the environment [18]. Cement, following steel and aluminum, is the third-highest energy intensive construction material in the world [19]. Cement itself contributes around 8% of the total environmental CO_2 emissions [20], whereas the equivalent CO_2 emissions during the production of cement is nearly 80% of the amount that cement produces [21]. Due to the expansion of the construction industry, the annual rate of cement manufacturing is growing at 2.5%, with an increase of 52% from 2005 to 2020 [22], and the expected production rate by 2050 is 3700 to 4400 million tons per year [23]. To counteract the production of greenhouse gas (GHG) emissions, researchers are using waste materials to partially or completely replace cement. Some of the most used materials are fly ash [24], silica fume [25], steel slag [26], foamed slag [27], desulfurized gypsum [28], red mud [29], glass powder [30], marble powder [13], and biomass [31] to produce eco-friendly composites for construction [32–35].

The rise in GHG emissions is linked with the world's population level, linked to which it will rise with the passage of time [36]. Thus, curbing the effects of GHG emissions by only reducing emissions is not a sustainable solution to achieve the targets of mitigating global warming, which means keeping the global temperature rise below 2 °C [37,38]. Climate action is one of the important aspects of the Sustainable Development Goals led by the United Nations [39]. In 2018, the Intergovernmental Panel for Climate Change (IPCC) stated that BC utilization is a carbon negative mechanism that has a minimal level of carbon footprint [40]. This situation has resulted in solutions for carbon capturing and carbon sequestration in the construction sector and given birth to carbon negative cement and concrete composites. The reduced environmental impact of BC, compared to other supplementary cementitious/additive materials, is much more significant, due to its characteristics including carbon capture and storing capabilities, sustainable sourcing and availability, adaptation, and alignment with sustainable construction methodologies.

BC exhibits potential as a cement replacement in cement-based composites, because of its pozzolanic properties [41]. BC could be incorporated into cement-based composites to partially substitute for cement, aggregates, and as a filler material potentially leading to decreased cement and aggregate usage while maintaining or improving certain cement composite characteristics. The utilization of BC in cement-based composites construction is a promising and rapidly evolving field, with several anticipated future developments and applications [42–44]. These include the establishment of regulated pyrolysis conditions to standardize BC production, the development of BC aggregates for lightweight cementitious composites, and the creation of nano-BCs to enhance material performance and reduce cement usage. The potential use of BC for accelerated carbonation in cementitious materials is an emerging area of interest, leveraging its porous nature for CO_2 sequestration. Storing CO_2 in concrete structures to capture carbon is a promising concept [45]. These advancements collectively point towards a future where BC plays a substantial role in improving the sustainability and performance of cement-based construction materials.

2. Purpose and Significance of the Study

Various reviews on the utilization of BC as a construction material have been conducted [46–50] covering the fresh and hardened properties of the cement composites incorporating BC. Some of the authors covered durability, environmental impacts, and economic benefits [51–55]. Various researchers focused on BC types, production methods, types of biomasses, and the capability of BC as a carbon sequester in cementitious composites [56–58]. As of today, reviews on BC use are carried out manually. Manual reviews mostly lack strong links between various aspects of the bibliometric data [59]. It is important to perform a scientometric analysis to examine the scientific visualization and mapping of the key parts of bibliometric data using appropriate software. In particular, keywords, documents, publication sources, authors, and regions are analyzed during the scientometric assessment.

This review employs a scientometric assessment to cover the necessary limitations of normal reviews. Specifically, this involves connecting journals/sources with the prominent publications, investigating the co-occurrence of keywords, authorial collaboration and co-citation, the highly cited papers and authors, and closely connected locations in the research of BC in cement composites, mainly including mortar and concrete. The representations drawn from scientometric analysis offer potential benefits to researchers in diverse geographical regions. It can assist in raising opportunities for joint initiatives and research collaborations and identifying novel concepts and technologies from this scientometric investigation. Moreover, this study evaluates the types of biomasses that produce BC, properties-based BC production methods, and the physiochemical properties of BC from the perspective of its use as a supplementary cementitious material. It also discusses the fresh and mechanical properties, durability, carbon sequestration properties, and environmental impacts of the cement composites produced by incorporating BC into cement-based composites.

3. Scientometric Analysis Methodology

This review study aims to evaluate the quantitative aspects of scholarly literature conducted over two decades on BC-modified cement composites through scientometric analysis. Researchers have been using scientific mapping for scientometric reviews to evaluate the literature, based on various relevant research-oriented statistical data [60]. There are various scientific databases available, of which Scopus and Web of Sciences are termed as more effective based on literature searches [61]. However, Scopus is more updated than Web of Sciences, and has a vast bibliometric range [61–63]. The bibliometric data for the "biochar cement" and "biochar concrete" was retrieved from Scopus on 9th September 2024. Applying the Boolean search command "biochar AND cement OR biochar AND concrete" for the keywords "biochar cement" and "biochar concrete" on the database resulted in 250 documents. Various filters, as shown in Table 1, were applied to filter out the unnecessary documents, and after screening, the number of documents was reduced to 189. The refined search data from the Scopus database was extracted in excel comma delimited (CSV) format for its further assessment in VOSviewer (version 1.6.20). Based on the procedure adopted by many scholars [64–66] the titles and abstracts of the extracted files were further assessed for irrelevant documents; however, there were none to exclude. VOSviewer is an open-source, publicly available tool that has been extensively used for visualization in the literature by various researchers [67–71] and was used for bibliographic data investigation to produce literature-based scientometric maps and statistical analysis of the published data. The CSV files extracted from the Scopus database were retrieved into VOSviewer, without compromising the reliability and integrity of the data. Scientometric assessments were performed on the source of publishing, frequently occurring keywords, the most cited authors, and the contributing countries. The scientometric findings, their connections, and their co-occurrence are illustrated by figures, whereas quantitative values extracted during the analysis are presented in tables. The scientometric investigation methodology employed in this review is provided in Figure 1.

Table 1. Scopus database data mining filters.

Data Type	Filters
Subject area	Engineering Material Science Environmental Science Energy

Table 1. *Cont.*

Data Type	Filters
Document type	Articles Conference papers Review Conference review
Source type	Journal Conference
Language	English

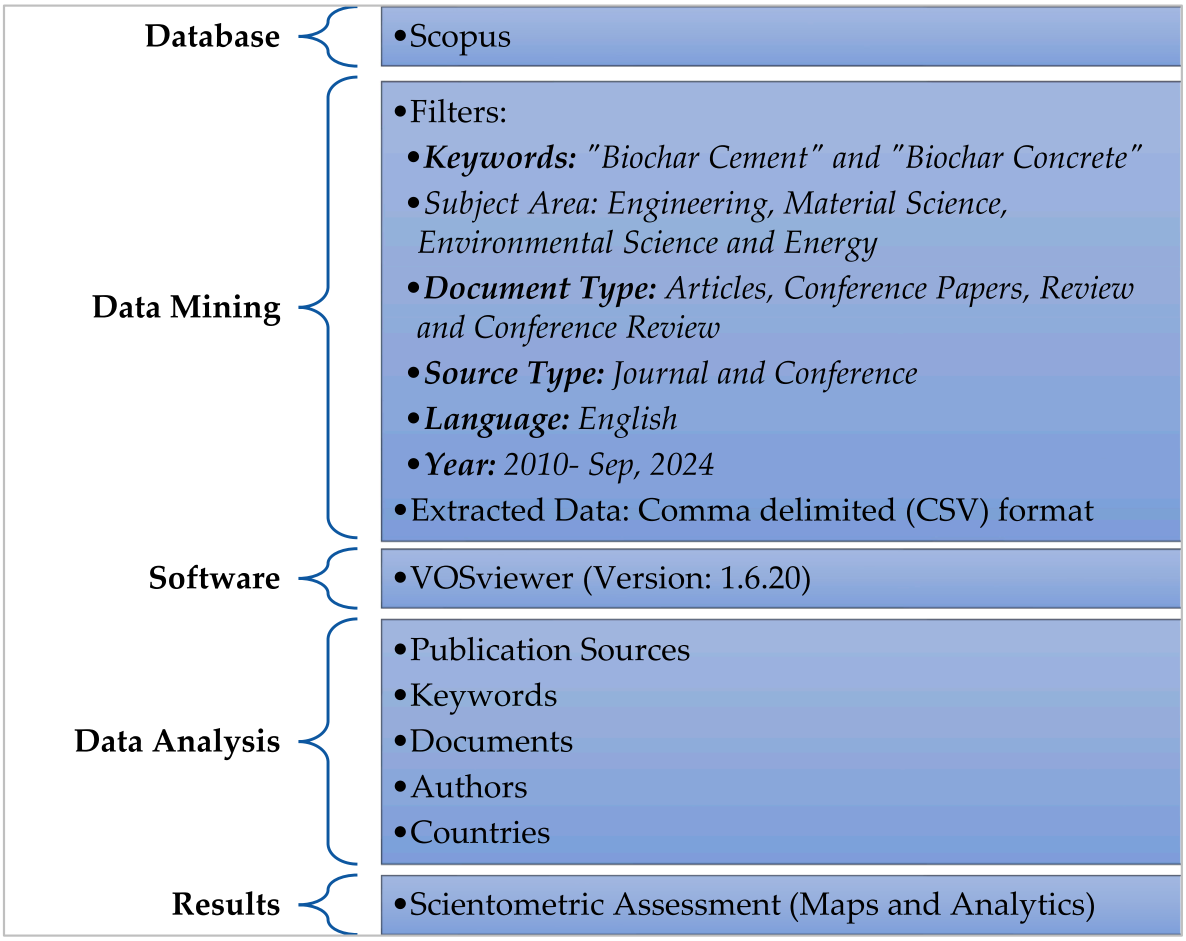

Figure 1. Scientometric analysis methodology flowchart.

4. Scientometric Analysis Results and Discussions

4.1. Subject Areas and Yearly Publication Trend

Data mining for the relevant subject area was performed by Scopus analyzer to collect the most up-to-date and appropriate data. During data mining based on the document's density and relevance to the Boolean search of keywords, Engineering, Material Science, Environmental Science, and Energy were top four source types, contributing 27.1%, 21.7%, 17.7%, and 9.75% of documents, respectively, from 2010 to September 2024, as shown in Figure 2a. These four fields contribute 76.25% of the total volume of documents, whereas each of the other individual sources is below 4%. Figure 2b depicts the contribution of document type, including journal articles (76.2%), reviews (11.9%), conference papers (9.3%), and conference reviews (2.6%). The yearly trend in the subject area is given in Figure 3. It can be seen from the figure that the research trend in this area until 2017 was almost negligible, as only three documents are mapped from 2010 to 2017. However, from 2017 onwards, a uniform increase in this area can be seen, which is fascinating and encouraging, suggesting that researchers are focusing on sustainable and green construction materials.

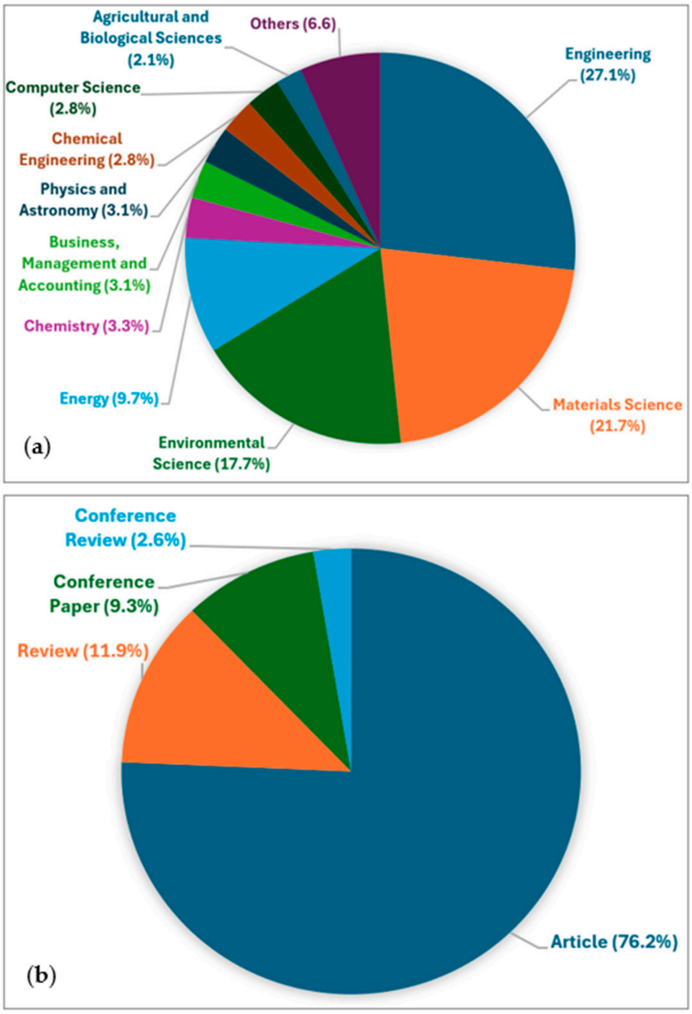

Figure 2. Research contributions based on (**a**) subject areas; (**b**) document type.

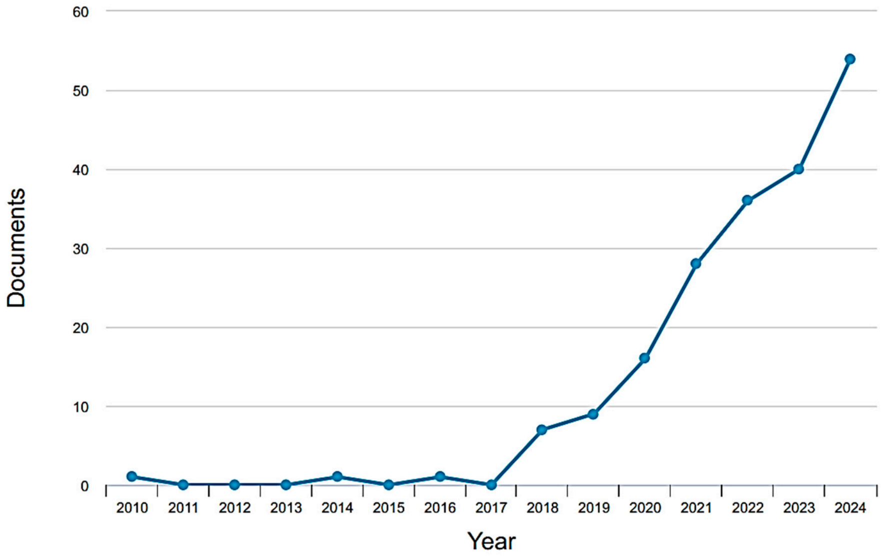

Figure 3. Annual publication trend (Scopus: 2010–2024) of BC cement and concrete.

4.2. Mapping of Related Sources

The mapping of sources facilitates the visualization of innovation and developmental trajectories in any specific field of research. These sources enable access to datasets constrained by unique parameters. The research methodology can be successfully applied within this analytical framework by mapping the research origins. This method enables a systematic exploration of the scientometric data landscape, with the potential to reveal the underlying relationships and trends during the research process' development in the relevant field. VOSviewer software was employed to analyze the bibliometric data extracted from Scopus. Various data analysis parameters and data input parameters used in the VOSviewer assessment are given in Figure 4. In the software input data, "bibliographic coupling" and "sources" were chosen as the "analysis type" and "analysis unit", respectively. The threshold for sources was set at 05, the number of documents against which 8 out of the total 89 sources meet the required criteria. Table 2 summarizes the leading journals/sources with a number of at least five publications on biochar cement and biochar concrete. In addition, it also presents their cumulative citation count and link strength.

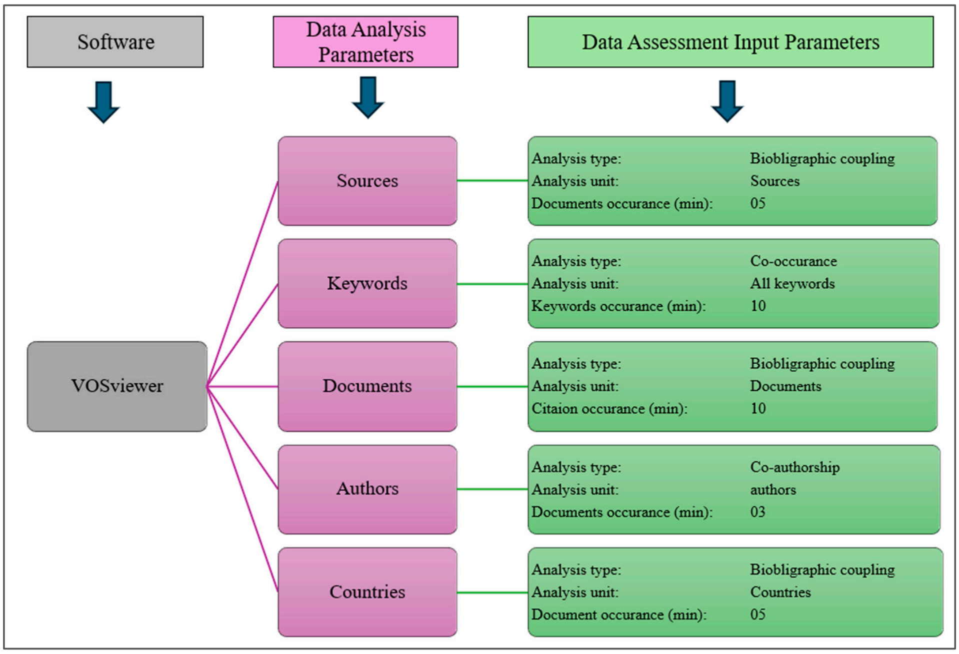

Figure 4. Scopus data assessment steps using VOSviewer.

Table 2. Sources of related published articles.

S/N	Source	Documents/Articles	Citations	Total Link Strength (TLS)
1	Construction and Building Materials (CBM)	34	1054	3191
2	Journal of Cleaner Production (JCP)	13	507	1509
3	Cement and Concrete Composites (CCC)	11	828	1716
4	Sustainability (Switzerland)	7	84	813
5	Case Studies in Construction Materials (CSCM)	6	11	673
6	Biomass Conversion and Biorefinery (BCB)	5	107	199
7	Journal of Building Engineering (JBE)	5	71	709
8	Science of the Total Environment (STE)	5	264	378

CBM, the JCP, and CCC contribute the highest number of publications, with 34, 13, and 11, respectively. Whereas, in cumulative citation count, CBM is at the top, while CCC has more citations than the JCP. The scientometric mapping of the eight sources with at least five published articles is reflected in Figure 5. The node size shows the article count of the source. The CBM node in Figure 5 is notably larger than the other sources, reflecting a greater number of publications and a higher contribution in the field of biochar cement and biochar concrete for sustainable development. The various colors of nodes identified through VOSviewer analysis represent distinct clusters. The red color represents the cluster containing CBM, the JCP, CCC and the JBE, indicating their close link based on relevant research and co-citation. It is important to note that BCB has a higher number of articles and citation count, but the link strength of the JBE is higher than BCB. The clusters are modeled based on the scope or the number of their co-citations [72,73]. Similarly, the weight of the lines/links between sources denotes the strength of their connections. The TLS shows the frequency of a journal being cited in the same article. For example, the TLS of CBM is 3191, and is spaced closely together in the cluster compared to others with a lower TLS. This scientometric-based visualized and analytical information will serve as a foundation for future scientometric reviews and provide in-depth organized research directions for the current field.

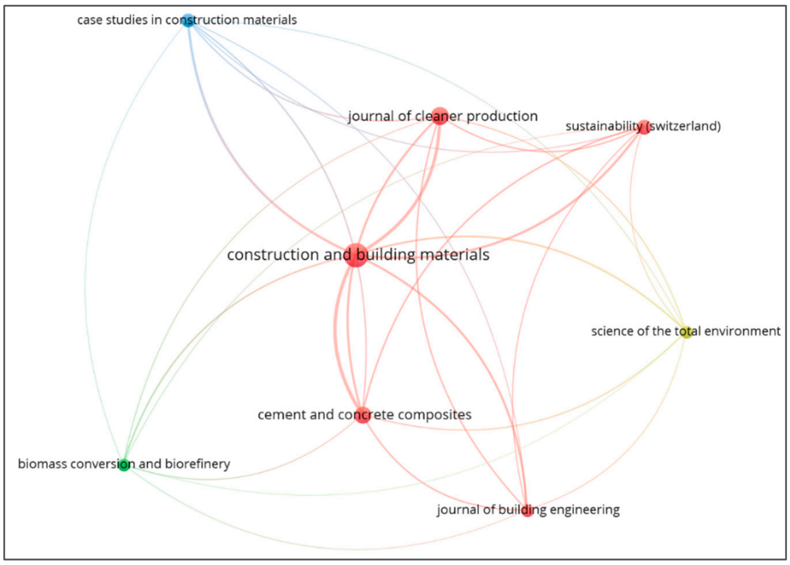

Figure 5. Scientific map of publication sources (a minimum number of five documents).

4.3. Mapping of Keywords Co-Occurrence

Keywords play an important role in identifying and representing the relevance of a research domain as they are the shortest possible explanation of the research area [73]. The input data "co-occurrence" and "all keywords" were chosen as the "analysis type" and "analysis unit", respectively. To identify the most relevant and prominent keywords, the threshold was set at a minimum of 10 numbers, which resulted in 44 out of the total 2081 keywords. Table 3 represents the top 20 most frequently appearing keywords used by the researchers in the field of BC-modified cement composites.

Table 3. Top 20 relevant keywords.

S/N	Keyword	Occurrence	TLS	S/N	Keyword	Occurrences	TLS
1	biochar	156	786	11	bio chars	26	187
2	compressive strength	64	406	12	construction industry	26	205
3	cements	57	413	13	mortar	23	160
4	concrete	46	294	14	hydration	22	167
5	concretes	41	298	15	pyrolysis	22	148
6	carbon dioxide	32	232	16	durability	21	154
7	carbon	30	237	17	charcoal	20	138
8	sustainable development	30	237	18	concrete aggregates	20	115
9	water absorption	28	221	19	mechanical properties	19	126
10	carbon sequestration	27	226	20	curing	18	124

The top five keywords, which are biochar, compressive strength, cements, concrete, and concretes are the most relevant keywords to the Boolean search command used. Similarly, the later keywords are more prominent in sustainable construction practices, including reducing carbon footprints by CO_2 curtailing and sequestration by utilizing BC in cement composites. The scientometric mapping of the keywords is visualized in Figure 6. Figure 6a depicts the co-occurrence visualization; the node size shows the frequency, whereas the co-occurrence is shown by the node location. The visualization depicts that the keyword biochar has a larger node and is directly connected, with strong links, with keywords in all the clusters. These links indicate that BC has been used by researchers to produce sustainable cement composites with the added property of carbon sequestration. There are three network clusters indicating the co-occurrence of keywords across different publications. Notable keywords in the red cluster are biochar, concrete, carbon, pyrolysis, cement, soil, concrete mixtures, etc. Similarly, blue clusters contain compressive strength, biochars, concretes, water absorption, porosity, tensile strength, etc., and the green cluster contains cements, carbon sequestration, durability, construction industry, mortar, shrinkage, cementitious materials, carbon footprint, sustainability, etc. Figure 6b depicts the density visualization of keywords. The color contour density is categorized from red as the highest to blue as the lowest. Figure 6b shows that biochar, cement, concrete, compressive strength, carbon and carbon dioxide, and sustainable development are the higher-density keywords. It is important to note that keywords that are pertinent to durability are the least addressed. This gap paves the way for further investigation and research in the field of BC-based cement composites.

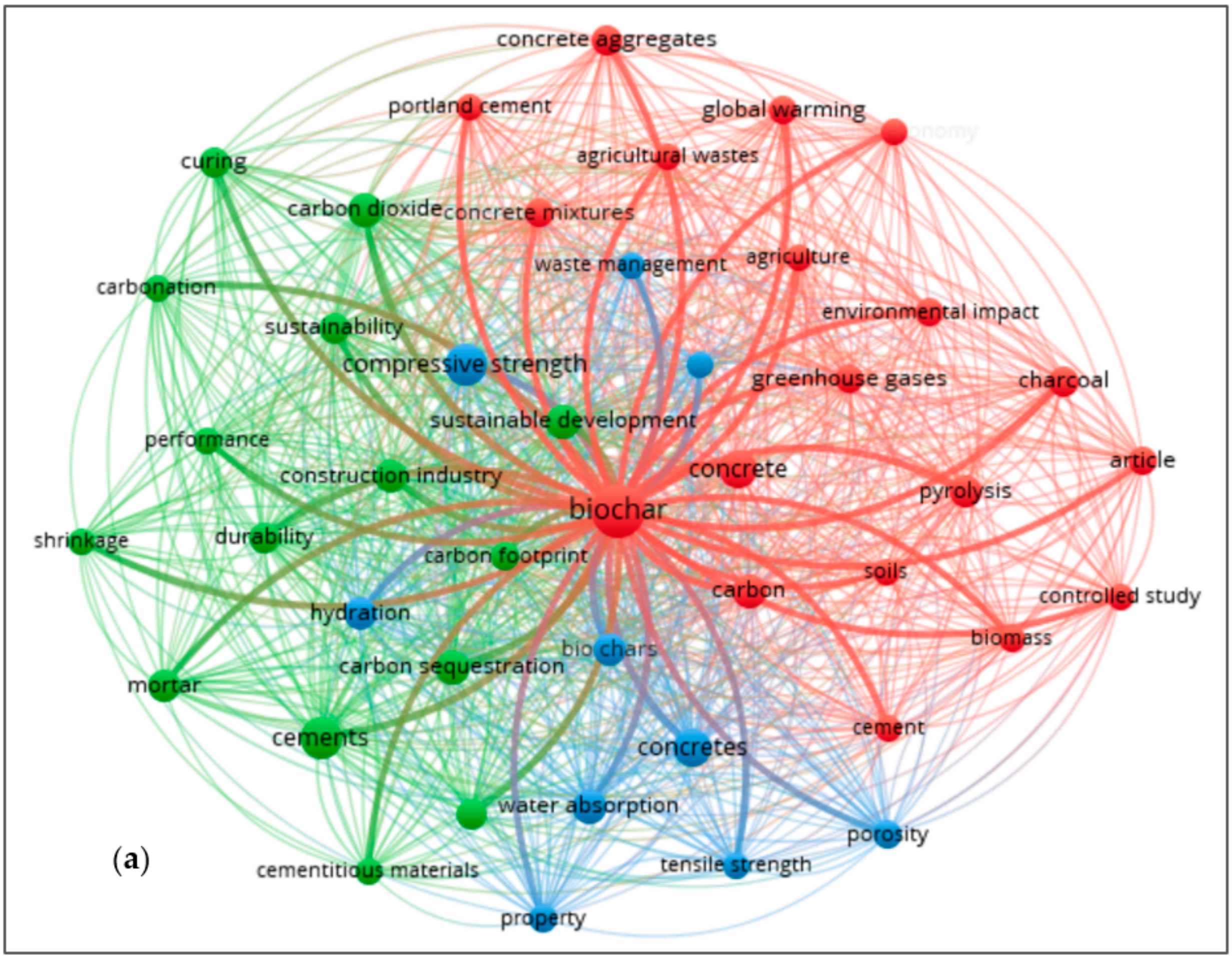

Figure 6. *Cont.*

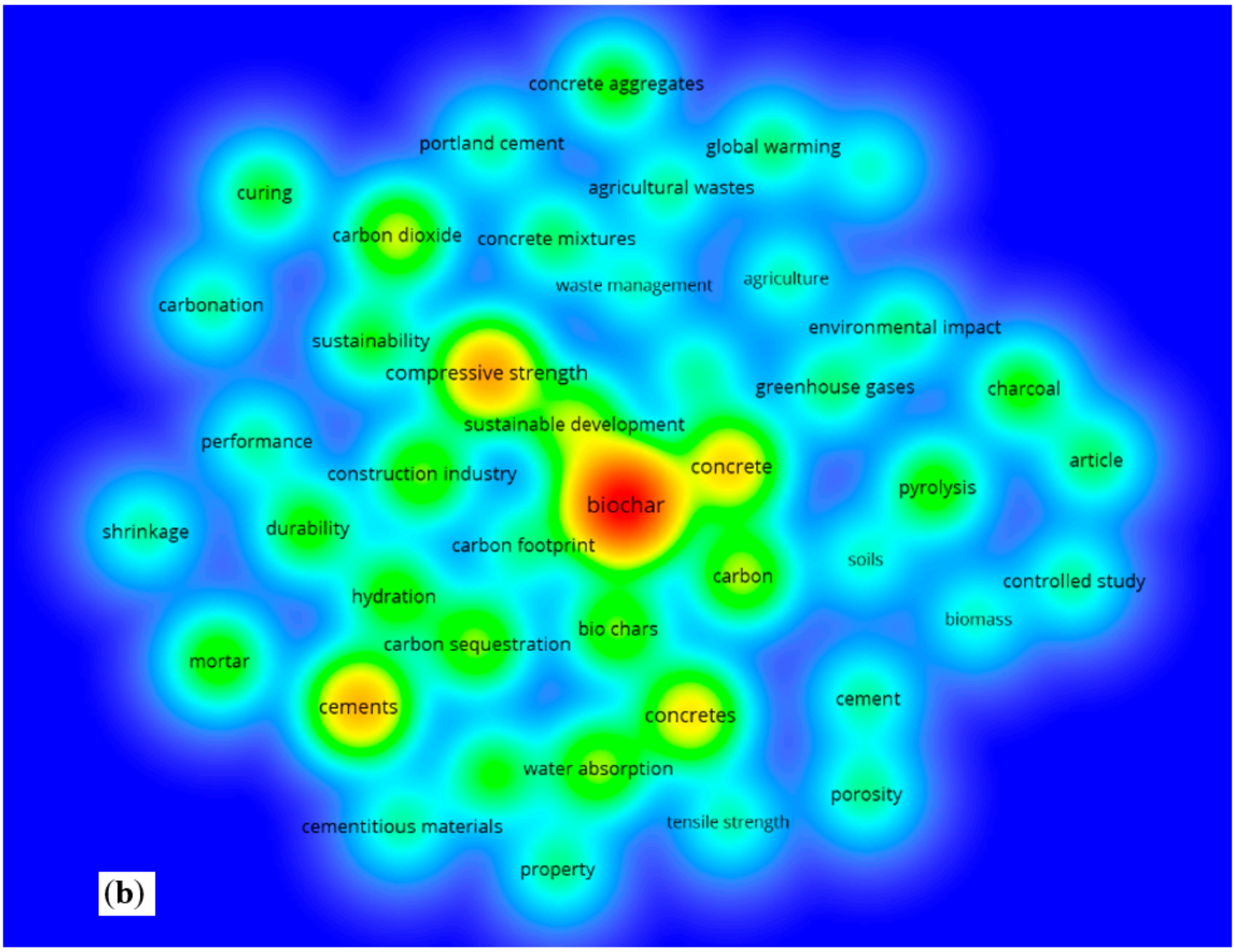

Figure 6. Scientometric mapping of keywords: (**a**) occurrence visualization; (**b**) density visualization.

4.4. Top-Cited Published Articles/Documents

The influence of published articles on their fields can be measured by the frequency of their citation. Articles that are frequently referenced by other scholars often become pivotal works within their domain of research. To analyze the impact of published articles based on their frequency of citation, the input data "bibliographic coupling" and "documents" were chosen as the "analysis type" and "analysis unit", respectively, in the VOSviewer. A total of 88 out of 189 documents met the criteria at a minimum citation count number of 10 for each article. The 15 top-cited research publications are listed in Table 4. The publication titled "Use of biochar as carbon sequestering additive in cement mortar", authored by Gupta S. et al. [74] has the highest citation count of 267, followed by the publications of Shen et al. [75] and Wang et al. [76] with citation counts of 215 and 199, respectively. It is important to mention that the publication by Gupta et al. [74] published in 2018, has a higher citation count and link strength than the publication of Shen et al. [75] which was published in 2014. The publication authored by Maljaee et al. [48] has a higher link strength than all of the top cited articles, despite having a lower citation score. Similarly, the publication authored by Dixit et al. [77] including Gupta as a co-author has the second-highest link score. Figure 7 illustrates the (a) visualization and (b) density mapping of the publications with the highest citation counts. The figure depicts that the articles are closely related based on their citations. The density map illustrates that the publications by Gupta, Wang, Akhtar, Shaheen, and Shen have greater citation densities based on the color contours. These visual representations highlight the contributions of the authors in their relevant fields and paves directions for future research.

Table 4. The 15 top-cited research publications.

S/N	Author (Year)	Title	Ref	Citations	Total Link Strength
1	Gupta (2018b)	Use of biochar as carbon sequestering additive in cement mortar	[74]	267	72
2	Shen (2014)	Porous silica and carbon derived materials from rice husk pyrolysis char	[75]	215	1
3	Wang (2020)	Biochar as green additives in cement-based composites with carbon dioxide curing	[76]	199	37
4	Akhtar (2018)	Novel biochar-concrete composites: Manufacturing, characterization and evaluation of the mechanical properties	[78]	196	2
5	Gupta (2018a)	Healing cement mortar by immobilization of bacteria in biochar: An integrated approach of self-healing and carbon sequestration	[79]	157	54
6	Dixit (2019)	Waste Valorisation using biochar for cement replacement and internal curing in ultra-high performance concrete	[77]	144	129
7	Cuthbertson (2019)	Biochar from residual biomass as a concrete filler for improved thermal and acoustic properties	[80]	141	17
8	Kua (2019)	Biochar-immobilized bacteria and superabsorbent polymers enable self-healing of fiber-reinforced concrete after multiple damage cycles	[81]	134	47
9	Asadi Zeidabadi (2018)	Synthesis, characterization and evaluation of biochar from agricultural waste biomass for use in building materials	[82]	121	3
10	Gupta (2020a)	Effect of biochar on mechanical and permeability properties of concrete exposed to elevated temperature	[83]	113	99
11	Tan (2021)	Biochar from waste biomass as hygroscopic filler for pervious concrete to improve evaporative cooling performance	[84]	104	53
12	Chen (2022)	Biochar-augmented carbon-negative concrete	[85]	96	7
13	Shaheen (2022)	Sustainable applications of rice feedstock in agro-environmental and construction sectors: A global perspective	[86]	87	8
14	Chen (2023)	Green construction for low-carbon cities: a review	[87]	82	6
15	Maljaee (2021)	Incorporation of biochar in cementitious materials: A roadmap of biochar selection	[48]	79	142

4.5. Authors Mapping

An author's influence, in addition to their publications, is gauged by the density of citation their publication receives [80]. To analyze the impact of authors based on their frequency of citation, the input data "co-authorship" and "authors" were chosen as "analysis type" and "analysis unit", respectively, in the VOSviewer. A total of 12 out of 724 authors met the criteria at minimum number of documents count of five for each author. The top contributing authors based on publication count are given in Table 5. The independent evaluation of the author is difficult to assess by the number of publications or citations alone. It is important to assess the other relevant variables. For this reason, the average citation score (ACS) was obtained by dividing the total publication count with the number of an author's total publications. However, this assessment is limited to the total number of publications, citation count, average citation score, and link strength. Based on publication count, Gupta and Kua have 11 articles, while Belletti, Bernardi, Malcevschi, Sirico, and Tsang have authored 8 articles, and Restuccia L. has authored 6 articles. When the citation count is compared, Gupta has 1104, Kua H.A. has 1081, and Belletti, Bernardi, Malcevschi, Sirico, and Tsang have 189 citations. Similarly, the average citation score of

Gupta is 100, Kua is 98 and Tan is 51. It can be seen from Figure 8 that the authors with an almost similar number of publications and citations are from the same clusters. It also highlights their co-authorship and collaboration in the relevant field. It is also evident that the authors from different areas are less connected.

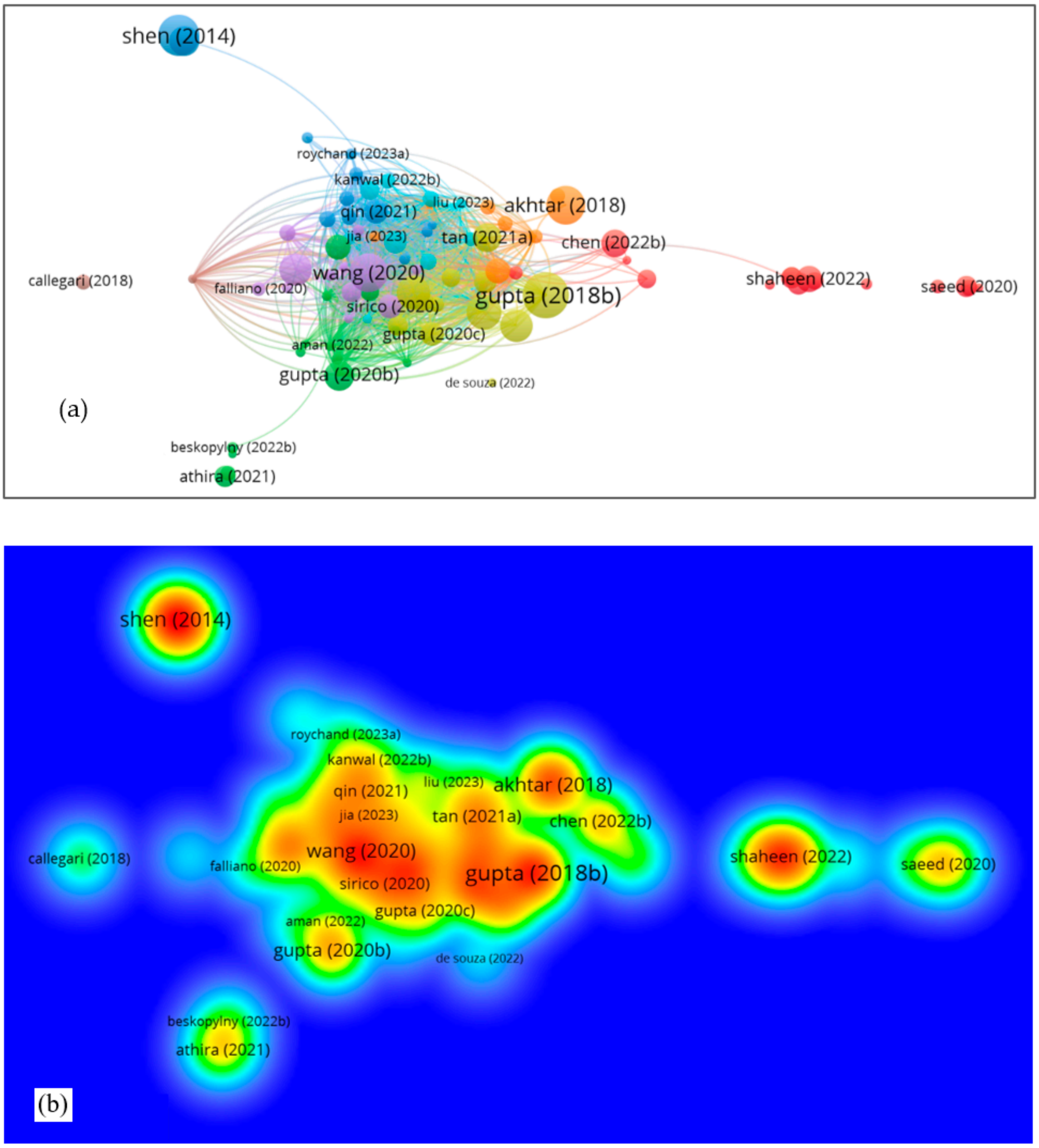

Figure 7. Scientometric mapping of the (**a**) visualization and (**b**) density of the connected articles.

Table 5. Top contributing authors with a minimum of five publications.

S/N	Author	Documents	Citations	ACS	TLS
1	Gupta, Souradeep	11	1104	100	12
2	Kua, Harn Wei	11	1081	98	12
3	Belletti, Beatrice	8	189	24	25

Table 5. *Cont.*

S/N	Author	Documents	Citations	ACS	TLS
4	Bernardi, Patrizia	8	189	24	25
5	Malcevschi, Alessio	8	189	24	25
6	Sirico, Alice	8	189	24	25
7	Tsang, Daniel C.W.	8	334	42	12
8	Restuccia, Luciana	6	83	14	7
9	Tan, Kanghao	5	257	51	0
10	Tulliani, Jean-Marc	5	84	17	5
11	Zhang, Yuying	5	109	22	9
12	Zhu, Xiaohong	5	18	4	9

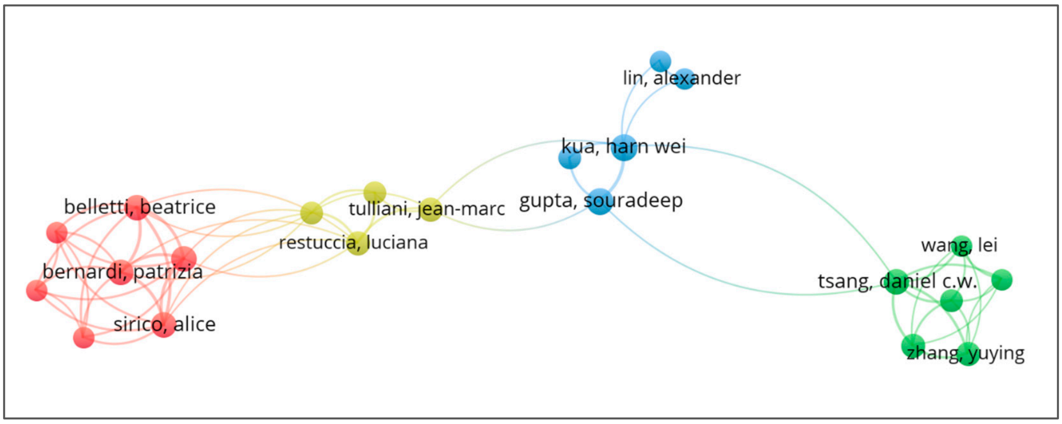

Figure 8. Scientometric visualization of top contributing authors and their connections.

4.6. Mapping of Countries

The visualization of the BC-based cement and concrete composites research of various regions is presented to identify the commitment and contributions to sustainable construction and environment reconstruction. The data presented in Table 6 will help readers to better understand the global dynamics of research in this critical area and identify opportunities for further development and collaboration. The input data “bibliographic coupling” and “countries” were chosen as the “analysis type” and “analysis unit”, respectively, in the VOSviewer. A total of 16 out of 48 countries met the criteria at the minimum document count number of five of for each country. China is the leading country in this research area with a publication count of 56, followed by India with 26, and Italy with 23. However, based on citations, China is in first place, counting 1431, Singapore is at second with 1194 citations, and Germany stands at third place with 506 citations with only eight publications. The link strength of the country shows the inclusion of their studies by other countries in their research. China, India, and Singapore are the leading countries based on the total link strength. It is important to mention that, overall, China is the leading country and the United Kingdom is the last country in the list of 16 countries with a minimum of five publications in the relevant area of research field. Figure 9 presents the scientometric network visualization of various countries with a minimum of five publications. This statistical and visual representation specifies the countries’ direction of research and their efforts in the implementation of sustainable development goals through this area of research.

Table 6. Contribution of various countries with a minimum number of articles of five.

S/N	Country	Documents	Citations	TLS
1	China	56	1431	17,107
2	India	26	475	7368
3	Italy	23	345	6978

Table 6. *Cont.*

S/N	Country	Documents	Citations	TLS
4	United States	21	360	6956
5	Singapore	15	1194	7003
6	Australia	13	332	4922
7	Hong Kong	12	450	4879
8	Canada	9	385	1883
9	Germany	8	506	4746
10	Malaysia	8	67	2889
11	Saudi Arabia	8	175	5743
12	Egypt	7	156	3553
13	Pakistan	7	206	4093
14	Sweden	6	104	2479
15	South Korea	5	313	3044
16	United Kingdom	5	259	3785

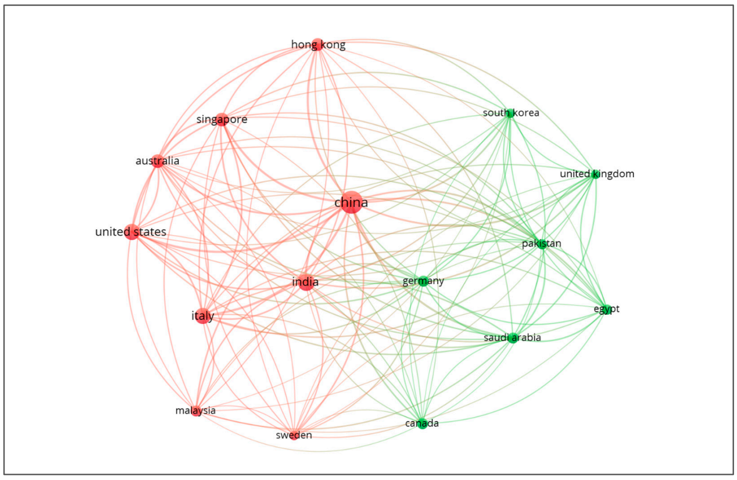

Figure 9. Scientometric network visualization of various countries.

5. Biochar

5.1. Overview of BC

Biomass is a complex organic or non-organic solid matter obtained from living or recently lived organisms, and it is naturally available. Other types of waste, such as wastepaper, sludge, animal manure, pulp, and many industrial litters are also termed biomass. This is because they are a mixture of organic and non-organic mixes and can be used to produce energy. Biomass is a viable alternative source of energy because of its availability and capability of reducing global warming and pollution. It is the only source of renewable energy which yields solid, liquid and gaseous fuel [88]. BC, a byproduct of biomass, is a carbon-rich sustainable material produced through pyrolysis, which offers no or very little oxygen during thermochemical combustion [89]. The temperature range during pyrolysis to produce BC typically ranges from 400 to 600 °C [90]. A study reported a 67% reduction in CO_2 emissions when rice straw waste is converted into BC in comparison to burning [91]. BC production requires a precise heating rate, temperature control, and residence duration to achieve stable carbon [92]. BC is termed a beneficial sustainable material due to its simple and fast manufacturing process, cost-effectiveness, and eco-friendly attributes [45]. Due to its promising features like high porosity, high surface area, high cation exchange capacity, stability, and functional groups, it opens new horizons for researchers and it is ideal for a vast number of applications [36]. BC has a vast number of applications, such as agriculture [93], effluent treatment [94], anaerobic digestion [95], chemical retrieval [96], and carbon capture [97]. Recent studies demonstrated that BC can be used as a cement replacement in the production of modified sustainable cement and concrete composites [76,82,98].

5.2. Types of BC

BC is a biproduct of biomass, a biological material made from various types of living creatures. Various types of biomass sources used for energy/power production, which are available in the world, are given in Figure 10a. These biomass sources can be used to create BC. Some of the BC used by various researchers include wood waste [99], rice husk [100,101], poultry litter [102], sewage waste [103], peanut shells [104], corn stalks [105], corn cobs [106], coconut waste [107], corn stover [108], date palm waste [109], aloe vera waste [110], kitchen waste [111], paper mill sludge [112], pine waste [113], wheat straw [114], shell fish waste [115], walnut shells [116], soybean stover [117], switch grass [114] tea waste [118], coffee waste [119], cotton gin waste [116], orange peel waste [120], pigeon waste [121], jasmine waste [122], tomato waste [123], cassava peel [124], and longan shell [125]. Some of the BC sources in raw biowaste form and ungrounded and grounded BC form after pyrolysis at 500 °C are given in Figure 10b. The accomplishment of net zero embodied carbon for BC is reliant on the effective application of pyrolysis by-products to counterweigh the use of fossil fuels. Achieving carbon neutrality depends on several variables, including physical and chemical attributes such as surface area, size, and pore volume in addition to the BC type [126,127].

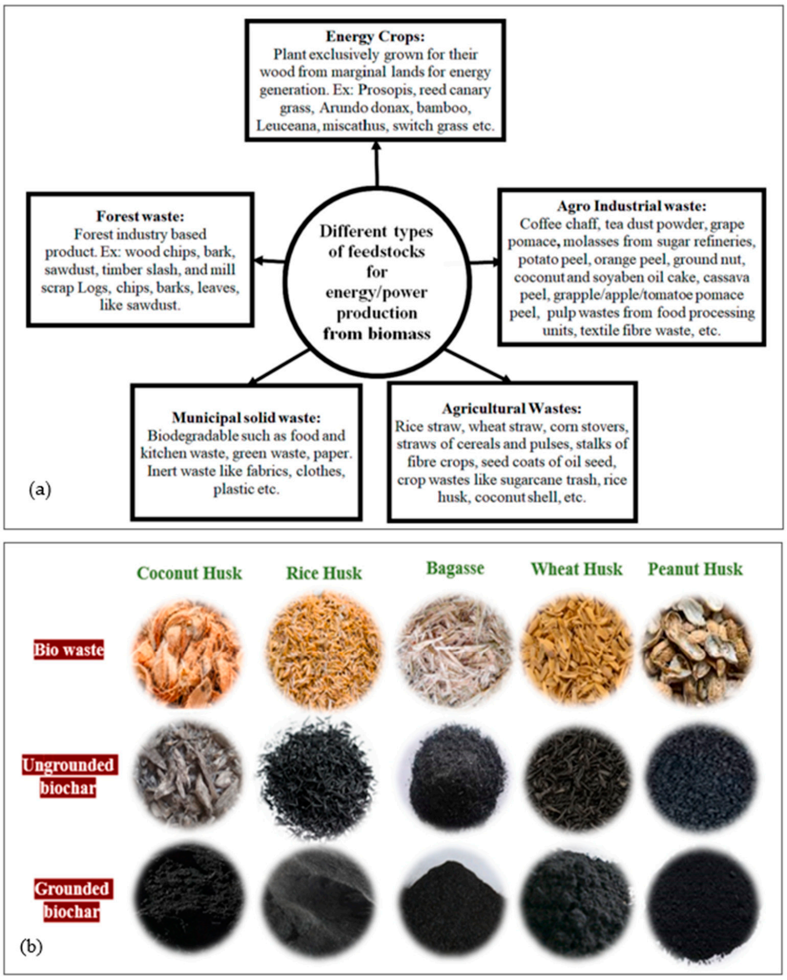

Figure 10. (**a**) Biomass types across the world [128] (**b**) different types of biomasses, raw biowastes, ungrounded and grounded BC after pyrolysis at 500 °C [129] (license no. 589446050826, 5894460817493).

5.3. Production of BC

The making process and technology classify the char product into three categories: charcoal, hydrochar, and BC. BC can be produced from dry biomass by pyrolysis, but the pretreatment of wet biomass with a moisture content of more than 10% is required for the control temperature in the reactor [130]. Pretreatment of the biomass makes the process energy-intensive. However, the heat produced during the pyrolysis can be utilized for the successive drying of biomass to counteract the overall effect of energy use [131]. The properties of BC depend upon the selection of biomass, which is influenced by availability, energy content, cost, and the specific attributes required in BC [132]. Similarly, the chemical composition, porosity, and reactivity of the BC is also dependent on the biomass feedstock [115]. BC production from biomass is achieved by thermochemical conversion techniques, which include the heating of biomass in the absence of or with limited oxygen to produce BC, syngas, and bio-oil [133]. The main steps involved in the production of BC by thermochemical method are provided in Figure 11. Different thermochemical methods, such as pyrolysis, torrefaction, gasification, carbonation, and microwave to make BC from biomass sources are summarized in Table 7, based on various important parameters including the temperature, residence time, heating rate, and production yield of bio-oil, BC, and syngas.

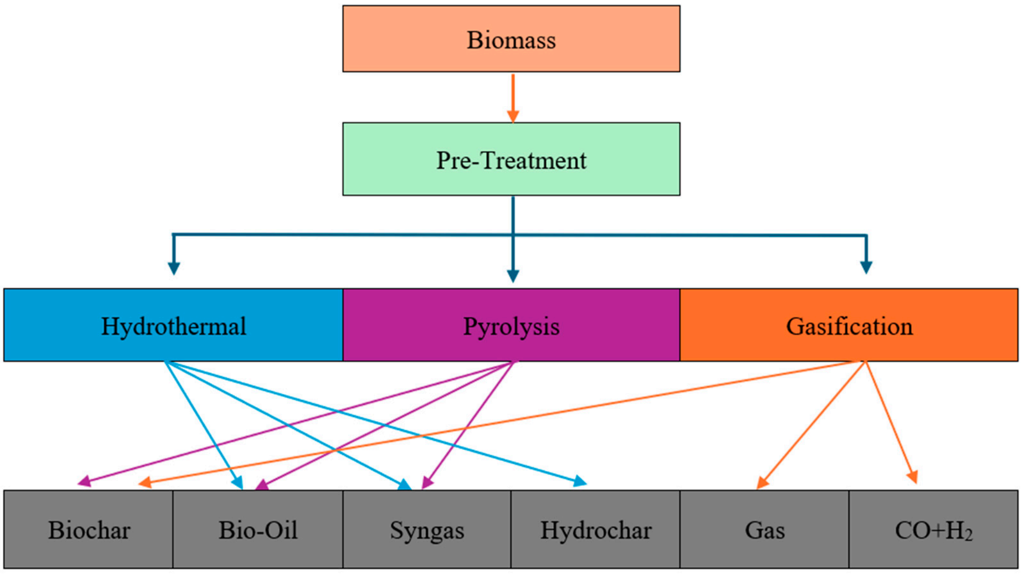

Figure 11. BC production methods by thermochemical procedures.

Table 7. BC production techniques and their functional conditions.

Parameters	**Pyrolysis**			**Gasification**	**Torrefaction**	**Flash Carbonation**	**Hydrothermal Carbonation**	**Microwave**
	Slow	**Fast**	**Intermediate**					
Residence Time	Min to hrs.	<2 s	1–15 min	10–20 s	10–120 min	<30 min	1–16 h	1–60 min
Heating Rate	<30 °C/min (common 5–10 °C/min)	≈1000 °C/min	1–10 °C/min	Moderate	<20 °C/min	Very Fast	Slow	25–50 °C/min
Temperature (°C)	300–700	300–1000	300–500	600–1500	200–300	300–600	100–300	350–650
Bio-oil yield (%)	30	50–75	35–50	5	5	0	5–20	8–70
BC yield (%)	21–80 (common 35%)	5–38 (common 12%)	30–40	10–16	60–80 (charcoal)	50 (charcoal)	45–95 (hydrochar)	15–80
Syngas yield (%)	35	13	20–30	85	20–40	50	0–5	12–60
References	[133–141]	[138,142–145]	[139,146,147]	[142,148–152]	[142,151,153,154]	[146,155,156]	[142,153,156–160]	[155,161–164]

BC yield primarily depends on operational parameters like feedstock properties, temperature, moisture content, particle size, pressure, reactor type, and heating rate [139]. Pyrolysis is the most used BC production technique, and slow pyrolysis yields the maximum BC output [165], which typically ranges from 25–50% BC, but sometimes exceeds the production by 70%, depending on the source and conditions of biomass feedstock [68,94,166]. The operating temperature is usually below 700 °C, with an extended time of residence and low rate of heating (0.01–2 °C/s) [146,167]. Fast pyrolysis prioritizes bio-oil production, only yielding about 12% BC [168]. It requires temperatures of up to 1000 °C, with an extremely high heating rate and vapor residence times of less than 2 s [169,170]. Intermediate pyrolysis maintains a balance between fast and slow pyrolysis processes, yielding almost similar amounts of BC as slow pyrolysis but at a much faster rate. It uses heating rates of about 1–10 °C/s and residence times of under 15 min [171]. Gasification is a thermochemical conversion process used for the conversion of organic materials like solid waste and coal, that are subjected to partial combustion in a gas flow with a given amount of air, oxygen, or steam at 600–1500 °C [139], primarily producing combustible syngas, some char, and minimal bio-oil/tar. Fluidized bed, updraft and downdraft gasifiers produce about 4–15%, 12%, and about 1% tar, respectively, at varying temperatures [149]. From the literature, it is evident that fast pyrolysis and gasification yields less than the rest of the technologies [172]. Torrefaction is best known for the enhancement of the thermochemical and physicochemical properties of biomass during thermal treatment, under atmospheric pressure with limited or no oxygen, at a slow heating rate for an extended residence time and at between 200–300 °C temperature [142,173]. Flash carbonization exercises partial combustion with a moderate residence time and temperature at a high heating rate to produce high gas and char yields without producing any liquid products [156]. Hydrothermal carbonization is suitable for wet waste streams that would otherwise require drying before pyrolysis [174]. Microwave-assisted pyrolysis is an emerging technology for bio-energy product generation, including bio-oil, BC, and biogas. It operates at moderate temperatures and residence times and is primarily controlled by microwave power [163,175].

5.4. Physiochemical Properties of BC

The physicochemical properties of BC depend upon the source of biomass, production technology and conditions [57]. These attributes aid in BC's ability to improve carbon sequestration and soil fertility and remediate polluted ecosystems. The specific structure and chemistry of BC make it suitable for use with nutrients, soil particles, microorganisms, cement, and make it an adaptable material for environmental, agricultural, and construction industry applications [176,177]. BC particle size distribution has a significant effect on the properties of resulting cement and concrete mixtures. Coarser particles are used as fillers or lightweight aggregate in cement mortar and concrete, whereas finer BC can be used as a secondary cementitious material and has an impact on cement hydration. The particle size distribution impacts the workability, strength development, and microstructure of the cementitious matrix [178]. BC bulk density ranges from 0.3 to 0.5 g/cm^3 [179]. BC has a lower density than cement, which affects the concrete mixture's overall density. BC incorporation reduces the weight of concrete, and thus reduces the structural weight. However, a careful mix design is required as it has a significant impact on the strength and durability of the resulting concrete [77]. The surface area of BC as an additive normally ranges from 50 to over 400 m^2/g. It affects cement hydration, water absorption and other composite properties [180]. BC with a higher surface refines the cement paste pore structure and potentially enhances its strength and durability; however, it increases the water demand due to having a higher surface area and a porous structure [47,90]. The pore size distribution of BC influences the performance of cementitious composites. These pores are categorized into three types: micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) [181]. A study reported that fine, medium, and coarse BC have a porosity of 51.5%, 63.9%, and 72.4%, respectively. These pores influence the kinetics of cement hydration and water absorption capacity, and act as internal curing tanks [77].

Similarly, the water holding capacity of BC is important for the hydration process and w/c ratio of the composite. Internally held water in BC pores helps prolong internal curing by the gradual release of water, which ensures continuous hydration. This property has beneficial effects in reducing autogenous shrinkage in high-strength concrete [182]. The pH of BC is an important parameter which affects the alkalinity of cementitious composites. BC is mostly alkaline and the value ranges from 7–10, which suits the high alkaline environment of the cement composites. The pH of BC is crucial in cement and concrete applications as it can affect the alkalinity of the cementitious system. Most BC are alkaline, with pH ranges from 7–10 [179,183], which is compatible with the high pH environment of cement paste. However, changes in BC pH can affect cement hydration mechanics and the development of hydration products. It is important to investigate the long-term performance of BC-added cement composites [184]. During elevated temperatures or fire-resistant environments, the thermal stability of BC is relevant for concrete application. BC's stable structure and thermal resistance improves the fire resistance of cement composites [185]. Electrical conductivity (which ranges from 3.75–4 ds/m [179,181]) is the least studied aspect of BC in concrete applications. The effect of BC could be relevant for electromagnetic shielding or de-icing, and is influenced by the intrinsic conductivity and content of BC [186]. The chemical composition of BC is dependent upon the source of biomass. Various agricultural (bagasse, poultry litter, corn straw, corn stover, and rice husk) and industrial (bamboo, waste plywood, forest wood, sewage sludge, and dewatered sludge) biomass-based BCs with various sizes (75 to 300 µm) have been studied by various researchers, and their chemical compositions are mainly dependent upon biomass sources and other heating conditions and parameters. The minimum and maximum amount of each chemical composition, as reported in the literature by various researchers are: SiO_2 content 4.66% to 78.4% [42,187]; Al_2O_3 content 0.03% to 15.04% [52,188]; CO_2 content 0.28% to 82.57% [52,189]; K_2O content 0.59% to 12.81 [189,190]; CaO content 0.19% to 63.57% [52,191]; Fe_2O_3 content 0.05% to 19.6% [192,193]; MgO content 0.04% to 3.54% [42,52]; Na_2O content 0.05% to 21.53% [42,53]; and loss of ignition 0.43% to 45.02% [53,194]. Similarly, the carbon content ranges from 19.67% to 76.60%, oxygen ranges from 8.42% to 60.05%, and hydrogen ranges from 1.15% to 8.0%, accompanied by sulfur and nitrogen [58]. The presence of a relatively high silica content compared to other inorganic oxides in the BC is promising for the production of calcium silicate hydrate (CSH) [195,196]. The H/C and O/C ratio was slightly reduced when the residence time exceeded 2 h at 500 °C pyrolysis temperature. A significant impact on strength was noticed by pyrolysis temperature (500 °C and 2 h residence time) at 2% BC incorporation. [189]. BC with a higher carbon content withstands aggressive environmental effects; thus, biomass has less oxygen, and a higher carbon content is beneficial for calorific value and productivity.

6. Properties of BC-Enhanced Cement Composites

BC, a carbon-rich material produced from biomass through pyrolysis, has been used as a favorable additive for the improvement of cement-based composites. The incorporation of BC into cement-based composites has shown favorable effects on its mechanical properties, durability characteristics, and environmental sustainability. The morphology of BC enables the provision of additional nucleation sites for the growth of CSH gel, which contributes to improved composite properties. Furthermore, the inclusion of BC improves the durability of cement-based composites by enhancing their resistance to sulfate attack, chloride penetration, and carbonation. Additionally, the use of BC can alleviate the carbon footprint coupled with cement and its composites' production, thus encouraging more sustainable construction practices. Table 8 summarizes the influence of BC on the properties of cement-based composites in the literature.

Table 8. Effect of BC on the properties of cement-based composites.

Ref.	BC Source	Pyrolysis Characteristics	BC Incorporation (wt%)	BC Size	Findings
[197]	Rice husk	Pyrolyzed at 300, 500 and 700 °C. Residence time 2 h. Rate of heating 15 °C/min.	Replacement 1 to 7%	<150 µm	Cement replacement with BC up to 5% in foam concrete showed about 11 MPa compressive strength and 2.8 MPa flexural strength. However, beyond 5%, the mechanical properties of concrete mixes experienced decline.
[53]	Rice husk	Pyrolyzed at 450 to 550 °C	Replacement 2 and 5%	<500 µm	Flowability was reduced by 8% due to BC modification. Carbon-cured samples exhibit 1.3 times improved strength compared to normally cured specimens. Loss due to chloride ion penetration reduced due to BC inclusion subjected to 3% NaCl solution.
[41]	Rice husk waste	Pyrolyzed at 550 °C.	Addition 2 to 8%	<200 µm	The compressive strength showed marginal (2.32%) improvement at 4% BC incorporation. The flexural strength results reported 23.25% improvement at 4% incorporation. The durability was improved by 17.3%, accordingly.
[78]	Rice husk, Poultry litter, paper mill sludge	Pyrolyzed at 450 to 500 °C. Residence time 1 h. Rate of heating 10 °C/min.	Addition 0 to 1%	–	The tensile strength of control and BC-modified cement composites were comparable.
[198]	Rice husk, Poultry litter	Pyrolyzed at 450 and 500 °C.	Replacement 0.1 to 0.75%	–	The strength characteristics at 0.1% BC incorporation improved by 3.7% and 17.5% for poultry litter and rice husk respectively. At 0.75% BC, the strength was decreased by 33%.
[82]	Rice husk waste and sugarcane bagasse	Pyrolyzed at 700 °C. Residence time 2 h. Rate of heating 10 °C/min.	Replacement 0 to 20%	<100 µm	The maximum compressive strength improvement was observed at 5% BC incorporation. Marginal improvement in tensile strength at 5% BC incorporation.
[52]	wood waste, Rich husk	Pyrolyzed at 500 °C. Residence time 1 h. Rate of heating 10 °C/min.	Replacement 0 to 2%	<60 µm	The specimens were exposed to 5% Na_2SO_4 solution. The compressive strength loss was reduced with 2% BC-modified cement composites. The specimens were exposed to 5% Na_2SO_4 solution and the compressive strength loss was reduced in BC-modified cement composites.
[199]	Waste wood	Pyrolyzed at 500 °C. Residence time 2 h. Rate of heating 20 °C/min.	Replacement 1 to 10%	44.70, 73.28, 750, and 1020 µm	Wood waste BC experienced maximum strength improvement at 3% dose. Decrease of 32% in chloride diffusion coefficient when 1 to 3 wt% BC was used as cement replacement.

Table 8. *Cont.*

Ref.	BC Source	Pyrolysis Characteristics	BC Incorporation (wt%)	BC Size	Findings
[200]	Waste wood	Pyrolyzed at 500 °C. Residence time 1 h. Rate of heating 10 °C/min.	Addition 1 to 8%	<100 µm	Pervious concrete containing 3% BC exhibits an increase of 8.4% in the compressive strength of concrete compared to control mixture. However, the flexural strength of 5% BC-modified concrete experienced comparable values to that of control samples.
[83]	Woody biomass	Pyrolyzed at 500 °C. Residence time 1 h. Rate of heating 5 °C/min.	Replacement 0.5 and 2%	<200 µm	A slight improvement in the compressive strength was reported at BC up to 2%. However, the tensile strength of control specimens was more compared to BC-modified mixes.
[201]	Saw-dust wood waste	Pyrolyzed at 500 °C. Residence time 1 h. Rate of heating 10 °C/min.	Replacement 2 and 5%	<150 µm	BC inclusion has no significant effects on the strength characteristics of the modified concrete. The shrinkage was reduced by 32% and 21% at 5% and 2% cement replacement with BC.
[202]	Sawdust	Pyrolyzed at 400 °C. Rate of heating 10 °C/min.	Replacement 1 to 5%	<200 µm	The flowability was reduced by 13% due to BC inclusion.
[203]	Wood chips	Pyrolyzed at 400 °C	Addition 1 to 5%	<500 µm	Marginal improvement in compressive strength was observed up to 2% BC addition. Beyond 5% addition of BC, a significant decrease in the mechanical properties of concrete was reported. The flowability was reduced by 10% due to BC inclusion.
[108]	Wate wood	Pyrolyzed at 300 to 500 °C.	Replacement 1%	<200 µm	Initial and final setting time were reduced by 10.4 and 14.6% respectively
[77]	Wood sawdust	Pyrolyzed at 500 °C. Residence time 2 h. Rate of heating 10 °C/min.	Replacement 0 to 5%	<125 µm	The compressive strength of BC-modified cement showed comparable results to the control composites.
[90]	Wood sawdust	Pyrolyzed at 300 to 500 C. Residence time 1 h. Rate of heating 10 °C/min.	Replacement 0 to 5%	<400 µm	The tensile strength of BC-modified cement composites reported an increase of 6 to 7.5% compared to control specimens.
[204]	Wood chips	Pyrolyzed at 200 to 500 °C. Residence time 0.5 h. Rate of heating 10 °C/min.	Replacement 0 to 2.5%	<63.5 µm	Flexural strength enhancement of 6% was reported at 1% replacement of cement with BC.
[205]	Weedtree	Pyrolyzed at 600 °C.	Addition 2%	<300 µm	The compressive strength showed marginal improvement. The autogenous shrinkage of BC-modified composites decreased by about 16.3%.
[191]	Eucalyptus plywood boards waste	Pyrolyzed at 500 °C. Residence time 2 h. Rate of heating 10 °C/min.	Replacement 0 to 13.5%	<50 µm	The maximum compressive strength and splitting tensile strength improvement was observed at up to 6.5% BC incorporation compared to control specimens at both 7 and 28 days. However, at 13.5% replacement, there was a significant decrease of 27.5% in compressive strength.

Table 8. *Cont.*

Ref.	BC Source	Pyrolysis Characteristics	BC Incorporation (wt%)	BC Size	Findings
[206]	Virgin woodchips	Pyrolyzed at 500 °C. Residence time 1 h. Rate of heating 10 °C/min.	Addition 0 to 2.5%	<200 µm	Flexural strength improvement of 10% and 7% were reported at 1.5% and 1% BC addition, respectively, compared to control specimens.
[207]	Wood waste, coconut shell	Pyrolyzed at 450 °C. Residence time 1 h. Rate of heating 10 °C/min.	Replacement 5%	<50 µm	Autogenous shrinkage at 5% cement replacement with BC resulted in insignificant reduction.
[208]	Desert palm rachis	Pyrolyzed at 300 to 500 °C. Residence time 0.5 h. Rate of heating 10 °C/min.	Replacement 1 to 5%	<500 µm	Maximum enhancement in the flexural strength was reported at 1% BC replacement.
[187]	Sugarcane bagasse	Pyrolyzed at 400 to 500 °C. Rate of heating 10 °C/min.	Replacement 5 to 10%	–	Improved strength of BC-modified composites at 56 and 90 days compared to control specimens when subjected to 5% Na_2SO_4 solution.
[42]	Corn straw	Pyrolyzed at 300 to 550 °C. Residence time 1.5 h. Rate of heating 10 °C/min.	Replacement 1 to 5%	<100 µm	The BC-modified composites showed an improved microstructure and reduced permeability compared to control specimens.
[209]	Corn straw	Pyrolyzed at 450 °C. Residence time 1 h. Rate of heating 10 °C/min.	Addition 1 to 4%	<300 µm	The autogenous was significantly reduced by BC-modified cement composites.
[210]	Corn straw	–	Replacement 1 to 15%	<150 µm	Enhancement in the properties of concrete was observed at 1% BC for cement replacement. The enhancement was attributed to the reduction of cement-to-binder ratio and concrete carbonation.
[188]	Bamboo chips	Pyrolyzed at 650 to 750 °C. Rate of heating 15 °C/min.	Replacement 0 to 4%	<200 µm	Increase of 20% in compressive strength at 1% BC incorporation.
[129]	Peanut husk, wheat husk, coconut husk, rice husk, bagasse	Pyrolyzed at 500 °C. Rate of heating 10 °C/min.	Replacement 1 to 5%	<75 µm	Initial and final setting time of coconut hush BC was reduced by 26 and 14.2% respectively. Increase of 18% in compressive strength at 2% bagasse BC.
[55]	Peanut husk	Pyrolyzed at 500 °C. Residence time 1 h. Rate of heating 10 °C/min.	Replacement 3%	<100 µm	Initial and final setting time was reduced by 11.2 and 16% respectively
[51]	Peanut husk	Pyrolyzed at 450 °C. Residence time 1 h. Rate of heating 10 °C/min.	Replacement 0 to 3%	<100 µm	Shrinkage of the BC-modified composites was reduced compared to control specimens due to internal curing of capabilities of BC.
[44]	Peanut shell	Pyrolyzed at 500 and 700 °C. Residence time 2 h. Rate of heating 15 °C/min.	Replacement 1 to 5%	<200 µm	BC pyrolyzed at 700 °C exhibits better performance compared to BC pyrolyzed at 500 °C on lightweight concrete. The significance of BC inclusion was up to 5%. The maximum compressive strength was 11.1 MPa and flexural strength was 2.8 MPa.
[178]	hazelnut shell, coffee power	Pyrolyzed at 800 °C. Residence time 1 h. Rate of heating 6 °C/min.	Replacement 0 to 1%	<30 µm	Maximum 13% flexural strength enhancement was reported.
[211]	Polluted dredged sediment	–	Replacement 0 to 2%	–	The lightweight concrete with BC inclusion from 0 to 2% could reduce the CO_2 emissions by reducing, capturing, and storing the CO_2 compared to conventional concrete.

Table 8. *Cont.*

Ref.	BC Source	Pyrolysis Characteristics	BC Incorporation (wt%)	BC Size	Findings
[212]	Municipal solid waste	Pyrolyzed at 600 °C	Replacement 1 to 30%	<48 µm	The strength of BC-modified concrete was comparable to the control specimens, with up to 10% replacement of cement with BC. However, beyond 10%, the mechanical properties of all concrete mixes experienced significant decline.
[189]	Dewatered sludge	Pyrolyzed at 300 to 600 °C. Residence time 0.5, 1, 2, and 3 h. Rate of heating 10 °C/min.	Replacement 2%	<600 µm	The compressive strength showed 5.8% improvement. The H/C and O/C ratio were slightly reduced when the residence time exceeded 2 h at 500 °C pyrolysis temperature. The significant impact on strength was noticed by pyrolysis temperature (500 °C and 2 h residence time) at 2% BC.
[213]	Poultry litter	Pyrolyzed at 450 °C. Residence time 1 h. Rate of heating 10 °C/min.	Replacement 0 to 10%	<200 µm	The BC-modified composites showed improved microstructure and reduced permeability compared to control specimens.

6.1. BC as a Binder

BC demonstrates potential as a partial cement replacement in cement composites due to its pozzolanic properties [41]. This feature suggests that BC could be incorporated into cement composites to partially substitute their cement content, potentially leading to decreased cement usage while maintaining or improving certain cement composites' attributes. The effect of various properties of BC on the characteristics of cement composites are summarized in Figure 12 [48]. A study was conducted on softwood-derived BC, which was pyrolyzed at 680 °C for a residence time of 12 min, to study its fracture energy and the modulus of rupture of the cement composites at 0.8% and 1% replacement. The results showed improved fracture energy and flexural strength compared to the control mixtures [214]. Milled and coarse sawdust BC, pyrolyzed at 500 °C with a heating rate of 10 °C per minute, accelerated the cement hydration process and influenced the early strength development with minimal influence on the rheology of cement-based composites with 1–2% BC content. It also reported reduced capillary absorption by about 50%, and suggests the use of sawdust wood-derived BC as a filler for water tightness and strength development in concrete construction [215]. The effect of water entrainment from pre-soaking BC after pyrolysis at 300 and 500 °C at a rate of 10 °C/min was studied to assess the strength and permeability of cement mortars incorporated with 2% BC as partial replacement of cement. The results showed 23 to 32% higher compressive strength after air curing for 28 days compared to the mortar without BC, and 10 to 12% reduction in hydration for air curing compared to moist curing [90]. Another study that used forest waste-derived BC by gasification at 800 °C reported that a 1% BC content could positively impact the flexural strength, compressive strength, and fracture energy compared to the control specimens [204]. Gupta et al. [184] used waste wood BC in cement mortars, and reported that a 1–2 wt% addition of BC could reduce permeability and improve the strength characteristics of the mortar. Ahmad et al. [216] pyrolyzed bamboo at 850 °C to generate carbonized particles, and added this to cement paste at 0.05 to 0.20 wt%. Their results indicated that a 0.08 wt% addition increased toughness by 103% and strength by 66% compared to the control mortars. This improvement in toughness was due to the crack deflection process caused by the BC's filler effect in the mortar. Akhtar and Sarmah [78] investigated the effect of poultry litter and rich husk BC (0.1% of cement volume) on the water absorption and strength of concrete. The results reported a 20% improvement that showed that the addition of BC improved flexural strength by 20%. It also improved the compressive and split tensile strength of the concrete, with almost no change on the water absorption compared to control samples. Zeidabadi et al. [82] used bagasse and rice husk BC (0, 5, and 10 wt%) pyrolyzed at 700 °C to investigate the compressive and tensile strength of concrete. The results showed a 5% pretreated bagasse BC resulted in a 54.8% and 78% increase in compressive and tensile strength, respectively. Rice husk BC (pyrolyzed at 650 °C), was examined to study its effect on various properties of cement-based materials. The results illustrated an improved durability, reduced shrinkage, a 12% increase in water and an increase of 17% in compressive strength [182]. BC particles can divert the crack trajectories which increase the fractured energy and flexural strength of the matrix. Restuccia and Ferro [217] used 0.8 to 1 wt% of hazelnut shell BC, and reported a 60% and 30% increase in fracture energy and modulus of rupture of the cement mixture, respectively. It also increased the shielding effect of electromagnetic radiation at 0.5 wt% BC in cement composites compared to plain cement matrix [186]. Gupta et al. [202] used food waste (pyrolyzed for 60 min at 500 °C) BC in cement mortar with 1 to 2 wt%. The results of 1 wt% BC incorporated samples demonstrated a 35% reduction in sorptivity and a 40% reduction in water penetration. It also increased the compressive and tensile strength by almost 20%. Praneeth et al. [108] used corn stove BC as filler in fly ash concrete. The results showed an improvement in compressive strength, which was attributed to the nucleation sites for CSH gel offered by BC, resulting in a densified concrete matrix. Wheat straw BC, pyrolyzed at 650 °C with a heating rate of 18 °C/min, was examined to understand its influence on magnesium phosphate cement. Incorporating 0.5% to 1.5% BC resulted in a 4.1% to 17.3% increase in compressive strength and a reported reduction in sorptivity and water absorption from 4.7% to 5.7% [218]. Based on the reported findings in the literature, BC can be used in the production of sustainable additives for cement composites with improved fresh, mechanical, and durability characteristics. The performance of cement-based composites can be improved by the careful selection of biomass sources with definite organic composition; optimizing pyrolysis temperatures, residence time, and heat rate to control the BC surface area and porosity; and applying required treatments (such as functionalization or acid washing) to enhance BC's compatibility with cement composites. It can enhance the mechanical strength, durability, and overall performance of BC-modified cement composites. However, the more in-depth assessment of BC types and properties based on sources and production needs exploration for its intended use in cement composites.

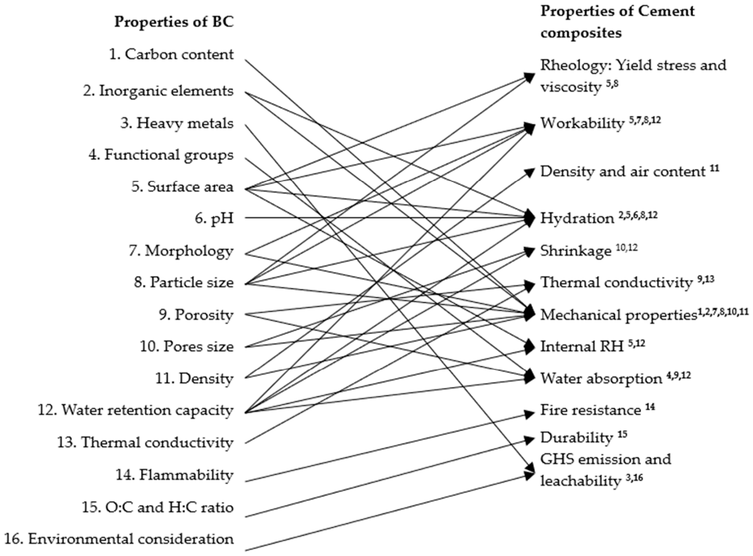

Figure 12. Correlation between properties of BC and cement composites.

6.2. Effect of BC on the Hydration of Cement Composites

Various types of BC differ in their chemical compositions due to the sources of biomass from which they are derived. Most studies suggest that BC usually improves cement hydration [48,52,189,219]. Fine BC particles usually accelerate the hydration process [77,220–222]. Milled BC enhances the early-age strength of cementitious composites, attributed to its filling ability due to its high specific surface area [204,207]. However, BC containing sugar products could cause delays in the cement hydration process [51]. Adding 1% and 2% wood waste BC marginally speeds up the hydration process and lowers the dormant period by around 30 min [52]. Dixit et al. [201] observed a 6% and 10% increase in hydration heat when 2 and 5 wt% cement was replaced by BC, respectively, which could be attributed to an enhanced rate of hydration due to water retention in the pores of the BC particles. Wang et al. [76] investigated the effect of BC on the heat of hydration of cement composites. Incorporating 1 to 5% BC increased hydration heat by 1.86% to 6.98%. Gupta and Kashani [51] examined mortar hydration rates with a 1 to 3 wt% peanut shell BC replacing cement. They found that a peanut shell BC containing 8.5% phosphorus dissolved during hydration, slightly extending the induction period. Rodier et al. [223] reported a significant 9% increase in cement hydration with 2 wt% BC addition. Notably, specimens containing BC produced at temperatures above 500 °C showed no significant variations in hydration heat.

6.3. Effect of BC on the Workability of Cement Composites

BC has a porous structure and high specific surface area, and because of this, it absorbs a lot of water during the initial mixing stage, which causes a reduction in the workability of the mix. However, at the same time, it enhances the continued hydration due to the water stored in the pores of the BC acting as internal curing tanks [184,193,224,225]. The main factor responsible for the reduction in consistency of the cementitious composites is the highly porous nature of the BC [74]. BC added in the cement composites at a higher dosage could significantly reduce the flow characteristics of the cement composites, which can be attributed to the water capture capacity of the BC and the dilution effect [225]. A study reported a decrease of up to 13% in the workability of concrete incorporated with BC (particle size < 200 μm) as a partial substitute for cement of up to 5% [202], whereas, in another study, BC (particle size < 500 μm) extracted from the same biomass source reported a 10% decrease [203]. Similarly, a decrease of 2.5–10% was observed when BC extracted from rice husk was used as a 2–5% cement replacement [193]. It can be observed that different types of biomass sources exhibit a reduction in workability. Some of the studies reported an even higher percentage reduction in the workability of the cementitious composites, to the tune of 10–30% [184,224]. The fresh properties, especially flow characteristics, play an important role in the compactness and porosity of the hardened matrix. It is important to maintain a minimum desirable workable mix for easy mixing, handling, and placing, to ensure that the matrix is desirable for its intended use. Therefore, the selection and use of plasticizers could be used to enhance the consistency of the cement composites incorporating BC [203]. A few of the studies reported an increase in the workability of the cementitious mix incorporated with BC derived from food waste, rice husk and wood waste [49,202]. The studies reported an about 9–13% increase in the workability of the cement mortar with BC added. Based on the results from various studies, to achieve the optimal rheological characteristics of the cement composites incorporated with BC, a proper assessment of the BC is required, identifying type, morphology, specific surface area and porosity. In addition, the amount of BC and suitable use of plasticizers could also play an important role in design considerations.

6.4. Effect of BC on the Setting Times of Cement Composites

Multiple studies have demonstrated that the incorporation of BC into cement composites can reduce both the initial and final setting times [50,127,226]. This reduction is attributed to the improved hydration of the cement [77,220,221,227]. The addition of a cement substitute, including BC, can significantly affect the free water content, leading to shorter setting times. BC enhances the early-age strength of cementitious composites, which can be attributed to its filling ability due to its high specific surface area and porous nature acting as nucleation sites, thus increasing the generation of hydration products like calcium hydroxide and silicate hydrate, which potentially decrease the initial and final setting times of the cement composites [74]. Tan et al. [224] examined the influence of BC produced at various pyrolytic temperatures on the setting times of cement mortar. The research indicated that the setting times of the BC-modified mortar decreased, regardless of production conditions. A study reported an 11% reduction in the initial setting time and a 16% reduction in the final setting time when 3% BC was used in cement composite, attributed to an accelerated hydration process due to the nucleation effect of BC [51]. In another study [129], the 2% substitution of cement with coconut husk BC resulted in 26% and 14% reductions in the initial and final setting times, respectively. BC with a higher surface area (finer particles) accelerates the initial setting time but may delay the final setting time, because of enhanced water demand; however, coarser particles inhibit both phases [228]. BC inclusion above 5–10% in cement replacement, shown by the delay in the setting time due to the enhanced water demand and dilution effect of the cement contributing to a reduced rate of hydration [47]. Similarly, the BC type has shown influence on the setting time, for instance carbon-rich and lower reactivity BC leads to slower setting times, whereas BC with a higher ash content or alkaline attributes (woody biomass sources) can accelerate setting by rising the pH and improving pozzolanic reactions [127,202,207]. Although this is rare, BC containing sugar products could cause delays in the cement hydration process, which could possibly prolong the initial and final setting time of the cement composite [51].

6.5. Effect of BC on the Density of Cement Composites

The density of the cement composite plays an important role in its strength and durability characteristics, resisting aggressive environmental attacks. The addition of BC in cement composites affects the resulting composites depending on the properties of the BC source and production. BC with a higher carbon content is favorable for use in the cementitious composites, but it has a lower density compared to low-carbon BC [48]. According to a study, the density of BC ranges from 0.06–0.7 g/cm^3 [229]. Various studies reported the densities of different types of BC, including bagasse BC having a density of 0.76 g/cm^3 [187] and wood chip BC with one of 0.3–0.35 g/cm^3 [230]. The density of BC influences the density of cement composites. Poultry litter BC reduces the density of the cement composite when it is used as sand replacement [213]. The use of BC in cementitious composites as a partial replacement of cement is more prominent compared to its use as filler or fine and coarse aggregates. Different studies reported that the inclusion of BC in cement-based composites affects the density of the resulting composite. This is mainly attributed to the high porosity and low density of the BC [204,231,232]. The finer BC particles increase the packing density of the matrix by occupying the voids between cement and sand particles and producing dense and compact composite [44,129]. BC-added concrete exhibits almost the same density as the control mix, whereas at 5% replacement, a 2% reduction in concrete density occurs, which is not a significant variation [58]. Another study reported a change of 3–5% in the concrete density at a 5 wt% addition of BC in lightweight concrete, but this exhibits higher compressive strength compared to control samples [44]. Similarly, another study reported the loss of 5% in density when 10% BC was used as a substitute for cement [231]. The density of BC-incorporated composites range from 2245 to 2330 kg/m^3 in a fresh state, to 2013 to 2195 kg/m^3 in a hardened state [58]. It is recommended that further investigations are conducted on the effect of higher BC content on the density and brittleness induced to the cement composites beyond a 10% incorporation.

6.6. Effect of BC on the Modulus of Elasticity of Cement Composites

The modulus of elasticity of BC is low compared to the cement composites [58]. A study [223] investigated the use of sugarcane BC in the cement composites and reported an inverse relation between modulus of elasticity and BC percentage addition to the cement composites. A study conducted on food, rice, and wood waste BC reported that 1 wt% BC pyrolyzed at 300 and 500 °C slightly improved the elastic modulus, from 28.20 GPa to 29.82 GPa and 31 GPa, respectively, compared to plain mortar. The behaviors of 2% BC replacement exhibit the same trend, whereas 5% and 8% BC replacement resulted in 84% and 71% reductions, respectively, compared to plain mortar [184]. Similar results have been described in another study stating the decrease in the elastic modulus of the composites with a BC content higher than 1 wt% of cement in the cement-based composites [202]. The decrease in the elastic modulus of cement composites is attributed to the lower elastic modulus of BC compared to that of cement-based composites. The elastic modulus of pine wood sawdust reported in a study [233] was around 12 GPa when pyrolyzed at 350 °C, which is significantly lower than that of cement mortar. Therefore, the addition of low modulus BC particles can decrease the effective elastic modulus of the cement composites, and this effect is more prominent beyond 2% incorporation. However, the reduced elastic modulus makes the composite flexible, and therefore further investigation of its use in structures subjected to vibrations and earthquakes is suggested.

6.7. Effect of BC on the Compressive Strength of Cement Composites

The use of BC in cement composites extracted from different biomass sources could have a promising impact on the compressive strength, up to certain percentage. Various studies have reported positive effects from a small amount of BC addition on cement-based composite compressive strength compared to plain cement mixes [217,234]. The BC-modified mixes showed improved hydration and continued improvement in compressive strength over time [202]. The optimal content of BC for improving compressive strength varies conditionally to the BC source and processing method and characteristics. A study [202] determined that replacing up to 1% of cement with BC extracted from waste food and wood resulted in a considerable improvement in compressive strength. However, additional substitutions beyond 1% led to a decrease in strength. The increase in strength was attributed to the absorption capacity of BC, due to its porous morphology and high surface area leading to a reduced water-to-binder ratio and dense matrix. In contrast, BC from rice waste did not demonstrate a similar trend in strength improvement, up to 5 wt% replacement [78]. Another study investigated cement pastes modified by BCs extracted from rice husk, bagasse, coconut husk, wheat husk, and peanut husk through pyrolysis at 500 °C at the rate of 10 °C/min for a residence time of 60 min. The results reported that 2 wt% produced favorable results compared to plain mortars. BC extracted from bagasse exhibited an 18% increase in compressive strength, which was the highest of all compared to the control. The study also highlighted that BC with a higher amorphous silica were more effective in improving compressive strength [129]. Like the other properties, the size of the BC also affected the compressive strength of the cement composites. A study [202] investigated the influence of BC particle size on the compressive strength of high-strength concrete, and reported that the compressive strength of finer BC particles incorporated mixes were comparable to those of control, whereas the strength reduction was higher for larger particles at same replacement ratio. This phenomenon could be attributed to pore filling ability and the higher reactivity of the finer BC particles. To assess the effect of processing BC before its use in the cement composites, bagasse, and rice hush were used in a study, it was found that a 5 wt% BC replacement was optimum for compressive strength, irrespective of the BC source and treatment. However, higher replacements decreased compressive strength, which could be attributed to a dilution effect and reduced cement content [82]. The addition of BC reduces the water-to-binder ratio to a considerable level, which, if not catered for properly, could result in the self-desiccation of cement, resulting in chemical shrinkage. A study reported on the effects of the pre-soaking of BC and moist curing of cement composites for an optimal improvement in compressive strength [90]. The porous morphology of the BC particles acts as internal micro-curing tanks, and, during prolonged hydration, the pre-soaking of BC could better utilize the internal curing capability of the BC to provide water for hydration and reduce the risk of self-desiccation [116]. This internal curing could promote the production of hydrates at interfacial transition zones and supplement the pore-filling ability of the overall composite [74]. Similarly, the pyrolysis temperature of BC can also influence the cement composite strength characteristic. On the effect of pyrolysis temperature on the strength of concrete samples (carbon-cured), no substantial change was found between BC processed at 700 °C and 500 °C. However, at 1 wt% substitution of BC, as cement replacement showed a 10% increase, this showed an improved hydration under a carbon-curing regime [76]. At the same time, higher BC additions imparted brittleness to the composites and resulted in a decrease in strength. The influence of different types of BC, including pulp, rice husk, paper sludge, and poultry litter, on the compressive strength was studied in [78]. The results showed that the pulp and paper sludge BC at 0.1% addition resulted in an increased strength, by 10% and 6%, respectively. The optimal amount of BC that could positively impact the properties of cement composites, including compressive strength, is from 2 to 5% incorporation of BC with cement [51,197,201]. In contrast, a study reported a positive impact on the mechanical properties of modified concrete; up to the properties of that, the strength of BC-modified concrete was comparable to the control specimens, with up to 10% replacement of cement with BC. However, beyond 10%, the mechanical properties of all concrete mixes experienced a significant decline [212]. In conclusion, BC has a minor-to-moderate influence on the compressive strength of cement composites, depending upon type, dosage, morphology, and other properties of BC. However, further investigation into the optimization of BC use in cement composites is required for sustainable construction.

6.8. Effect of BC on the Flexural Strength of Cement Composites

The replacement of cement with BC enhances the flexural strength [58]. The enhancement in the flexural strength of the cement composites modified with BC is attributed to the pore-filling effect of the BC [235–237]. A study [85] reported that the use of palm BC in cement composites, by replacement of 1 wt% cement, increased the flexural strength of the modified composite by 5%. Another study reported a similar trend for BC incorporated in concrete [210]. However, the flexural strength decreased beyond a 5% replacement of cement, due to the formation of increased voids and insufficient dispersion. Similarly, the rice husk BC exhibits an improvement in the flexural strength at 2% replacement of cement, whereas, from 6 to 10%, the increase was minimal [48]. *Washingtonia filifera* palm BC, pyrolyzed at 500 °C, resulted in a 5% increase in the flexural strength of cement composites [208], and almost the same trend can be seen for bagasse BC [223]. Jointly, these findings indicate that excessive porosity in BC-based cement composites at higher dosages results in a less dense structure, thereby reducing strength capacity, as reported by other researchers [223,238]. A study [239] conducted on BC extracted from rice husk and poultry litter improved the flexural strength of cement composites by 20% when added to the mixture at 0.1% as a partial replacement of cement. They concluded that BC has the capability to enhance concrete properties and can replace minimal amounts of cement. Whereas, in another study conducted on rice husk ash and rich husk BC, this resulted in a decrease in the flexural strength of modified mortars, by 16 to 27% compared to plain cement mortar [182]. This suggests that the pozzolanic reaction and filler effect by rice husk ash and rich husk BC have a less substantial effect on the development of flexural strength compared to compressive strength. Similarly, waste rice and discarded food-based BC resulted in an 18% and 14% reduction in the flexural strength of the modified cement composite for a 5% replacement of cement with BC [202]. This decrease in flexural strength is attributed to the dilution effect of cement and the poor dispersion of BC particles, which aligns with the conclusions from other researchers [186,240,241]. Smaller BC particles have shown a significant improvement in strength compared to larger sizes [178,204,208].

BC with a particle size of less than 500 µm resulted in a 5% improvement in flexural strength [204], which is lower than the results shown by BC with a particle size of less than 30 µm [178], 63.5 µm, and 200 µm [204]. The most significant enhancement was noted with high surface area BC particles measuring less than 30 µm [178], which developed a 13% increase in the flexural strength capacity of the BC-modified matrix. This improvement is attributed to the capacity of finer BC particles to fill more voids, helping hydration and reinforcing the bond between the BC and the cement matrix.

Various studies reported the effect of the curing regime on the flexural strength of BC-modified cement composites [90,215]. The results of these studies recommend that moist-cured BC resulted in the higher strength of the composite compared to air-cured BC-modified composites. A study [238] utilized wood chip BC as a filler in cement mortar to assess the flexural strength of the modified matrix, a 6% increase in flexural strength, with a 1% BC having the highest increment observed. Various studies [83,129] attribute the enhancement of the flexural resistance of BC-modified cement mixtures to their denser microstructures and decreased matrix pores. Therefore, it can be concluded that finer BC particles are more effective in enhancing the flexural strength of BC-modified cement composites.

6.9. Effect of BC on the Tensile Strength of Cement Composites

BC has the tendency to improve the tensile strength of cement composites when substituted as filler or at a lower level of cement replacement than in the cement composites. The type of BC and curing regime also influences the tensile strength of the composite. BC improves compressive strength more than tensile strength in cement-based composites [58]. The tensile strength of the cement composites ranges from 1.9–4.9 MPa with BC inclusion to the tune of 0.1–5% [58]. The effect of pre-soaked and dry BC being pyrolyzed at 300 and 500 °C, at a rate of 10 °C/min, was studied for the tensile strength of cement mortars incorporated with 2% BC as a partial replacement of cement. The results showed a 6% to 7.5% improved tensile strength under curing for 28 days compared to the plain cement mortar [90]. Another study reported a similar trend up to 5 wt% of BC as a partial replacement of cement; however, higher replacement, past 5%, led to a decay in tensile strength, which was attributed to the increased porosity of the cement composites [82]. A study [83] reported a decrease in the splitting tensile strength at elevated temperatures of the cement composites modified with BC at 1% and 2% compared to the control samples. This decrease in strength is attributed to the porous morphology of the BC and the induced porous interface between cement paste and BC producing weak links when exposed to tension. During the tensile forces, this existence of pores at the interface speeds up the propagation of cracks after initiation, resulting in decreased tensile strength. A maximum of 12% reduction in the split tensile strength at normal curing conditions at 28 days was observed at 2%, which is more than in the compressive strength [83]. A study investigated the influence of rice husk, paper sludge and poultry litter BC on the tensile strength of concrete, and depicted the decrease in splitting strength with the addition of BC. However, a slight increase was shown by rice husk BC at 0.1% [78]. Another study reported the same trend for waste wood BC at a 0.65 wt% addition [191]. BC, when used as filler, has a significant influence on split tensile strength as compared to cement replacement. The tensile strength range for BC as filler is 2.9 to 3.9 MPa, whereas, for cement replacement, it is from 2.9 to 3.2 MPa [58]. Similarly, various studies have reported that incorporating milled BC decreases the tensile strength of the cement composites [242,243]. To utilize the carbon capture capacity of BC at a higher percentage of addition or cement replacement, it is important to improve its splitting tensile capacity in cement composites. Therefore, the excellent performance of fibers in improving the splitting strength of cement composites could be clubbed together with BC for its optimal and maximum possible outcomes for the production of sustainable cement composites.

6.10. Effect of BC on the Durability of Cement Composites

Cement-based composites experience various aggressive environments which affect the durability attributes of the composite. It is therefore important to access the durability characteristics of novel material-modified cement-based composites to access their effects on chemical characterization and long-term performance. Similarly, BC utilization in cement-based composites has grown in importance due to its various positive characteristics, including carbon sequestration and enhancing matrix properties. Various researchers [41,53,187,193,207,244] have studied the durability of BC-modified cement-based composites, but due to the numerous variables associated with BC type, production technology characteristics, and size, the available literature is still limited. Cement-based composites' durability is substantially influenced by the porosity of the composite, which is mostly affected by the water-to-cement (w/c) ratio. A low w/c ratio has normally led to lower porosity, leading to improved durability. BC mechanics in cement-based composites contribute to their enhanced durability. BC produces calcium carbonate, which bridges the micropores within the composite matrix, thus decreasing their permeability [41,42,245]. A BC porous microstructure consumes the mixing water during the hydration process, which efficiently lowers the local w/c ratio and increases the water tightness of the composite [42,214]. This entrapped water, in the pores of BC particles due to capillary suction, acts as water tanks, offering supply for continuous hydration in the composite [201,246,247]. Furthermore, the filler effect in BC produces a denser microstructure of the composite. These mechanisms jointly influence the permeability of the composite, thereby reducing the ingress of deleterious constituents into the composite and enhancing its overall durability.

Various researchers [15,41,51,57,215] have suggested that the use of powdered BC in cement-based composites successfully fills voids, thereby facilitating the hydration process and substantially reducing permeability. A study [184] reported that the inclusion of 1 to 3 wt% sawdust BC significantly enhanced water penetration resistance by up to 35%, while a 5 wt% incorporation resulted in a nominal reduction in water permeation by up to 8%. It can be seen from the literature that up to a 5 wt% addition as cement replacement can reduce permeability without effecting the mechanical characteristics compared to conventional composites [41,42,213]. Cement-based composites are prone to autogenous shrinkage due to the self-desiccation phenomenon of the cement. BC offers the prolonged provision of water, which is stored in the pores of BC particles. A study reported a 16.3% reduction in autogenous shrinkage in 2% BC-modified cement composites [205]. Another study reported a reduction of about 13% in the autogenous shrinkage of the composite modified with 1 to 4% BC [209]. Similarly, sawdust BC reported a 20% reduction in the composite shrinkage, having 2 to 5% BC compared to control specimens [201]. However, a BC source containing salt should be properly processed before being transformed into BC because of its negative effects on the shrinkage of the composite [51]. Similarly, the presence of higher amounts of sodium could cause alkali–silica reactions in the composite, causing cracking and silica loss [248]. BC could be used as a cement substitute in cement-based composites, with the capability to reduce shrinkage [205,209]. The optimal amount of BC that could positively impact the properties of cement composites including shrinkage is up to 5% incorporation of BC with cement [51,201,205,207].

BC has exhibited significant potential for reducing the ingress of sulfate and chloride ions in cement composites, thereby improving their durability. A study [187] reported that 5 wt% bagasse BC incorporation improved the compressive strength of composites when exposed to 5% H_2SO_4 solution for 56 and 90 days. This improvement is recognized as the pore-filling effect and the internal curing properties of BC, creating a compact, less porous structure [187,249]. The porous structure of BC particles acts as a physical barrier, delaying the ingress of these harmful ions into the cement composites. Another study [52] stated that cement mortars with 2 wt% rice husk BC replacement demonstrated 17% compressive strength improvement compared to control specimens when exposed to Na_2SO_4 solution for 42 days. The enhancement is attributed to the formation of ettringite from reactions between tricalcium aluminate and sulphate ions, initially making the structure of the composite dense. However, exposure for 120 days led to strength damage due to formation of too much ettringite and cracking [52]. Similarly, studies on the effect of BC on chloride ion ingress in cement composites have exhibited positive results. A study [53] found that using BC up to 5 wt% as a replacement of cement has improved the microstructure of the cement composites, reducing chloride ingress. This enhancement is attributed to improved hydration and decreased permeability [53,250]. A study [199] stated a 32% decrease in chloride diffusion coefficient when 1 to 3 wt% waste wood BC was used as partial replacement of cement. However, [52] examined a loss in compressive strength in BC-modified mortars exposed to NaCl high-concentration solutions due to the formation of chloro-aluminate and internal cracking. In this study, finer BC with high specific surfaces showed notable resistance to chloride ion attack. The optimum BC content is about 2 to 5 wt%, as higher replacement rates may reduce the durability characteristics of the composites [54,193]. However, further research is recommended to fully understand the long-term effects of BC on the durability characteristics of the cement-based composites.

7. Environmental Benefits of BC Utilization in Cement-Based Composites

BC is a sustainable material and is recognized for its capability to remove pollutants. It has been used to address various environmental problems, such as cutting GHG emissions, treating wastewater, and improving soil quality [45]. BC has been used in numerous fields for a long time but has recently gained publicity in the construction industry, due to its carbon sequestration capacity, in addition to other positive impacts. It offers a win–win situation by utilizing waste; reducing the load on landfills; producing sustainable construction materials; and reducing CO_2 emissions to, and capturing CO_2 emissions from, the built environment [45,47,82,90,98,184]. Biomass waste ending up in landfills could cause deleterious emissions [251]; however, it can be used to produce BC and other useful products [90]. A study reported that waste wood utilization in cement composites is both an economical and environmentally friendly practice [74]. Similarly, BC derived from peanut shells can replace small amounts of cement, enhancing the cement hydration, freshness, and the hardened properties of the mixtures [51]. Utilizing waste products in cement and concrete products is a viable step in the recycling of waste materials. Furthermore, BC has the potential to lower cement demand and the CO_2-eq emissions associated with cement production [90,113]. The production of BC itself is an energy-intensive process which releases GHG emissions during production, so careful consideration is required during the selection of biomass and technology for the conversion of biomass into BC. A study reported that the BC-based cement mortar with 1% of sawdust BC pyrolyzed at 300 °C and 500 °C has a price of 225.38/m^3 and 226.21/m^3,which is almost the same as that of the control mixture (225.94/m^3) [90]. Another study conducted on poultry waste, rice husk and paper sludge BC-based cement mortars with a 1% replacement has reported the price of 144.12, 146.46, and 144.46, respectively, per meter cube of the mixture, which is close to the price of control mix (149.18/m^3) [78]. However, another study reported that a BC-based concrete mixture has a lower cost and environmental implications compared with traditional concrete mixtures [58]. To completely understand the complexities of the environmental and economic impacts of BC-based composites, proper life cycle assessment (LCA) and life cycle cost (LCC) analysis is required [56]. An LCA-based study indicates that BC can possibly reduce GHG emissions by 870 kg/ton of CO_2-eq in the dry biomass [252]. The environmental impacts from the conception to final utilization of forest waste wood, employing a cradle-to-grave approach, were presented in a study [253], which confirmed its environmental advantages and economic viability. The production of BC (1 ton) using the gasification technique resulted in 263.5 Kg CO_2-eq, including the raw material collection and power integrated with the combustion from syngas produced during the process [254]. In the extended scenario of concrete, the GHG emissions were 798.7 kg CO_2-eq by 1 ton of Portland Cement [255]. Another study based on LCA reported that, for concrete application, the GHG emissions are −567.8 kg CO_2-eq with the reduction of 349.9 kg CO_2-eq including the effect of avoided aggregate and cement for a functional unit [256]. According to the evaluation in [257], 1 m^2 of green area absorbs about 4.29 kg of CO_2, while the absorption value of CO_2 per tree is about 13.3 kg. Considering the environmental threat posed by the construction industry in particular, the need for carbon capture in cement composites and its proper LCA and LCC assessment is required from a broader perspective.

8. Carbon Sequestration Potential of BC in Cement-Based Composites

Implementing carbon-neutral or carbon-negative cement composites is an important and cost-effective plan for reaching sustainable development goals. The incorporation of BC into cement composites presents a promising strategy for carbon sequestration within the construction sector that promotes sustainability. BC, when utilized as an addition to or partial substitute for cement or fine aggregates, comprises around 80% stable carbon, and has the potential to sequester between 0.5 and 1.5 tons of CO_2 for each ton of BC employed [90]. The efficiency of this sequestration is dependent on various factors, including the type of biomass, method of production, proportion of BC in the concrete mixture, and conditions under which the cement composite is cured [77]. The main factor that affects the carbon capture capacity of cementitious BC-based composites is the presence of unstable carbon in BC, which depends on the biomass source and parameters of the conversion process [258] Cement-based composites, such as cement and concrete, through the carbonation mechanism during its hydration process, sequester the CO_2 [108,259–261]. The cementitious composite contains an unstable compound of calcium hydroxide which, if attacked by any aggressive environment, can cause harm to the composite structure through unfavorable reactions. However, the absorbed CO_2 reacts with calcium hydroxide to create stable and densified calcium carbonate precipitation, resulting in CO_2 sequestration [127]. BC's porous nature offers suitable sites for precipitation formation and enhanced carbon capture properties [201,207,259]. The formation of secondary cementitious products in the pores of BC-based pervious concrete made by the addition of 3% cement replacement can be seen in Figure 13 [200]. The porous nature of BC can be seen in the figure which serves as a nucleation site for the formation of secondary hydration products. Similarly, it can be seen in the magnified portion (to the right) of Figure 13 that CSH is formed in the BC pores. Secondly, enhanced cement hydration due to BC produces more calcium hydroxide, which allows more CO_2 capture through carbonation [51,201,202,223]. Consequently, the advantageous properties of BC could substantially augment the potential of biochar–cement matrices in mitigating GHG emissions [211]. A study reported that using waste wood BC coupled with silica fume and fly ash in concrete can sequester 10% more CO_2 through the process of carbonation [55]. Another study reported that corn straw BC (pyrolyzed at 500 °C) used as partial replacement of cement by 5 wt% could save 32.4 kg GHG emissions from cement, and 15.8 Kg from the use of BC per meter cube of concrete. As a result, a total decrease of 14.7% could be achieved from GHG emissions, which is estimated by considering all GHG emissions from concrete mixture materials [42]. Similarly, peanut shells BC pyrolyzed at 500 °C and 700 °C, used in concrete at 5 wt% and 3 wt% of cement, captured about 387 kg and 980 kg of CO_2-eq, respectively [44]. Gupta and Kashani reported that using 1% and 3% BC by the weight of cement can reduce 0.018 kg and 0.052 of GHG emissions without taking into consideration the energy and transportation consumption [51]. Storing CO_2 in concrete structures to capture the carbon is a promising concept [45]. Thus, various researchers [42–44] have proposed that the use of BC in cement composites could be a sustainable solution to address low-carbon cement composites, establishing proper environmentally friendly structures. In addition to its environmental advantages, the vast use of carbon-neutral cement composites enables an eco-friendly cement and construction sector, bypassing its reliance on a simultaneous growth in carbon capture, utilization, and storage [262]. A study reported that 2.3 gigatons of CO_2 have been released by the cement sector in 2019, whereas the carbon capture, utilization, and storage captured only 75 kilotons/year, which leaves a huge deficit [263]. In addition to its carbon sequestration abilities, BC may offer several other benefits to concrete, such as improved strength, enhanced durability, decreased permeability, and potential thermal insulation characteristics. It can be summarized that incorporation of 1 to 5% BC as a partial replacement of cement could reduce about 20% of CO_2 emissions due to sequestration properties if BC is compared to non-modified cement-based composites. Additionally, the use of BC in concrete has the potential to reduce the CO_2 by up to 0.6 kg per kg of BC addition, depending on the biomass source and pyrolysis conditions. This seems difficult due to various limitations but, if achieved at a full-scale level, around 1.36 tons of CO_2 can be captured and stored within the buildings. Nevertheless, challenges persist in achieving a consistent quality of BC, optimizing concrete mix designs for diverse applications, and evaluating long-term performance. As research in this area advances, BC-modified cement composites hold substantial potential as a sustainable construction material that could significantly mitigate the carbon footprint of the built environment. Therefore, it is required to reinforce these policies and practice codes in the implementation of carbon-neutral cement materials and composites. Production of BC on a massive scale is required to amplify its mass-scale utilization in concrete structures for its long-term carbon sequestration applications.

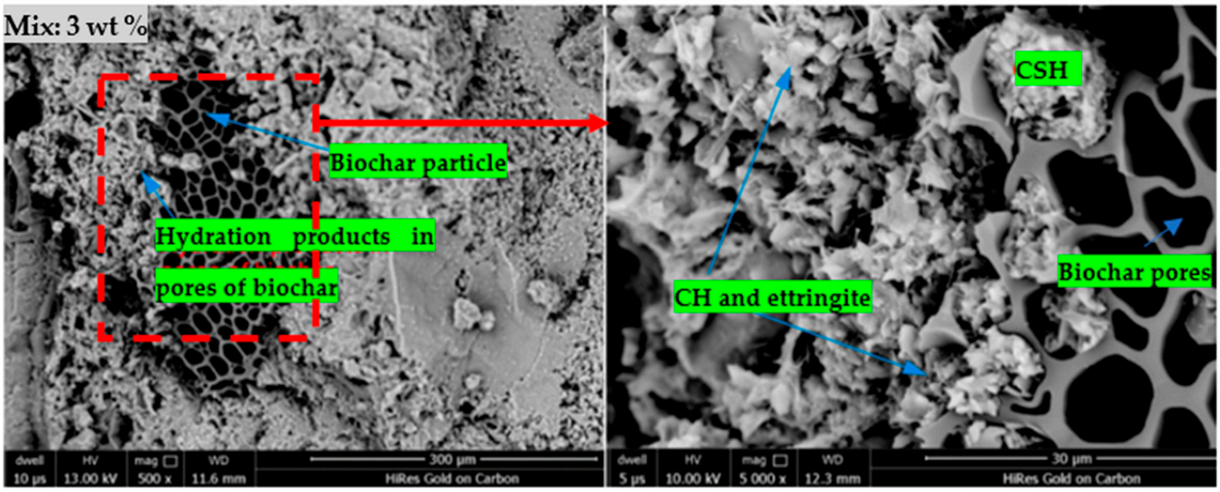

Figure 13. Formation of secondary cementitious compounds in the pores of BC [200] (license no. 5894460125832).

9. Way Forward Towards Advancing Sustainability in Construction

In general, the use of BC in cement-based composites offers promising prospects for sustainable construction and revolutionizing the construction sector by playing its part in achieving sustainable development goals. To fully understand its capability, further research is required in several key areas. Firstly, optimizing BC properties through varying biomass sources, production attributes, and post-treatment methods for synchronization of various BC types used in cement-based composites to enhance their compatibility with the BC-modified composites. Secondly, in-depth characterization of their fresh and mechanical properties, durability, and performance is needed to identify the advantages of BC-modified cement-based composites. Thirdly, investigating their carbon sequestration capacity, LCA and LCC assessment analyses of the BC-modified cement-based composites are required to assess its environmental and economic impacts on the construction industry. Fourthly, establishing standardized testing methods, guidelines, and specifications will foster widespread implementation and ensure quality control in BC-modified cement-based composites. Finally, research on the performance of BC-modified cement-based composites for specific structural purposes under different conditions and cost-effective production methods will contribute to its application and economic viability. By addressing these key areas, the construction industry can confidently integrate BC into sustainable and high-performing sustainable construction practices.

10. Conclusions

The purpose of this study was to carry out a scientometric review and a traditional review of the available research on BC-modified, cement-based, and carbon-negative composites for sustainable construction. The scientometric assessment was used to identify the relevant fields of study, the yearly publication trend of the articles, the most prominent sources, the co-occurrence of the most used keywords, highly cited authors and articles, and actively participating countries in the current field of study on BC-modified cement-based composites for sustainable construction. Additionally, the influence of BC pre- and post-production properties and production techniques on its use in the cement-based carbon-negative composites were examined. Furthermore, the influence of BC on the fresh state, hardened state, carbon sequestration, and LCA properties of the BC-modified, cement-based, carbon-negative composites were reviewed. The following conclusions were drawn based on the review conducted.

1. Scientometric assessment of the research data extracted from Scopus database from 2010–September 2024 revealed that a total of 189 documents were published in the current research area after applying the various referred filters. Among these, Engineering, Material Science, Environmental Science, and Energy accounted for 27.1%, 21.7%, 17.7%, and 9.75% documents, respectively. The research trend until 2017 was almost negligible. However, after 2017, a notable increase can be seen until 2024. The three top contribution journals were CBM, the JCP and CCC with 36, 21, and 16 publications, respectively. The most frequently co-occuring identified top ten keywords were BC, compressive strength, cements, concrete, concretes, carbon dioxide, sustainable development, water absorption, and carbon sequestration. Additionally, China, India, Italy, United States, and Singapore are at the top of the list of contributing countries based on the number of documents produced.
2. BC is produced by various thermochemical methods. However, pyrolysis is the most commonly employed method, and is easily scalable for the commercial production of BC. The physiochemical properties of BC depend on the biomass source and the production technology and parameters employed during conversion, including temperature, residence time, and rate of heating. Temperature mainly affects the pH, specific surface area, and porosity; however, the bulk density, carbon content, and various oxides are mainly dependent on the biomass source.
3. BC particles can be utilized both as additives and partial replacements of cement. Cement-based composites modified with finer BC particles exhibit better performance due to a high specific area and filler effect. Finer BC particles enhance early-age strength by promoting the cement hydration process attributed to the internal curing capability of the BC. Due to enhanced hydration process, BC addition resulted in a reduction in the initial and final setting times of cement composites.
4. Cement composites modified with BC experienced a decreased permeability due to the filler effect and carbonation process. Similarly, the BC addition reduced shrinkage due to the filler effect and continued internal curing due to the absorbed water in the pores of BC particles.
5. Addition of BC decreases the workability of the cement-based modified composites due to their porous morphology. BC added in the cement composites at a higher dosage could significantly reduce the flow characteristics of the cement composite attributed to the water capture capacity of the BC and dilution effect. About 2.5% to 15% of reductions in the workability have been reported at higher dosage of BC. Therefore, proper plasticizers could be used to keep the mix workable for its intended use.
6. The addition of BC in the cement composite decreases the effective elastic modulus of the composites. The decrease in the elastic modulus of cement composites is attributed to the lower elastic modulus of BC compared to that of cement-based composites. Despite this, BC up to 2% has no significant effect on the overall elastic modulus as, up to 2%, the dilution effect of the BC addition is not prominent within the composites.

7. The optimal percentage replacement of cement with BC ranges from 1% to 2% and has a significant effect on compressive and flexural strength. The increase in strength is attributed to the absorption capacity of BC, due to its porous morphology and high surface area leading to reduced water to binder ratio and dense matrix. Higher percentages beyond 6% to 10% showed a significant reduction in the strength characteristics of cement-based BC-modified composites, which could be attributed to the dilution effect and a reduced cement content.
8. The increase in the splitting tensile strength is minimal compared to the compressive strength. This decrease in strength is attributed to the porous morphology of the BC and the induced porous interface between cement paste, and BC producing weak links when exposed to tension. During the tensile forces, this existence of pores at the interface speeds up the propagation of cracks after initiation, resulting in decreased tensile strength.
9. BC incorporation of up to 5% enhanced the durability of the cement composites against chloride ion penetration and sulphate attack. It also decreased the permeability of the matrix and reduced the early shrinkage due to the prolonged curing effects. These attributes are associated with the filler effect of BC particles, increased hydration, and improved microstructural properties. The controlled incorporation of BC can serve as an efficient approach for enhancing cement composites' durability; however, further examination is suggested for long-term performance optimization.
10. The incorporation of BC into cement composites presents a promising strategy for carbon sequestration within the construction sector, promoting sustainability. In BC-modified cement composites, the carbonation process sequesters CO_2 through its reaction with calcium hydroxide to create stable and densified calcium carbonate precipitation, making the composite compact and dense.
11. Utilizing BC in cement-based composites supports a circular economy model in the construction industry, by converting biomass waste into a constructive material and thus reducing its reliance on cement. This approach would prioritize waste reduction, resource efficiency, and long-term ecological benefits. This move is vital for building a more robust and sustainable built environment.

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