

Biochar as Cement Replacement to Enhance Concrete Composite Properties: A Review

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Abstract: In recent years, concrete has been accessible and economical in the construction industry, resulting in high demand for its components. Cement is known for its negative impact on the environment, which has led researchers to investigate alternative supplementary materials. Recently, biochar has been proposed as a replacement to cement in small amounts, with an optimum amount of 0.08–5, resulting in increased strength and enhancement of other properties of concrete composites. The biochar production process and its components are more economical and environmentally friendly than that of cement. In this review, we focus on research highlighting the properties of biochar that aid in the enhancement of biochar mortar and concrete composite properties. We explore properties of biochar such as water absorption, as well as compressive, flexural and tensile strength. Progress has been made in research on biochar concrete composites; however, additional investigations are required with respect to its carbon-sequestering abilities and life cycle assessment for its production process.

Keywords: cement; supplementary cementitious materials; biochar; biochar concrete composites; economical; carbon sequestering



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1. Introduction

Concrete is one of the most highly demanded building materials worldwide due to its unique advantages in comparison to the other materials used in the construction industry [1]. It is among the most accessible materials due its low cost, and high strength [2]. More than 10 billion tons of concrete are generated annually generated [3]. Growth in the construction industry has led to considerable amounts of cement being produced [2]. Recent research has proven that cement production has negative impacts on the environment, with high demand for concrete production increasing those impacts over the years [1]. These impacts include the ecological imbalance caused by the harvesting of raw materials, as well as the release of greenhouse gasses and dust (particulate pollution) during its production. It has been speculated that a decrease in cement demand would decrease pollution released during its production. Researchers have investigated mixing cement with alternative materials (fly ash, recycled aggregate, rice husk ash and biochar from various biomasses) to promote more sustainable and economical concrete production [1,4–6].

Biochar is a carbon-rich sustainable material obtained via thermochemical combustion of biomass, animal waste, municipal waste and other organic materials in an oxygen-limited environment [7]. It has attracted the attention of researchers owing to its unique properties, such as high surface area, high porosity, functional groups, high cation exchange capacity and stability, making it suitable for various applications. Biochar is also an advantageous sustainable material owing to its fast and easy preparation, eco-friendly nature, reusability and cost-effectiveness [8]. It has been utilized in many applications, such as wastewater

treatment [9], chemical recovery [10], agriculture [11], carbon sequestering [12] and anaerobic digestion [13]. Recent research has proven that biochar can be used as a supplementary cementitious material (SCM) for sustainable concrete production [6,14–16].

A handful of reviews have been conducted on biochar incorporation in building materials [17–21]. These reviews discussed the mechanical properties of biochar, such as workability, hydration kinetics and durability. The authors of these reviews highlighted the economic and environmental benefits of using biochar as a cement replacement. However, none of these reviews covered the use of biochar in concrete or mortar mix design or discussed limitations of past research in depth, which we cover in this review. Herein, we focus on the varieties of biomass used for the production of biochar, providing an overview of the biochar production process via pyrolysis, the types of biomass used as cementitious material and the performance of biochar concrete composite mixes under stress. Additionally, this study highlights the favorable properties of biochar through characterization and analysis of past experiments involving the use of biochar as SCM for concrete or mortar composites. Furthermore, we discuss the possibility of further investigations with respect to the carbon-sequestering abilities of biochar, as well as the environmental and economic benefits of the use of biochar in concrete composites.

2. Biochar Production

The products that result from the conversion of biomass into fuel include biochar, syngas and bio-oil. The most popular processes for the conversion of biomass to char are gasification, pyrolysis, torrefaction, flash carbonization and hydrothermal carbonization [7,8,17]. Table 1 provides an example for each thermochemical conversion and their product yields. In this review we discuss the pyrolysis process, which is the most commonly used process [8,17]. The biomass used for these processes is composed of cellulose, hemicellulose and lignin components. These components are thermally decomposed during pyrolysis [8]. Yaashikaa et al. (2020) [8] studied multiple processes to determine which process is most favorable in terms of cost, ease of preparation and maximum yield. There are two known methods to achieve pyrolysis, fast pyrolysis and slow pyrolysis, which differ in terms of the heating rate, temperature, residence time and pressure. Generally, fast pyrolysis is used when the maximum yield is desired in the form of a liquid product, whereas slow pyrolysis is conducted if the maximum yield is desired in the form of a solid product, i.e., biochar [22]. Al Arni (2018) [22] conducted an experimental study to compare the two types of pyrolysis using bagasse produced as a byproduct of extraction of sugar from sugarcane. All experimental conditions and process were kept constant except for the residence time and heating rate. The study confirmed that slow pyrolysis is preferable when biochar is the desired product. Due to the thermochemical conversion of biomass in the absence of oxygen, the material undergoes chemical and physical changes. In this transformation process, pores are formed as a result of the release of vapors, and eventually, a carbon skeleton of the material is formed. The most common changes are the loss of mass, formation of pores, increase in carbon content and decrease in oxygen content. The yield [23] and surface area [24] of the resulting biochar, as well as its stability in terms of the oxygen-to-carbon ratio [25], were found to be strongly dependent on the pyrolysis temperature. Table 2 summarized the types of characterization analyses that have been conducted in recent research on biochar [15,21,26,27].

Table 1. Thermochemical conversion techniques.

Technique	Temperature (°C)	Biomass	Residence Time	Yield of Biochar (%)	Yield of Bio-Oil (%)	Syngas Production (%)	Ref
Pyrolysis	390–980 (slow)	Sugarcane	60 min	30–33	19–27	26–37	[22]
	380–780 (fast)	Sugarcane	20 min	27–28	38–47	11–21	[22]
Hydrothermal carbonization	220	Rice husk	60 min	68–76	N/A	N/A	[28]
Gasification	550–920	Wood	30 min	11–16	N/A	≈80	[29]
Torrefaction	200–300	Olive stone	30–120 min	40–90	8–49	0.3–10	[30]

Table 2. Biomass and biochar categorization analyses according to their properties.

Analysis Method	Purpose
Proximate	Determination of moisture content, volatile matter and ash content.
Ultimate	Determination of C, H, N, O, H/C and O/C contents.
SEM (scanning electron microscopy)	Biochar and biomass morphology (pore size) characterization.
BET (Brunauer–Emmett–Teller)	Determination of surface area, pore volume and mean pore diameter.
FTIR (Fourier transform infrared spectrometry)	Determination of functional groups.
XRD (X-ray diffraction)	Assessment of the presence of various crystalline materials.
TGA (thermogravimetric analysis)	Determination of thermal stability.
NMR (nuclear magnetic resonance)	Determination of structural composition.
EDX (energy-dispersive X-ray spectroscopy)	Determination of elemental composition.
PIDS (polarized-intensity differential scattering)	Determination of particle size distribution (PSD).
ICP-MS (mass spectrometry with inductively coupled plasma)	Elemental and isotopic inorganic analysis.
EDS (electron-dispersive spectroscopy)	Determination of elemental composition.
PDS (particle size distribution)	Determination of the size of the majority of particles.

Fast pyrolysis requires high temperatures, and rapid heating leads to increased energy consumption, making the process more expensive in comparison to slow pyrolysis. As shown in Table 1, despite the higher energy consumption, fast pyrolysis yields less biochar than slow pyrolysis, making it a favorable method for the production of biochar as a cementitious material. Yaashikaa et al. (2020) [8] reported that the conditions required for fast pyrolysis are: (i) a biomass heating rate of 100 °C/min, (ii) short intervals between biomass particles and pyrolysis fumes in the range of 0.5–2 s at high temperatures and (iii) moderate pyrolysis temperatures of 400–600 °C. In the same study, it was also reported that in most slow pyrolysis cases, the heating rate is 5–7 °C/min or lower, with a residence time of more than 1 hr. The authors also mentioned that this type of pyrolysis is most commonly used because it requires low energy consumption and yields more biochar than slow pyrolysis. These findings prompted Gupta et al. (2018) [31] to conduct a study on slow pyrolysis conducted in the temperature range of 250 °C to 500 °C at a heating rate of 10 °C/min using food waste, rice waste and wood waste as biomass. Gupta and Kua 2018 [15] reported that a heating rate of 10 °C/min and pyrolysis temperatures of 300 °C and 500 °C yielded 40% and 25% biochar, respectively. Study conducted by Maljaee H. et al. 2021 [32] has also used 500 °C as their slow pyrolysis temperature with residence time 20 min. Table 3 provides details about the biomass materials used in previous studies to produce biochar used as cement replacement.

Table 3. Summary of various studies on biochar production and characterization, as well as optimum biochar content as cementitious materials and respective composite properties and limitations.

Biomass	BC ^a Characterization		Temp (°C)	Sample	BC	Optimum BC	Ratio			Tested Properties	Limitations of Research	Ref									
							S:C ^b	A:C ^c	W/C ^d												
Wood waste (sawdust)	• C: 62.25% • O: 25.60% • K: 0.42% • Si: 0.40% • 2–400 nm pores	300	Dry BC300_M	2	2% with curing in fog room at 26 ± 2 °C (Pre-soak BC500)	2.75:1	N/A	0.4	• Compressive strength: inc ^e by 26% (72 MPa) of Pre-soak BC500. • Degree of hydration: inc by 5% (67%) of pre-soak BC500.	• Understanding the absorption–desorption kinetics of dry biochar and pre-soaked biochar within hardened mortar mix. • Investigating biochar produced from other feedstocks with varying parameters, such as temperature and heating rate, as potential materials for internal curing.	[15]										
			Presoak BC300_M						0.25			• Hardened density porosity: dec ^f by 17% (≈0.83 mm) of pre-soaked 500BC. • Flexural strength: inc by 6% (≈13 MPa) of pre-soak BC500.									
			Dry BC500_M						0.4			• Split tensile strength: inc by 12% (≈4.7 MPa) of pre-soak BC300_M. • Sorptivity: inc by 33% (0.64 × 10^{−2} mm/s^{0.5}) of pre-soak BC500.									
			Presoak BC500_M						0.22			• Depth of water penetration: dec by 68% (≈7 mm) of pre-soak BC500. • Investigation of curing: moist curing preferable.									
Waste wood sawdust (Mason pine wood)	• TGA • XRD • SEM	500	• Yield 30% • 152 m²/g • 0.036 cm³/g	• 500-1 • 500-2 • 500-5	1% CO ₂ curing	1:1	N/A	0.3	• Compressive strength: inc by 8.9% (≈73 MPa) with 700-1 and 6% (≈71 MPa) with 500-1.	• Carbon-sequestering abilities to analyzed under different curing conditions.	[14]										
			700	• Yield 25% • 388 m²/g • 0.057 cm³/g					• 700-1 • 700-2 • 700-5			• Hydration process: inc by 12% (≈235 J/g) with 700-5. • Different curing methods: concrete mix with CO₂ curing most favorable.									
		Rice husk		• Si:246.7 mg/g • Ca: 4.58 mg/m • C: 36.06% • O: 49.23%					500			• RH0.1 • RH0.75 • RH1	• 0.1 • 0.75 • 1	RH0.1	N/A	6:1	0.32	• Water absorption: inc by 45% (8%) with RH0.25. • Compressive strength: dec by 10% (≈34 MPa) with RH0.1. • Splitting tensile strength: inc by 5% (≈39 MPa) with RH0.1. • Flexural strength: inc by 23% (≈4.8 MPa) with RH0.1.	• Long-term influence of biochar in its strength development. • Detailed durability studies to determine the potential of biochar reducing the shrinkage and carbonation resistance. • BET analysis to understand the effect of surface area, pore size and volume on the tested mechanical properties.	[27]	
			Pulp and paper mill sludge									• TGA • ICP-MS • XRF	• Si: 15.9 mg/g • Ca: 49.21 mg/g • C: 30% • O: 68.5%								• PP0.1 • PP1
Poultry litter	• Si: 29.3 mg/g • Ca: 33.3 mg/g • C: 19.03% • O: 77.63%	450		• PL0.1 • PL0.75	• 0.1 • 0.75																
			Eucalyptus plywood	• XRF • EDX • BET: 250 m²/g • C: 85.13% • Si: 0.4%	500	• G3 • G4 • G5	• 3.2 • 6.5 • 9.5	6.5%	N/A	5:1	0.35	• Compressive strength: inc by 30% (≈12.3 MPa) with 6.5% of BC. • Splitting tensile strength: inc by 25% (2 MPa) with 3.2% of BC. • Solar reflectance: dec by 17% (0.138) with 3.2% of BC.	• Investigation to determine solar reflectance and carbon-sequestering abilities. • Further studies on the water purification and hydration of BC cement pervious concrete.								[33]
• G6	• 13.5	• Water absorption: inc by 32% (≈3.7%) with 3.2% of BC. • Water permeability: inc by 4% (≈5.2 mm/s) with 3.2% of BC. • Porosity: inc by 14% (33%) of 3.2% of BC.																			
Waste wood chips	• pH: 10.22 • TGA • ICP-MS • PSD • BET: 28.06 m²/g • Water capacity • SEM	700				M BC 2%_Sost						2		2% Curing with humid environment 24 ± 1 °C	3:1	N/A	0.5	• Flexural strength: dec by 2% (4.54 MPa) with 2% BC as substitute. • Fracture energy: inc by 36% (0.071 N/mm²) of 2% used as filler.	• Exploring the application of BC derived from different biomasses, such as food and other wood waste. • Testing the compressive strength for improved mechanical properties.	[6]	
						M BC2%_s_Sost															
			Mixed sawdust	• C: 87% • 196.92 m²/g • 0.071 cm³/g	500	MWBC	• 1 • 2 • 5	1–2 wt% FWBC and MWBC	2.75:1	N/A	0.4		• Compressive strength: inc by 20% (58.08 MPa) of 1% MWBC. • Flexural strength: inc by 4.6% (12.80 MPa) of 1% MWBC. • Elastic modulus: inc by 2.8% (29 GPa) of 1% MWBC. • Split tensile strength: similar trend to that of flexural strength.					• Economic analysis of optimized biochar cement composite mix for industrial use. • Testing of replacement percentages of less than 1% BC.			[31]
						Food waste	• SEM • BET • EDS • CHN • PIDS						• C: 71% • 9.70 m²/g • 0.00288 cm³/g								
Rice waste	• C: 66% • 35.70 m²/g • 0.016 cm³/g	• 2 • 5										• Depth of water penetration: dec by 40% (9.33 mm) of 1% FWBC; dec by 64% (5.50 mm) with 1% MWBC.									

Table 3. *Cont.*

Biomass	BC ^a Characterization			Temp (° C)	Sample	BC	Optimum BC	Ratio			Tested Properties	Limitations of Research	Ref			
								S:C ^b	A:C ^c	W/C ^d						
Rice husk	• • •	XRD BET SEM	• 37.5 m ² /g	700	RHB Treated RHB Treated RHB Ash	5 10 5 10 5	5% Treated RHB & BB	N/A	N/A	0.5	• •	Compressive strength: inc by 36% (≈50 MPa) and 54.8% (≈55 MPa) with 5% of treated rice husk and bagasse biochar. Tensile strength: inc by 78% (≈4.5 MPa) with 5% treated bagasse biochar.	• •	Further mechanical properties can be tested such as workability and durability. Carbon sequestering studies on casted samples for comparison of the impact of different biomasses.	[16]	
Bagasse			• 52.3 m ² /g		Treated BB BB	5 10 5 10										
Olive stone			• • • •		Size: 0.04–40 μm C: 76.60% 1.635 g/cm ³ 3.38 m ² /g	OSB_0.5 OSB_1 OSB_2 OSB_4	0.5 1 2 4									
Rice husk	• • • • • •	XRD TGA SEM PSD CHNS BET	• • • •	500	Size: 0.04–40 μm C: 53.07% 1.710 g/cm ³ 9.44 m ² /g	RHB_0.5 RHB_1 RHB_2 RHB_4	0.5 1 2 4	Up to 4% of and Rice Husk	3:1	N/A	0.5	• • • •	Workability: inc by 3.4% (152 mm) of 1% OSB, by 8.8% (160 mm) of 0.5% FWB and 2% (150 mm) of 0.5% RHB. Compressive strength: inc by 9% (28.44 MPa) 2% of OSB; inc by 5.7% (27.53 MPa) and 7% (27.87 MPa) with 1% of FWB and RHB. Flexural strength: inc by 8.2% (7.39 MPa) and 4% (7.11 MPa) with 2% of RHB and OSB. Capillary water absorption: inc to 5.6% of water absorption by 0.5% FWB; inc to 5.9% water absorption of 4% OSB.	• • • •	Standardization of BC size before casting for improved comparison. Carbon sequestering studies on casted samples for comparison of the impact of different biomasses. Economic analyses of casted mix to optimize potential industrial use. BC can be used as cement replacement for non-structural concrete elements. Further understanding of the use of BC and other nanoparticles in the same mix.	[32]
Wood chips			• • • •		Size: 0.2–100 μm C: 77.23% 1.551 g/cm ³ 4.58 m ² /g	FWB_0.5 FWB_1 FWB_2 FWB_4	0.5 1 2 4									
Corn stover (cement and fly ash)	• • • • • • •	PSD XRF SEM-EDS CHNS ATR-FTIR C:45.06%		550	M20 M40 M50	2 4 6 8 2 4 6 8 2 4 6 8	4%	N/A	N/A	N/A	• •	Compressive strength: inc by 6.6% (40.5 MPa) of 6% M20 BC, by 7% (37.5 MPa) of 4% M40 BC and by 2.7% (37 MPa) of 2% M50 BC. Carbon sequestering: inc with 4.6% (0.477 CO ₂ equivalents/Kg of block making) for 6% of M20.	• •	Investigation of the use of BC as replacement rather than filler. The long-term durability properties of BC fly ash–cement composites under various curing conditions, such as water, steam and ACC, can be further studied.	[34]	
Rice husk	• • •	TGA XRD SEM		550	B2-M B5-M	2 5	2%	2.5:1	N/A	0.5	• • • • •	Ultrasonic pulse velocity: 2% with BC-like control ≈4490 m/s. Workability: dec by 2.5% (195 mm) and 10% (180 mm) of 2% and 5% BC. Compressive strength: dec by 5.5% (42.07 MPa) of 5% BC. Degree of hydration: dec by 2.3% (88.7 DOH %) and 5.4% (85.9 DOH%) of 2% and 5% of BC. Chloride diffusivity: inc to 12.36 × 10 ^{−12} m ² /s by 5% of BC. Electrical resistivity: inc by 13% (9.10 KΩ.cm) of 5% BC.	•	Investigation of replacement percentages less of than 2% BC.	[35]	
Wood waste (wood chips)	• • • • • • •	Grain size: 63.5 μm PSD XRPD TGA XRF PAH		500	A1 A2.5 B1 B2.5 C1 C2.5	1.0 2.5 1 2.5 1 2.5	1%	N/A	N/A	0.42 0.55 0.4	• • •	Compressive strength: dec by A1 to 89 MPa, B1 to 43 MPa, C1 to 67 MPa. Flexural strength: inc by B1 sample to 4.5 MPa. Fracture energy: inc by C1 to 110 N/m.	•	Investigation of replacement percentages of less than 1% BC.	[36]	
Coffee powder	• •	Avg particle size: 10/15 μm XRF TGA FE-SEM	• • • • •	800	PY-HS0.5% PY-HS1.0% PY-CP0.5% PY-CP0.8% PY-CP1.0%	0.5 0.8 1 0.5 0.8 1	PY-CP0.5%	N/A	N/A	0.35	• • •	Compression strength: inc by 72% (57.79 MPa) of PY-CP 0.5%. Fracture energy: inc by 72% (0.033 N/mm) of PY-HS 0.8%. Modulus of rupture: inc by 46% (4.02 MPa) of PY-HS 0.8%.	•	Limited industrial adaptability due to the use of high temperature during pyrolysis, resulting in increased energy consumption.	[37]	

Table 3. Cont.

Biomass	BC ^a Characterization			Temp (°C)	Sample	BC	Optimum BC	Ratio			Tested Properties	Limitations of Research	Ref
								S:C ^b	A:C ^c	W/C ^d			
Chitosan (shellfish)	• C: 72.9% • H: 1.3% • N: 6.8% • FTIR • TGA			800	C800	0.1	0.1%	N/A	N/A	0.45	• Toughness: inc to 2.12 J with BC. • Flexural strength: dec to 2.07 MPa with BC. • Compression strength: dec to 16.43 MPa with BC.	• Improvement in the dispersion of char to avoid defects in the cement composite mix. • Further analysis of char samples, such as BET and particle size distribution.	[38]
Peanut shells	• FESEM • Raman	• Avg diameter 600 nm • C:93.8% • 2.20 g/cm³		850	0.025 wt%HS 0.05 wt%HS 0.2 wt% HS 0.5 wt% HS 1 wt% HS	0.025 0.05 0.2 0.5 1	0.08% Peanut shells	N/A	N/A	0.35	• Fracture energy: inc by 70% (1.6 fracture energy/fracture energy of pure cement) of 0.08 wt% HS. • Electromagnetic radiation shielding: inc by 0.5 wt% of both BC. • Flexural strength: inc by 80% (5.33 MPa) of 0.08 wt% HS.	• Elemental analysis for improved understanding of the differences among BC.	[26]
Hazelnut shells		• Avg diameter 750 nm • C:87.7% • 2.35 g/cm³			0.025 wt% PS 0.05 wt% PS 0.2 wt% PS 0.5 wt% PS 1 wt% PS	0.025 0.05 0.2 0.5 1							
Sugarcane bagasse	• SEM • FTIR • TGA			200	CLA 2B CLA 4B	2 4					• Thermal properties: dec with 4% of BC by 25% (0.228 W/m.K). • Flexural strength: inc with 2% BC (2.77 MPa) rather than biomass. • Water absorption: BC has less absorption than biomass; owest porosity by 2% BC (43.54%).	• Standardization of the size of biomass and biochar before adding to cement mix composite. • Low pyrolysis temperature used for production of biochar. • Early strength testing for 7 days not conducted.	[39]
					CLA 6B	6	2%	N/A	N/A	0.8	• Modulus of elasticity: inversely proportional to BC content; highest by 2% of BC (1.97 GPa). • Cement hydration: inc with 2% of BC (≈10.8 mW/g).		
Rice husk	• SEM • BET • XRD • CHNS	• C: 41.01% • O: 56.19% • Si: 19.24%		500	MWBC 2%	2					• Hydration kinetics: inc at early stage by 1% for MWBC (≈247 J/g) and RHB (≈260 J/g).		
Wood waste		• C: 79.86% • O: 16.71% • Si: 0.15%			MWBC 1% RHB 2% RHB 1%	1 2 1	1% of MWBC and RHB	2.5:1	N/A	0.4	• Compressive strength: inc by 15–18% for MWBC (70 MPa) and RHB (65 MPa). • Water permeability: dec for MWBC (1.6%) and RHB (2.25%). • Expansion: dec of 62 to 68% for MWBC (0.035%) RHB (0.03%).	• Use of more samples with different replacement weightage of both BC.	[40]

BC ^a: biochar, S:C ^b: sand-to-cement ratio, A:C ^c: aggregate-to-cement ratio, W:C ^d: water-to-cement ratio, inc ^e: increase, dec ^f: decrease, DOH ^g: degree of hydration.

3. Applications of Biochar in Building Materials

Recent studies have shown that biochar enhances some attributes in concrete when used as a cementitious material. For example, biochar as a cementitious material enhances chemical stability and storage potential; promotes low conductivity; and can be used as an internal curing agent, filler material and carbon absorbent [6,15,23]. In previous Research, biochar has been used to develop building materials, such as natural inorganic clay composites, red clay binder, bituminous materials and geopolymers [19]. Gupta and Kua (2018) [15] reported that concrete composites with biochar enhanced mechanical properties when added as microparticles and that they could be used to develop shotcrete mixes for tunnel lining and underground construction.

3.1. Biochar as Cementitious Material

Table 3 summarizes the experimental procedures conducted in previous studies using biochar as a supplementary cementitious material (SCM), including the biomass material, the properties tested in the biochar concrete composites, the optimal amount of biochar added to the concrete mix and the properties of concrete composites enhanced by the addition of biochar. All these studies are discussed further with respect to the water absorption abilities, static modulus of elasticity and strength capabilities of the tested samples. The summary of these previous studies can provides insights for future studies with respect to which tests and which type of analysis should be conducted to obtain enhanced biochar concrete composites. To this end, Table 3 summarizes the admixture ratios tested in previous studies, including the biomass used, the pyrolysis temperature, the percentage of biochar addition, the ratio of concrete mixture (sand, aggregate and water ratios), the concrete compressive strength and the concrete flexural strength (after 28 days). Researchers can use these summarized data to inform their choice of concrete mix to achieve enhanced concrete strength and obtain further improvements or for comparison with new data obtained through exploration of the use of different biomass constituents in concrete. Figure 1 shows the types of biomass that have been used as SCM in previous studies, with the aim of encouraging further research on materials that have not yet been extensively investigated, such as marine biowaste (4%).

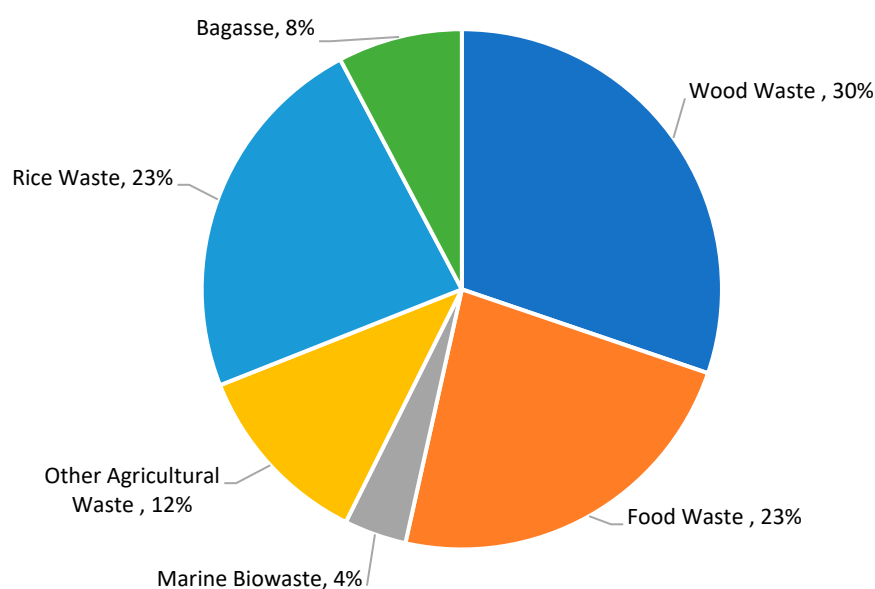


Figure 1. Biomass categories used as supplementary cementitious materials.

A study conducted by Qin et al. [33] is distinctive from other studies, as the authors investigated biochar as a cementitious material for pervious concrete. As pavement concrete is exposed to direct sunlight, they also tested the solar reflectance of their samples, indicating that increased biochar content reduces albedo, which is the amount of light reflected. Most

studies listed in Table 3 used biochar–cement ratios, such as 0.1 or 1% [14,15,21,22,27,28,30]. However, Yang and Wang (2021) [35] used a higher biochar contents of 2% and 5%. Similarly, Asadi Zeidabadi et al. (2018) [16] investigated 5% to 10% biochar addition. Yang and Wang (2021) [35] conducted an uncommon test, investigating biochar concrete composites using ultrasonic pulse velocity (UPV). They concluded that an increase in biochar decreases the UPV, indicating that the presence of biochar causes a decrease in the concrete density and elastic properties, in agreement with the results reported by Praneeth et al. (2020) [34]. Khushnood et al. (2016) [26] investigated the average modulus of rupture of concrete with the addition of biochar derived from peanut and hazelnut shells; most of the tested concrete composites exhibited increased bending strength with increased biochar addition. Gupta et al. (2021) [40] investigated the performance of biochar composite mortar exposed to sodium chloride and sodium sulfate solutions. Composite mortar containing 1–2 wt% wood waste biochar was found to be 8–11% stronger than the control after exposure to NaCl for 120 days. In addition, mortar composites with wood waste and rice husk biochar exposed to sodium sulphate solution exhibited an increase in compressive strength of 14–17% after 120 days of exposure to reaction products in the pore spaces of the composite [41]. Ofori-Boadu et al. investigated the influence of swine waste biochar on the early aging properties of hardened cement paste [42]. The authors reported that biochar reduced flowability by promoting porous and negatively charged carbonaceous surfaces, leading to adsorption of capillary water. The initial setting time was also reduced as a result of the reaction between the carboxylate anions of the biochar and the calcium cations of the cement, resulting in the formation of calcium polycarboxylate salts.

3.2. Water Absorption

The water absorption of concrete mixes is determined by measuring the amount of water that penetrates the concrete samples, which depends on the pore volume of the concrete. Water absorption is important because it expresses the durability of the mixes under investigation. The presence of macropores in a concrete mix increases with increased biochar content. Macropores are known to strongly influence the transport and permeation properties of cementitious composites, resulting in high sorptivity and penetration depth [15,23]. Asadi Zeidabadi et al. also found that the water absorption rate in cement mortar cast with 1% biochar was significantly reduced by 41% [15] using biochar samples that had previously been soaked in water. This resulted in a reduction in porosity due to the compaction effect on the mortar paste. The authors also suggested that mortar with soaked biochar has better durability because it protects the mortar sample from foreign liquids. However, the results of a study conducted by Akhtar and Sarmah in 2017 [27] contradicted this conclusion; the water absorption rate of cement mortar cast with biochar derived from rice husk and paper mill sludge was similar to that of the control sample. We assume that the difference between the results of these studies is due to the fact that the biochar used in the latter study was not previously soaked in water. The results of most samples prepared by Maljaee et al. (2021) [32] confirm this phenomenon, except for samples cast with 0.5% olive stone biochar and 4% forest wood biochar. Tests conducted by Qin et al. (2021) [33] using plywood as biomass for biochar confirmed that the addition of biochar had no effect on the water permeability and porosity of concrete. Gupta and Kua (2018) [15] reported that fine biochar particles increased the compactness of hardened mortar by blocking macropores, which increased the strength of the samples. The authors also reported that biochar had no significant effect on the drying rate and dimensional change of mortar. On the other hand, another study proved that biochar improves overall cement hydration by regulating the moisture effect but does not accelerate or delay the hydration process [14] according to isothermal calorimetry measurement results.

Gupta and Kua (2018) [15] used the tea bag method to determine the water absorption capacity of biochar samples before casting concrete composites. The authors reported that the absorption capacity in water and cement filtrate did not vary significantly, implying that biochar can maintain its absorption potential in a high-pH solution. They also conducted

tests to determine the water sorptivity of the samples, which is a measure of the tendency of a porous material to absorb water through capillary suction. Their results showed that the higher the biochar dosage, the more water was absorbed in the samples. These results demonstrate that the sorptivity feature of biochar reduces the amount of free water in the mortar mix by absorption, which means that a smaller amount of evaporable water escapes from the capillary pores, in agreement with the results of a study by Maljaee et al. (2021) [32], who further prepared samples with varying water–cement ratios, concluding that concrete strength was significantly increased with the addition of biochar produced at 500 °C compared to biochar produced at 300 °C with water–cement ratios of 0.45 and 0.50, respectively.

When biochar is mixed with mortar paste, its water-binding properties reduce the local water-to-cement ratio. Choi et al. (2012) [43] tested the water-retention effects of hardwood biochar and reported that mortar mixes with biochar exhibited a lower moisture evaporation rate than the control samples. The authors also reported that mixes with biochar required more water to achieve the desired workability. Another study reported that retained water was later used to cure the mortar, suggesting that biochar particles act as a self-curing agent [31]. The authors also conducted tests to determine the permeability of the biochar added to the mortar and found that in all their samples, the permeable void content was lower than that of mortar without biochar addition. The percentage of biochar content indicates the proportion of pores responsible for absorbing and storing water. Maljaee et al. (2021) [19] reported that the water retention capacity of biochar promoted the internal curing of mortar and early-age hydration. Asadi Zeidabadi et al. (2018) [16] confirmed that the larger the surface area of biochar addition, the higher the water requirement. To maintain the water-to-cement ratio, superplasticizers were added to control the required slump values. A study on cementitious composites with biochar from rice husk and wood waste was conducted to investigate the hydration kinetics [40]. The authors reported that the addition of 1–2 wt% biochar derived from rice husk and wood waste significantly reduced water permeability compared to the control mortar, as reflected by a 15–18% increase in the strength of the cement mortar after 7, 42 and 120 days. The authors also found that the addition of 1 wt% of both types of biochar increased the hydration rate due to the high specific surface area and smaller particle size of the biochar compared to that of cement.

As demonstrated by the experiments discussed above, the sorptivity attribute of biochar is a crucial aspect to consider when it is used as a cement substitute. These experiments also demonstrate that the water retention capacity of biochar is dependent on the type of biomass from which it is derived because each biomass reacts differently when converted into biochar at the same temperature in terms of pore formation and particle surface area. Furthermore, when using the same biomass but converting it into biochar at different temperatures, the higher the temperature, the larger the pore volume. The presence of pores increases the water retention capacity of biochar, promoting internal self-curing of concrete composites. Numerous studies have been conducted with the aim of standardizing the water-to-cement ratio using superplasticizer in order to determine which other properties of biochar affect the mechanical properties of concrete composites, which can be adapted when using novel biomasses.

3.3. Static Modulus of Elasticity

The modulus of elasticity is important because it demonstrates the ability of concrete to resist deformation caused by stress. Gupta et al. (2018) [31] determined the average static modulus of mortar mix samples cast with biochar derived from food waste, rice waste and wood waste. The highest elastic modulus of the mortar mix samples was reported in the cast samples with 1% biochar derived from wood waste, although the difference was insignificant relative to the control sample. Rodier et al. (2019) [39] investigated the modulus of elasticity of concrete composites containing biochar derived from sugarcane and found that the modulus of elasticity decreased with increasing biochar content. These

results demonstrate that biochar concrete composites can be further investigated for use in earthquake-resistant structures, as flexibility increases with a low modulus of elasticity. As biochar content increases, the desirable properties of concrete composites decrease. As shown in Table 3, most reported optimum biochar contents are less than 6%.

3.4. Compressive Strength

The load capacity of a concrete sample is one of the most important properties to determine. The range of load that a concrete mix can withstand determines whether it can be used for structural or pavement purposes. Gupta and Kua (2018) [15] found that the addition of 1–2 wt% BC 300 and BC 500 (biochar produced by pyrolysis at 300 °C and 500 °C, respectively) to concrete composite increased the strength of the samples on days 7 and 28 of testing. The maximum measured strength increase of BC 500 on day 7 was 35%, with only a 16% increase on day 28 relative to the control samples. A proportion of biochar greater than 1–2% of the total cement volume reduces the compressive strength of the mixture, irrespective of the pyrolysis temperature. We assume that the reduction in compressive strength was related to the low density and high porosity of the mortar, as the results showed a negative correlation between porosity and compressive strength for both BC 300 and BC 500. An early increase in strength on day 7 was also observed in [22,25,28]. These results indicate that the strength of concrete mixes decreases with increased biochar content, similar to the results reported with respect to other properties. Maljaee et al. (2021) [32] compared the effects of increasing the proportion of biochar derived from olive stone, forest wood and rice husk from 0.5% to 4% and reported that the compressive strength of all samples increased after 28 days of curing, except those cast with 2% and 4% biochar derived from forest wood. This may have been the result of the particle size of the forest wood, which is much coarser than cement particles, increasing the porosity and thus decreasing the compressive strength. Yang and Wang (2021) [35] conducted tests on samples cast with 2% and 5% biochar on day 3 and day 28 and reported a reduction in strength of 12.8% and 5.5%, respectively. The decrease in strength was the result of the formation of hydration products in the pores of the biochar.

Another study reported that 1% biochar increased the compressive strength of concrete samples by 8.9% [14]. Biochar pyrolyzed at 700 °C improved the compressive strength of the concrete sample more than that pyrolyzed at 500 °C due to its high porosity and large surface area, facilitating cement hydration. These results contradict those reported in a study by Gupta and Kua (2018) [15], highlighting the importance of biomass selection. In one study, food waste, rice waste and wood waste were used as biomass and converted to biochar, with each biochar added separately to compare the effects on compressive strength [31]. The mortar composite with 1% wood waste exhibited a 20% increase in compressive strength after 28 days due to the high water absorption and retention capacity of the biochar, which reduced amount of free water present in the mortar composite, resulting in rapid curing of the samples. Asadi Zeidabadi et al. (2018) [16] added 5% and 10% both-treated and untreated biochar to concrete samples. They concluded that 5% biochar derived from rice husk was adequate and improved the compressive strength due to its filler effect in early stages and its pozzolanic reaction in later stages. The authors also highlighted that pretreatment of the biochar improved the compressive strength of samples cured for 28 days by 36% compared to samples containing unpretreated biochar. In addition biochar, silica fume was also added to the mortar mix [44]. The addition of 10% silica fume resulted in an increase in 28-day compressive strength of 18–20% compared to the control. The authors attributed this result to the pozzolanic effect enhanced by the addition of silica fume, which eventually led to increased hydration and late strength development. Sirico et al. (2020) [36] reported a decrease in the compressive strength of concrete cast with 1% biochar but an increase in flexural strength. Although an increase in the compressive strength of concrete containing 1% biochar has been reported in most studies [14,15,21], consistent with the physical and chemical properties of biochar concrete, the actual

degree of improvement is highly dependent on the biomass used to produce the biochar, as well as pretreatment conditions.

Liu et al. investigated the increase in compressive strength and crack resistance of cement composites containing bamboo biochar [45]. The results showed that the addition of biochar increased the compressive strength of the samples as a result of filling and self-curing effects, with an optimal dosage of 1–3 wt% biochar recommended. In a study in which cement was replaced with biochar derived from peanut shell waste, the addition of 1 wt% and 3 wt% increased the compressive strength of samples at an early stage by 18–20% compared to plain mortar [46]. In the same study, the addition of 3% biochar and 20% fly ash to the cement mix together and separately improved the 7-day strength by 19% compared to the addition of only 20% fly ash. Choi et al. (2012) [43] used biochar derived from hardwood; a proportion of up to 5% was found to increase the compressive strength of the cement mixture to 46.5 MPa compared to the control (43.7 MPa on day 28). However, the authors found that the use of biochar in proportions of 10%, 15% and 20% decreased the strength of the samples. These results are in agreement with most of the reported optimum biochar contents shown in Table 3.

3.5. Flexural Strength

Gupta and Kua (2018) [15] reported that no significant improvements in flexural strength were observed in tests but that increasing the biochar dosage slightly improved flexural strength due to the formation of air voids in the tensile plane, owing to the fine particle size and the porous nature of the biochar addition. They also observed that mortar containing pre-soaked and dry biochar had the highest flexural strength. The authors attributed the increase in strength to the formation of air voids in the tensile plane. Akhtar and Sarmah 2017 [27] reported that replacing 0.1% of the total cement volume with biochar derived from poultry litter, rice husk and paper mill sludge improved the flexural strength of samples by as much as 20% compared to the control. Maljaee et al. (2021) [32] reported similar improvements in flexural strength and compressive strength. However, the sample containing 4% forest wood biochar had increased porosity in the tensile plane, resulting in an increase in the formation of cracks during tensile loading in comparison with samples containing olive stone and rice husk biochar. In a study on the replacement of sand with biochar derived from poultry litter at a dosage of 10 to 40% of the total weight in cement, the authors investigated the mechanical strength, durability and microcomputed tomography of the samples [47]. The results showed that the flexural strength of the composite with 20% biochar was improved by 26% compared to the control. In addition, a reduction in the thermal conductivity and density of the cement composites was reported.

Suarez-Riera et al. (2020) [6] conducted tests to investigate the use of biochar for two applications: as a filler in concrete mix and as a cement substitute. Their results showed that when biochar was used as a cement substitute, the flexural strength decreased slightly by 2%. However, when used as a filler and premixed with water-superplasticizer solution, an increase of more than 15% was reported. In the same study, the authors determined the fracture energy of the mortar mixes and reported higher increase when biochar was used as filler than a cement substitute. The fracture energy was determined to confirm the increase in ductility in the presence of biochar in the concrete. Another study highlighted that the effect on flexural strength depends on the feedstock from which it was derived [6]. This observation is consistent with the results of a study conducted by Khushnood et al. (2016) [26], who compared biochar concrete composites containing hazelnut and peanut shell biochar. Their results indicate that peanut shell biochar has better mechanical strength due its lower density. However, Gupta et al. (2018) [31] reported that biochar addition did not significantly affect the flexural strength and splitting tensile strength of concrete mixtures, regardless of the type of biomass used. Only samples cast with 1% biochar derived from wood waste showed a slight improvement. Most of the studies reviewed herein also proved that increasing the biochar content in the mortar or concrete mix eventually results in a decrease in flexural strength [26,31,32,36]. Furthermore,

the flexural strength of concrete mixes is also highly dependent on the type of feedstock used to produce the biochar.

3.6. Tensile Strength

Asadi Zeidabadi et al. (2018) [16] reported that concrete samples cast with 5% treated bagasse biochar showed an increase in tensile strength of 78%, whereas samples cast with treated rice husk ash showed a decrease in tensile strength. This is due to the increase in the porous microaggregate structure of the rice husk ash particles which weakens the concrete matrix, thus decrease the split tensile strength. In a study conducted by Akhtar and Sarmah (2017) [27], 0.1 wt% rice husk content was found to be the most suitable ratio to promote split tensile strength but had negative impact on compressive strength due to the irregular pore structure. On the other hand, in a study conducted by Gupta et al. (2018) [31], no significant increase in the split tensile strength was observed in samples containing food waste and rice waste biochar, except for a sample containing 1% wood waste biochar, probably due to the biochar particles acting as self-curing agents.

4. Carbon-Sequestering Potential of Biochar

Past research has suggested that carbon sequestration can be achieved through carbonation of concrete, although limited to concrete without reinforcement due to the risk of corrosion [15,48]. Reinforcement is required for structural; therefore, the addition of biochar has been further investigated for carbon sequestration. Maljaee et al. (2021) [19] reported that the chemical and physical properties of biochar remained unchanged after CO₂ saturation, although leading to a reduction in strength when mixed with mortar. Praneeth et al. (2020) [34] investigated the carbon-sequestering abilities of concrete composites containing corn stover biochar. Their experimental samples were subjected to mineral carbonation for two hours after demolding to enhance the CO₂ uptake and carbon sequestration. Test results indicated that post carbonation and further calcium carbonate (CaCO₃) formation in the biochar-containing composites were responsible for an increase in strength. A study conducted by Wang et al. 2020 [14] proved that carbon dioxide curing is more effective than air curing for biochar concrete composite samples. Carbon dioxide curing is an eco-friendly procedure used to accelerate the cement reactions in composite mixes, such as hydration and strength development [14,33].

Gupta et al. investigated carbon sequestration in foamed mortar by the addition of biochar derived from wood waste through accelerated carbonation with a 2% CO₂ concentration [49]. According to thermogravimetric analysis, the carbon dioxide uptake of foamed mortar with silica fume and fly ash was 30% after 28 days, which is higher than the 3% reported for the control without biochar. In another study, Gupta investigated the effect of the technique of accelerated carbonation curing of cement composites with the addition of biochar and silica fume on carbon sequestration, strength and hydration [50]. The cement blocks showed similar carbon sequestration following carbon mineralization as that of the control and mix containing silica fume paste after 28 days of carbonation. In the sample prepared with carbon-stored biochar, the CO₂ equivalent for carbonated and uncarbonated biochar cement was 6–7% lower than that of the control without biochar. Gupta et al. also investigated the addition of fly ash and biochar to improve CO₂ uptake and carbonate mineralization in cement mortar [51]. The authors reported that 23% fly ash and biochar replacement in cement enhanced the carbon sequestering ability by 7–13% through mineralization relative to the control.

Because a limited amount of research has been conducted on carbon sequestration of biochar concrete composites, we can shift our attention to studies that have on the carbon-sequestering abilities of biochar alone. Dissanayake et al. (2020) [12] concluded that the volume of micropores and the presence of basic functional groups play crucial roles in the carbon dioxide absorption capacity of biochar. Accordingly, biochar can be modified through chemical and physical treatments, such activation conditions involving steam or ammonia. With the help of these pretreatments, when mixed with concrete

components, the carbon absorption capacity of biochar is predicted to remain effective. Gupta et al. (2017) [52] recommended the use of unsaturated biochar as SCM to sequester stable carbon, as saturated biochar can trigger carbonation, which affects strength development. Fawzy et al. (2021) [53] emphasized that the production, use and storage of biochar are highly carbon-negative, resulting in an estimated sequestration of 0.3–2 gigatons of CO₂ year^{−1} by 2050, further highlighting that the development of an industrial biochar production system would be advantageous for atmospheric carbon removal.

5. Engineering Biochar as Cement Replacement

Characterization and analysis of biomass to be used for biochar production is critical for determination of elemental composition, surface functional groups, thermal stability and structure. It must be determined whether a biomass is suitable for its intended use, as this review concerns SCM. Maljaee et al. (2021) [19] conducted extensive research on the various biomass factors that affect biochar, as shown in Figure 2. This information can inform future research with respect to the selection of biomass for the production of biochar as SCM. Figure 2 also shows the pyrolysis conditions, i.e., production temperature, heating rate, residence time and biochar properties, that affect the concrete properties. However, this review in Section 3 focuses only on the mechanical properties and water absorption of the biochar concrete composites, which are linked to biochar properties, i.e., inorganic elements, carbon content, pore size, density, particle size, water retention, surface area and morphology, as shown in Figure 2. The detailed roadmap shown in Figure 2 highlights the biochar properties that are interrelated, such as porosity and density, as confirmed in [15]. Figure 2 also shows the relationship between the water absorption and durability of concrete composites, which was explained in detail in Section 3.2.

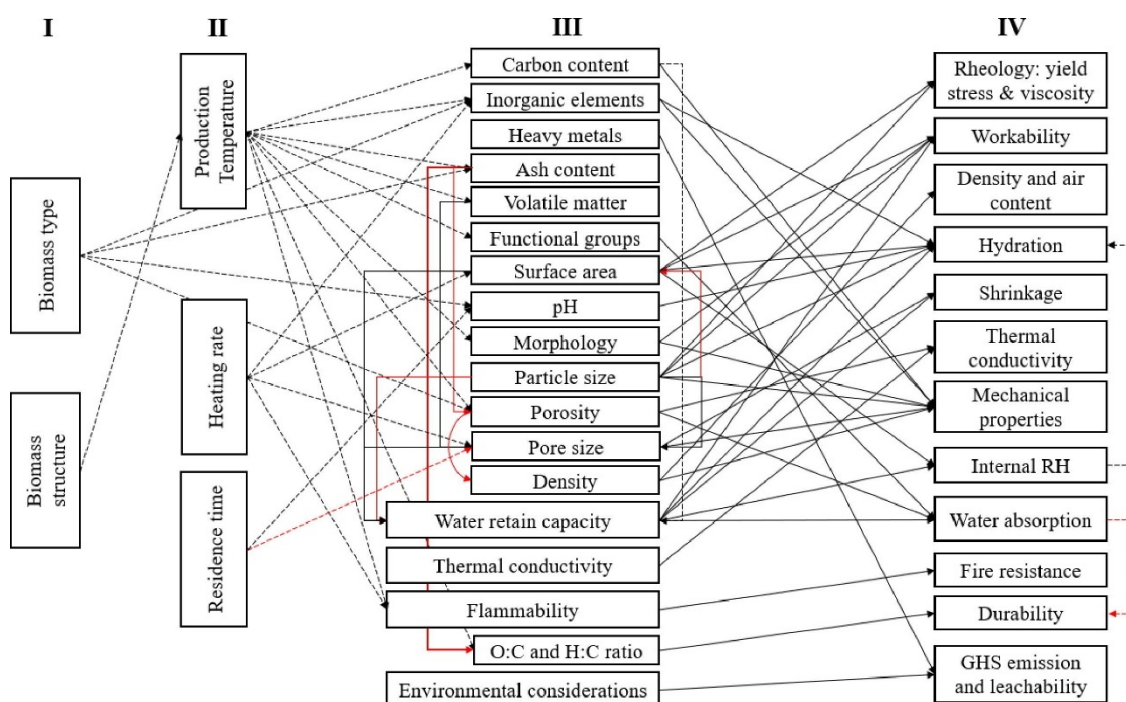


Figure 2. Detailed map describing factors influencing biochar and cement composite properties. Reprinted with permission from Ref. Maljaee H. [19] Note: I: biomass factors, II: pyrolysis production, III: biochar properties, VI: cement composite properties. Red lines represent inverse effects.

Biomass pretreatment prior to pyrolysis is known to affect biochar properties. Yaashikaa et al. (2020) [8] reported that high moisture content in biomass is an important factor with respect to biochar formation, i.e., the higher the moisture content, the more energy and the higher the temperature required for pyrolysis. Therefore, biomass with lower moisture content is preferable

because it requires less heat and energy, making it economically feasible. Furthermore, reducing the size of the biomass, immersing it in a dilute acid solution and using the baking method reduce the moisture content, thus increasing the biochar yield. The physicochemical properties of biochar can be further improved after production through treatment with acids, alkalis or oxidizing agents, and the biochar surface area can be modified by using acid treatment. In this review, we have highlighted that the use of biochar produced from waste could increase efficiency in the circular bioeconomy, which could result in the selection of biomass for biochar concrete composites to enable economical concrete production. Figure 1 can provide an indication of which biomasses should be further investigated.

Biomass analysis is also necessary to detect impurities. As suggested by You et al. (2018) [54], biochar may contain harmful components during pyrolysis or gasification, resulting from the use of contaminated biomass. Asadi Zeidabadi et al. (2018) [16] highlighted the importance of the presence of amorphous silica in biochar, which improves the mechanical strength of concrete composites when it reacts with portlandite (CH) to form calcium silicate hydrates (C-S-H), as also reported by Maljaee et al. (2021) [32]. Maljaee et al. 2021 [19] reported that even the shape of biochar particles has an effect on the properties of mortar. If biochar particles have an angular shape, they restrict the movement of hardened cement paste, leading to a decrease in the spreading diameter during the flow table (slump) test. Some characteristics highlighted in this study include the ratios of hydrogen to organic carbon (H:C) and oxygen to organic carbon (O:C), which determine the aromaticity and maturation of biochar, which, in turn, are related to the features that make biochar an efficient additive in cement mortar. Additionally, the decomposition of cellulosic matter in biochar during pyrolysis can ensure the long-term durability of cement composites.

Each property of biochar complements an aspect desirable for a cement composite mix, as shown in Figure 3. Recent research (Table 3) has shown that the use of biochar as SCM at an optimal concentration increases strength. Moreover, numerous experimental studies that have been conducted to identify the preferred properties of biochar necessary to achieve strength enhancements. Although it has been proven that the performance of biochar is primarily dependent on the type of biomass, it is clear that some properties must be matched to achieve the desired properties of the resulting biochar. A summary of research conducted on this topic is shown in Figure 3, which indicates the properties that can be altered and the changes that can be made to obtain the biochar concrete composites with the desired properties. For example, if the desired biochar concrete composite requires high durability and increased cement hydration, high cellulose content would be required during biochar production.

Figures 4 and 5 illustrate the summative data obtained in this literature review in reference to the mentioned research in Table 3, highlighting the trend of the most used biochar production temperatures and biochar composites relative to control samples. Figures 4 and 5 can serve as a benchmark for future research; as shown in the graph, most previous studies used a temperature of 500 °C for biochar production, with most samples exhibiting increased compressive and flexural strength relative to control samples. This information can serve as a basis for further tests on biochar concrete or cement composites containing biochar produced at temperatures near 500 °C, as increasing the temperature further to 700 °C or 800 °C would require the use of more energy during batch production.

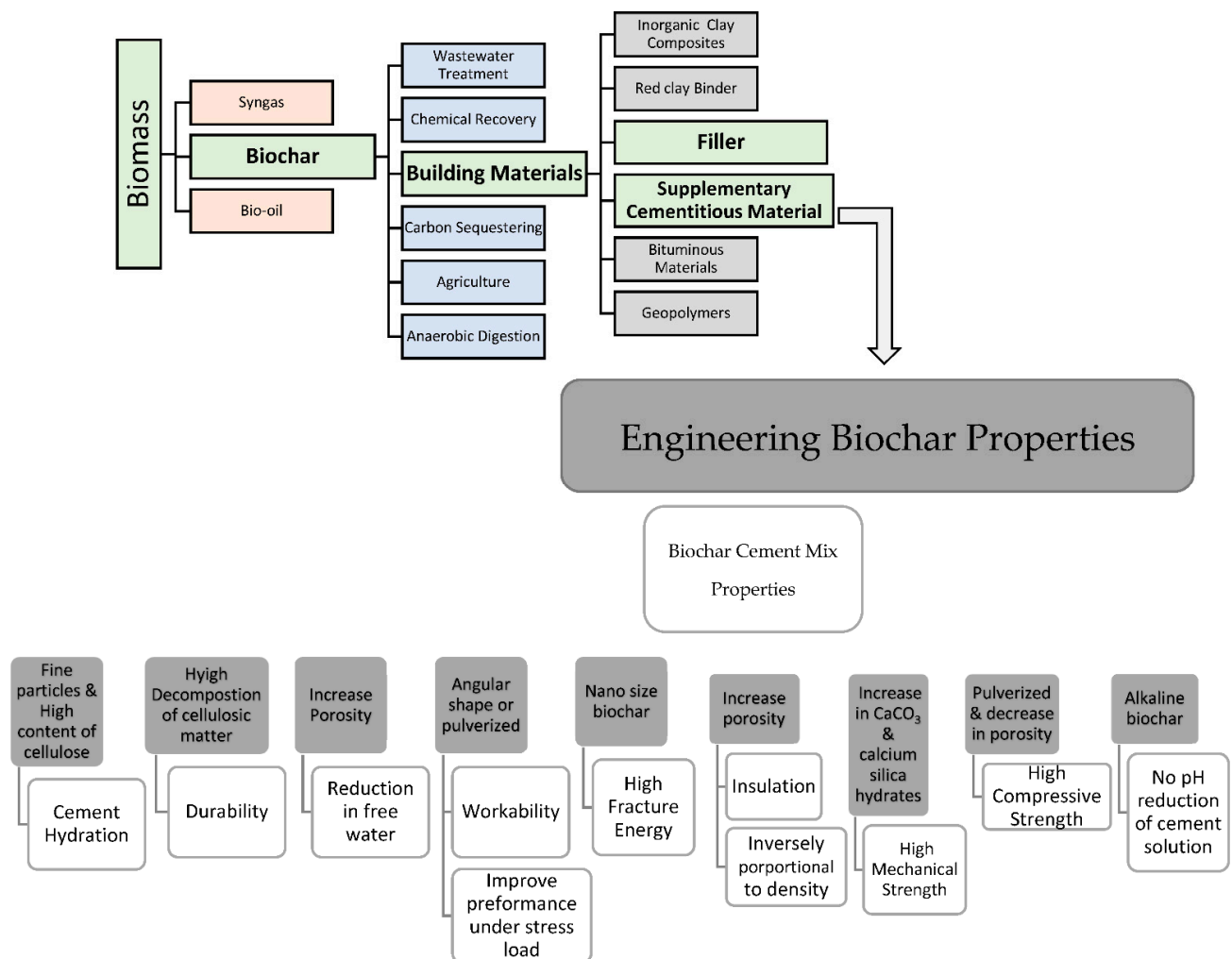


Figure 3. Breakdown of the process of biochar production from the source (biomass) to product (biochar) and its subsequent applications in building materials, in addition to the properties of biochar that can be engineered to improve biochar cement mix composites.

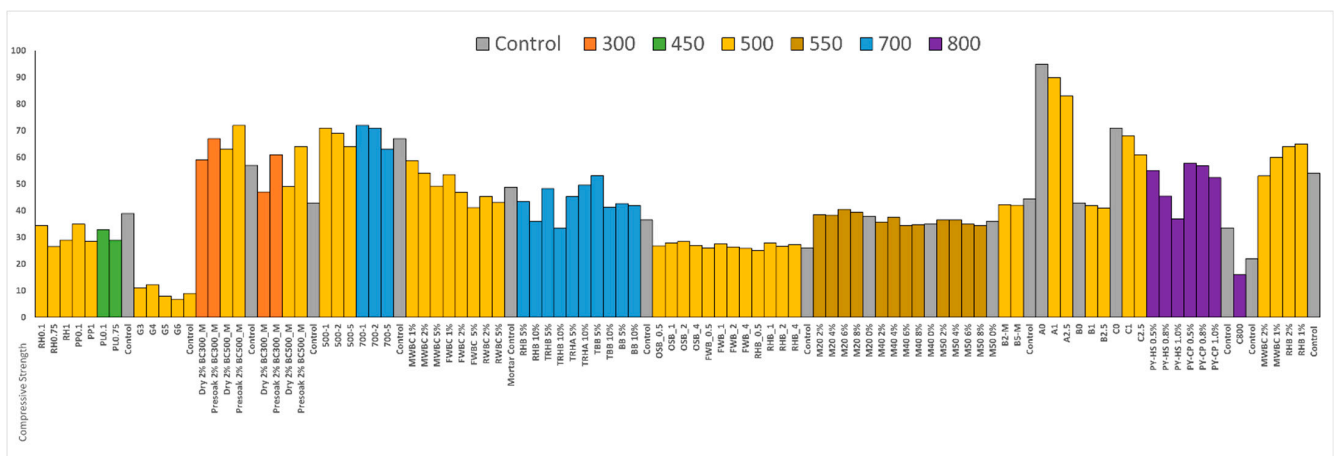


Figure 4. Compressive strength of biochar cement and concrete composites reported in previous studies.

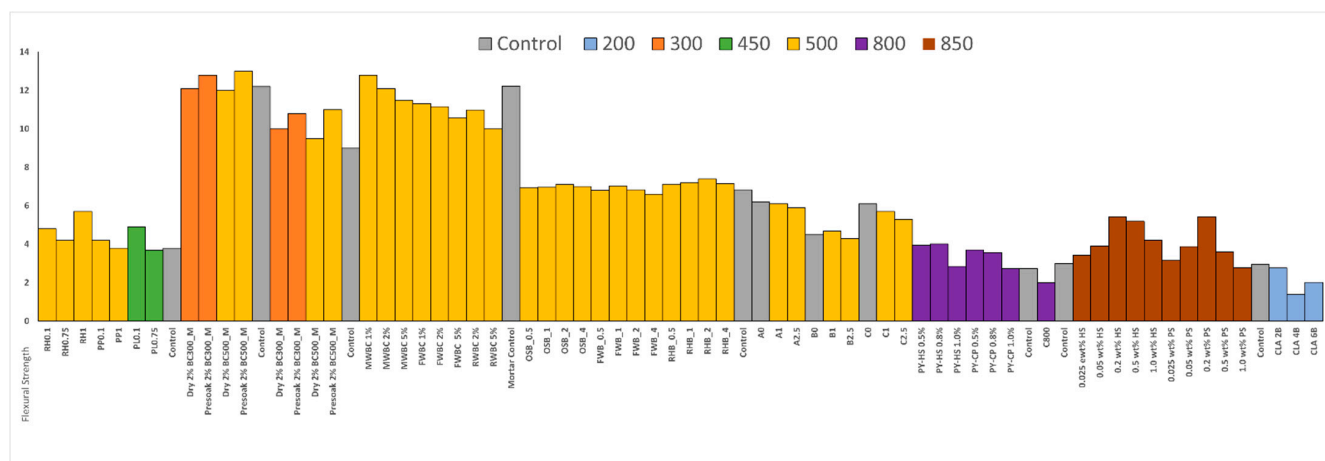


Figure 5. Flexural strength of biochar cement and concrete composites reported in previous studies.

6. Environmental and Economic Impact

Biochar is an environmentally friendly material that has been used to resolving many environmental problems, for example, to reducing greenhouse gas emissions, wastewater treatment and soil remediation [8]. Biochar is also known to remove pollutants due to the presence of functional groups such as hydroxyl and carboxyl groups. Gupta and Kua (2018) [15] reported that the conversion of wood waste into biochar increases the value of wood waste compared to its use for landfill. This would definitely have a positive impact on the environment, as landfilling of wood waste has been proven to cause toxic emissions in life cycle assessment studies (LCA) [55]. To mitigate the impact of landfilling, a study was conducted in China on plywood framework that could no longer be reused as biomass for biochar production [33]. Moreover, biomass from food waste could eventually be used as an economical resource, as there is no cost for collection [21,26]. Gupta et al. (2017) [52] that the use of wood waste in concrete composite mixtures is sustainable and cost-effective. Gupta and Kashani used processed local waste peanut shells into biochar and replaced small amounts of cement, which was found to substantially improve the hydration, setting and strength development of the tested mixtures [46]. These results could promote the use of recycled waste. In addition, the use of biochar could reduce the CO₂ equivalent of cement mortar and cement fly ash mortar due to the reduction in cement demand and the negative net CO₂ equivalent of biochar production.

LCA revealed that biochar has the potential to reduce net greenhouse gas (GHG) emissions by 870 kg CO₂ equivalent per ton of dry feedstock, depending on the type of feedstock and the method of preparation, of which 62–66% is accounted for by the storage and sequestration of carbon by the biomass feedstock of biochar [56]. Studies using waste materials to produce biochar suggest that this process could reduce landfill to avoid emissions and increase the value of produced waste [6,8,15,16,18,57], in turn reducing environmental impacts. According to Gupta and Kua (2018) [15], the estimated price of using biochar in mortar composites is similar to that of control mixtures. In order to evaluate the economic benefits, it is recommended to determine the environmental impact through LCA and life cycle cost (LCC). As economic factors vary from one region to another, it would be beneficial to conduct LCA and LCC in accordance with the rates in each region. J. Campus et al. (2020) [58] investigated biochar as a partial replacement for Portland cement and concluded that the mix with the shortest distance covered for the use of biochar reduced the environmental impact compared to conventional concrete mix without biochar.

A technoeconomic analysis (TEA) and a cradle-to-grave LCA study was carried out for biochar produced with portable systems from forest residues and applied to the soil, confirming its environmental benefit and economic feasibility [59]. All the portable systems investigated, such as Oregon kiln and air curtain burner, showed a negative global warming

impact, also highlighting that the use of forest residues can help to mitigate wildfires. LCA and cost benefit analyses were conducted on biochar-augmented concrete; biochar was used as an aggregate in combination with other SCMs, resulting in a significant reduction in CO₂ emissions and demonstrating the successful production of carbon-negative concrete with overall economic profits [60]. Concrete containing biochar and metakaolin was found to be the most promising mix, sequestering 59 kg CO₂ per ton and achieving a potential total profit of USD 35.4 m^{−3}.

Tests on concrete have proven that it can reduce pollution by absorbing NO₂ due to the reaction with highly alkaline cement hydrates, such as calcium hydroxide and C-S-H. Kruo et al. (2013) [61] reported that the addition of activated carbon to concrete used for road tunnels and parking garages can significantly increase the absorption of NO₂. The authors demonstrated that conventional concrete can absorb NO₂ to a significant extent, leading to the formation of nitrite and nitrate salts in the alkaline aqueous solution covering the hydrates. They reported that conventional concrete absorbed $7.4 \times 10^{-7} \text{ mol} \cdot \text{m}^{-2} \cdot \text{min}^{-1}$ after 20 h of exposure, whereas the activated carbon concrete absorbed $1.7 \times 10^{-6} \text{ mol} \cdot \text{m}^{-2} \cdot \text{min}^{-1}$. Another study also tested the entrapment of NO_x but with cement pastes [62], reporting that absorption varied depending on the temperature and carbonation of the cement paste and that the addition of activated carbon increased the NO₂ absorption.

7. Conclusions

The use of sustainable concrete could reduce the negative environmental impact of concrete production. Biochar has been tested as a supplementary cementitious material and analysed using a number of approaches, as mentioned in this review. In this review, we discussed selected mechanical properties, such as water absorption capacity, as well as compressive, flexural and tensile strength. The temperature and type of biomass used to produce biochar is critical with respect to its use as a cement substitute. It is also important to optimize the percentage of replacement to obtain desirable biochar–concrete composites. As reported in most previous experimental studies, the lower the percentage (less than 6%) of replacement, the better the composite properties. Further analysis suggests that the properties of biochar concrete or mortar composites can be modified by adjusting the properties of the added biochar. Research demonstrates that the production of biochar and its use as a carbon-sequestering medium would create a carbon-negative environment and be economically beneficial.

Although a considerable amount of research has been conducted on biochar, some factors can be further investigated to improve its efficiency and encourage further industrial adoption:

- The influence of different lignocellulosic biomasses on cement hydration during curing of biochar concrete composites;
- The resistance of biochar concrete composites to impact loads and harsh chemical environments;
- Mechanical properties of biochar concrete composites made from various types of food waste;
- Carbon sequestration capabilities of biochar concrete composites made with pre-treated biochar;
- Evaluation of the potential to adapt biochar concrete composites as carbon-sequestering materials in industrial applications through LCA and LCC studies;
- Optimization of the production of a near-ideal biochar that has the chemical composition of a proven supplementary cementitious material to improve the mechanical properties of concrete composites; and
- Testing of biochar concrete composites for the ability to absorb pollutants, such as CO, NO CO₂, NO₂ and SO₂, without affecting mechanical properties, considering time as a dependent variable.

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