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Systematic Review of the Improvement of the Mechanical Properties of Concrete With Agave Fibers and Biochar

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ABSTRACT

The construction sector faces the urgent challenge of reducing the environmental impact associated with cement production. In response, biodegradable materials such as agave fibers and biochar have attracted growing interest as sustainable alternatives for improving concrete performance. This systematic review is based on an initial identification of 2250 records retrieved from the Web of Science and Scopus databases. After screening 1088 studies and applying the PRISMA 2020 methodology, a total of 45 scientific articles published between 2014 and 2025 were selected for detailed analysis. The literature on the use of agave fibers and biochar in concrete is diverse and challenging to compare due to variations in methods and dosages. The study is based on a comparative and critical analysis of the available experimental evidence to identify and propose optimal dosage ranges for using agave fibers (Agave sisalana and Americana) and biochar (produced from organic waste) that maximize mechanical improvements in concrete without compromising its structural integrity. The results indicate that agave fibers (0.25%–1.0% by volume, with lengths close to 25 mm), especially when subjected to thermal or chemical treatments, improve flexural behavior, while biochar (1%–5% relative to the weight of cement) increases compressive strength. However, the analysis identifies significant gaps in knowledge regarding the standardization of treatments, their large-scale use in real projects, and the lack of regulations. There is ample scope for further research into the use of agave fibers and, above all, biochar in concrete elements to promote sustainable construction technologies.

1 | Introduction

Concrete is one of the most widely used materials in the world, but it is also one of the most scrutinized due to its significant environmental impact. The production of cement, as an essential component of concrete, is responsible for approximately 4% of global carbon dioxide emissions (CO_2) [1] Given this reality, international institutions, such as the Sustainable Development Goals (SDGs), promote the need to adopt more responsible construction practices aimed at reducing environmental impact and promoting more sustainable production in the construction

sector [2]. As part of this effort, in the last decade, several strategies have been promoted to optimize the performance of concrete. These include the use of plastic polymers and powdered mineral admixtures to modify their mechanical and durable properties. However, these alternatives are environmentally polluting due to their nonrenewable origin and the waste they generate. In this context, there has been a growing interest in integrating materials of natural origin and lower environmental impact, such as agave plant fibers (as a substitute for synthetic fibers) and biochar (as a functional additive similar to powdered minerals, but derived from organic waste).

Agave fibers, particularly those of Agave sisalana and Agave americana, have demonstrated potential benefits in terms of mechanical properties, such as flexural and tensile strength, when used in specific proportions and under certain conditions [3]. Recent experimental research has shown that the mechanical response of sisal fiber–reinforced cementitious composites is highly sensitive to the combined effect of fiber length, dosage, and surface treatment, with specific parameter ranges leading to improvements in compressive and flexural strength. At the same time, nonoptimized combinations may result in performance deterioration [4].

However, biochar has emerged as a promising option for incorporation into concrete mixes. It is obtained through the pyrolysis of organic waste, such as rice husks, coconut shells, bagasse, and wood. The literature has documented improvements in compressive strength and, to a lesser extent, in flexural strength, depending on the type of waste, the process used to obtain the biochar, and the dosage applied [5].

In recent years, there has been significant growth in research focused on developing concretes that use bio-based materials to maintain or improve structural performance while reducing environmental impact. This trend reflects a shift toward more sustainable construction solutions (as can be seen in Figure 1), which visualizes the scientific landscape and connections between keywords related to biochar, agave fibers, and sustainable concrete technologies. In the figure, "biochar" and "compressive strength" appear as the most central and influential topics, closely related to terms, such as "cements," "carbon emissions," "concrete additives," and "natural fibers." The color gradient (from blue to yellow) represents the temporal evolution of publications between 2022 and 2025, showing a growing research interest in carbon capture, mechanical performance, and eco-friendly cementitious composites. This graphic network highlights the multidisciplinary expansion of studies since 2014, driven by the global need to reduce carbon emissions and develop viable alternatives to conventional industrial materials.

Publications on the incorporation of agave fibers and biochar into concrete remain highly variable and difficult to compare, mainly due to differences in experimental design, material processing, and dosage selection. This systematic review synthesizes and interprets these tests to identify dosage ranges that improve mechanical behavior in both agave fibers and biochar. By proposing the dosages associated with positive results in the publications, this review guides researchers who wish to explore the topic and avoid ineffective mixing ratios.

In addition, the focus on biodegradable materials derived from waste promotes the development of more environmentally friendly concrete and highlights knowledge gaps that remain to be investigated.

2 | Methodology

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA) methodology, which provides a structured framework for the identification, selection, eligibility, and inclusion of scientific studies [6]. The process was divided into the following stages:

2.1 | Identification

A search was conducted in the Web of Science (Clarivate) and Scopus databases. The search strategy focused on studies addressing the incorporation of plant-based materials in concrete, using a search equation combining the key terms: ("reinforced concrete" AND agave) OR ("reinforced concrete" AND biochar).

The initial search yielded 24 records in Web of Science and 2226 records in Scopus.

2.2 | Selection

Duplicate entries were removed, and thematic exclusion criteria were applied to discard unrelated areas, such as social sciences, business, medicine, and management. Only journal articles published between 2014 and 2025 were considered.

2.3 | Eligibility

Full-text reviews of the remaining articles were conducted to assess their relevance, excluding those not directly related to concrete applications, as well as review articles and conference abstracts.

2.4 | Inclusion

A final set of 45 peer-reviewed studies (2 from Web of Science and 43 from Scopus) was selected for detailed analysis. These studies were classified into two main groups:

Concrete with agave fibers (29 studies).

Concrete with biochar (16 studies).

The overall selection process is shown in Figure 2, which summarizes the PRISMA flowchart for this review.

3 | Results

3.1 | Agave Fibers in Concrete

Table 1 summarizes in general terms the total of 29 articles that have evaluated the use of agave fibers in addition to concrete, specifying that the works analyzed mainly use two agave variants: Agave sisalana and Agave americana, from both crops and agricultural residues. The applications vary from nonstructural concrete, such as mortars, to prefabricated elements and reinforced slabs. The fiber addition percentages range from 0.5% in the lowest value to 10.46% in the highest proportion, and different types of cement (Portland, ferrocement mortar, and geopolymer blends) were used. The tests performed were compressive strength (20 cases), flexural strength (17 cases), and resistivity (13 cases), conducted on different specimens: beams, cylinders, cubes, and slabs. The mechanical properties evaluated reported improvements in compressive and flexural strength upon incorporating the fibers. However, the results are not always comparable due to differences in methods, treatments applied, specimen dimensions, and test conditions, which will be discussed below.

3.2 | Biochar in Concrete

Table 2 presents a general overview of the 16 studies that have evaluated the use of biochar as an admixture in concrete mixes. The studies analyzed used biodegradable materials of

FIGURE 1 | Growth of green concrete research with bio-based materials, 2022–2025.

agricultural (38%) and forestry origin (56%), such as rice husks, coconut, pine nuts, bagasse, and wood, which were subjected to pyrolysis processes at different temperatures and times.

Applications of biochar concrete range from conventional and structural green mortars, CO_2 storage, ultra-high-performance concrete (UHPC), and impact-resistant elements.

FIGURE 2 | Search criteria and selection of the analyzed literature.

TABLE 1 | Comparison of studies related to the mechanical properties of concrete with agave fiber admixture.

No.	Agave variant	Origin	Type of cement	Specification of the use of concrete	Percentage of fiber addition (blends) (%)	Type and quantity of specimens (mm)	Maximum strength (MPa)			Reference
							Compression	Flexural	Voltage	
1	Agave sisalana	Grown without harvesting	Portland	Nonstructural (mortar)	2	9 beams of, 40*40*160	ND	5.5	ND	[7]
2	Agave americana L.	Agricultural waste	Portland CPC 30R	Nonstructural (mortar)	0.5, 1.0, 1.5, 2.0	NE beams of 40*10×*150	ND	13.45	10.45	[8]
3	Agave sisalana	Grown without harvesting	NE	NE	NE	Individual fibers, length 100	ND	ND	458.5	[9]
4	Agave sisalana	Grown without harvesting	Portland with geopolymer	Prefabricated geopolymer elements	1.0, 1.5, 2.0	NE cylinders of 100 Ø*200 NE prisms of 100*100*400 NE cubes of 100*100*100	ND	5.4	ND	[10]
5	Agave sisalana	Grown without harvesting	Ferrocement mortar	Ferrocement slab	0.5, 1.0, 1.5, 2.0, 2.5, 3.0	90 slabs of 500*250*25	31.2	ND	ND	[11]
6	Agave sisalana	Grown without harvesting	Portland	NE	2.0	18 cubes, 18 beams	32.67	8.74	ND	[12]
7	Agave sisalana	Grown without harvesting	Portland	Prefabricated mortar elements	2.91, 4.11, 5.48, 9.30, 10.46	NE plates of 200*50*10 21 plates of 400*100*10	ND	25.9	ND	[13]
8	Agave americana	Grown without harvesting	Mortar	Mortar elements	0.5, 1.0, 1.5	9 prisms of 40*40*160	41.90	8.27	ND	[14]
9	Agave americana	Grown without harvesting	Portland cement	Nonstructural	0.3, 0.6, 0.9, 1.5	NE cylinders of 150 Ø*300 Ne cylinders of 100 Ø*200 NE prisms of 150*150*530	27.33	5.35	2.75	[15]
10	Agave sisalana	Grown without harvesting	Portland	Paving blocks	0, 3, 5, 7	20 blocks of 200*100*80	13.2	ND	ND	[16]
11	Agave NE	Grown without harvesting	Portland	Nonstructural	0, 1.5, 3.0, 4.5, 6.0, 7.5	6 cubes of 100*100*100	+23.6%	ND	ND	[17]
12	Agave sisalana	Grown without harvesting	NE	Nonstructural	Fiber fabrics	NE	ND	47.93	28.39	[18]

(Continues)

TABLE 1 | (Continued)

No.	Agave variant	Origin	Type of cement	Specification of the use of concrete	Percentage of fiber addition (blends) (%)	Type and quantity of specimens (mm)	Maximum strength (MPa)			Reference
							Compression	Flexural	Voltage	
13	Agave sisalana	Grown without harvesting	NE	Nonstructural	1.0	5 cubes of 50 * 50 * 50	2.55	ND	ND	[19]
14	Agave americana L.	Grown without harvesting	NE	Earth blocks	0, 0.25, 0.5, 0.7, 1	30 cubes of 100 * 100 * 100 30 prisms of 120 * 240 * 100 30 cylinders of 150 Ø * 30	2.54	1.44	0.32	[3]
15	Furcraea cabuya	Grown without harvesting	Portland	Nonstructural	0.5, 1, 1.5, 2	720 cylinders	33.29	ND	ND	[20]
16	Agave sisalana	Grown without harvesting	NE	NE	Fiber only	Individual fibers	ND	ND	ND	[21]
17	Agave sisalana	Grown without harvesting	Portland	NE	0, 0.5, 1.0, 1.2, 1.5, 1.7, 2.0	NE cylinders, NE beams	37.37	ND	3.83	[22]
18	Agave sisalana	Grown without harvesting	Portland Pozzolana	M30 for structural use	0, 0.5, 1, 1.5, 2	NE cubes of 150 * 150 * 150 NE cylinders of 150 Ø * 300	35.17	ND	3.12	[23]
19	Agave sisalana	Cultivated without harvesting	Portland	Cement paste	0.1, 0.5, 1.0, 2.0, 3.	15 prisms of 40 * 40 * 160	−9.67%	+150.71%	ND	[24]
20	Agave sisalana	Grown without harvesting	Portland	Structural concrete M30	0.50, 1.00, 1.25, 1.50	12 cubes of 150 * 150 * 150	44.91	ND	ND	[25]
21	Agave sisalana	NE	Portland	NE	0.25, 0.5, 0.75, 1.0, 1.25, 1.	NE cubes and NE prisms	59.5	7.3	4.4	[26]
22	Agave sisalana	NE	Portland	NE	0, 0.5, 1.0, 1.5	NE cylinders of 100 Ø * 200	+35.98%	+11.80%	ND	[27]
23	Agave sisalana	NE	Portland Grade 53	NE	1	NE cubes of 150 * 150 * 150 NE cylinders of 100 Ø * 200 NE prisms of 500 * 100 * 100	49.74	3.58	6.56	[28]
24	Agave sisalana.	Grown without harvesting	Portland Grade 53	Structural concrete	0.5, 1.0, 1.5, 2.0	36 cubes of 100 * 100 * 100	54.30	5.83	3.87	[29]

(Continues)

TABLE 1 | (Continued)

No.	Agave variant	Origin	Type of cement	Specification of the use of concrete	Percentage of fiber addition (blends) (%)	Type and quantity of specimens (mm)	Maximum strength (MPa)			Reference
							Compression	Flexural	Voltage	
25	Agave sisalana.	NE	Portland Grade 43	NE	0.25, 0.5, 1.5	NE cubes of 150 * 150 * 150 NE prisms of 100 * 100 * 500 NE cylinders of 150 Ø * 300	+34.48%	+5.3%	+4.33%	[30]
26	Agave sisalana	Grown without harvesting	Portland Grade 53	NE	0, 1, 1.5, 3, 5	NE cubes of 150 * 150 * 150	24	ND	8.09	[31]
27	Agave sisalana	NE	NE	NE	NE	6 beams	ND	35	ND	[32]
28	Agave sisalana + PP	NE	Portland	Light slab	3.0 S + 1.7 PP	NE prisms of 165 * 40 * 5	ND	ND	ND	[33]
29	Agave sisalana	NE	Portland Grade 42.5	Structural concrete	1	NE cylinders of 100 Ø * 200 NE prisms of 100 * 100 * 400 NE cubes of 150 * 150 * 150	+14.0%	+30.9%	+36.8%	[34]

TABLE 2 | Comparison of studies related to the mechanical properties of biochar-added concrete.

No.	Biodegradable material	Origin	Biochar production and time	Type of cement	Specification of the use of concrete	Percentage of biochar additive (blends) (%)	Type and quantity of specimens (mm)	Maximum strength (MPa)		Reference
								Compression	Flexural	
1	Pine nut shells, coconut shells, and bagasse	Agricultural waste	Pyrolysis	Portland type PI 42.5	Concrete for carbonation resistance test	4	6 cubes of 40*40*40	+24.6%	ND	[35]
2	Wood sawdust	Forest residue	Slow pyrolysis	Low-alkalinity sulfoaluminate cement, grade 42.5	Structural green concrete	5, 10, and 15	15 cubes of 150*150*150 76 cylinders of 38 Ø*76	0.42	ND	[36]
3	Wood charcoal powder	Forest residue	NE	Dangote 3X Grade 42.5 R Portland cement	NE	0, 20, 40, 60, and 80	60 cubes of 100*100*100 30 cylinders of 75 Ø*150	29.37	ND	[5]
4	Waste wood chips	Forest residue	Typical pyrolysis	Portland type I	HVFC (high-volume fly ash concrete)	0, 2.5, 5, 6.5, and 8	60 cylinders of 100 Ø*200	46	ND	[37]
5	Palm, apricot, date, and peach shells	Forest residues and agricultural waste	NE	Ordinary Portland cement PO 42.5 R	UHPC (ultra-high-performance concrete)	1, 2, 4, 8, 10, 20, 30, and 40	24 cubes of 40*40*40, 24 prisms of 25*25*285 24 cylinders of 50 Ø*100	75.56	ND	[38]
6	Rice husk	Agricultural waste	Pyrolysis	Alkali-activated slag (not Portland cement)	Concrete with improved impact resistance	0, 2, 4, 6, and 8	18 cubes of 100*100*100	53.2	ND	[39]
7	Peanut shells	Agricultural waste	Pyrolysis	Portland P.II 42.5R	NE	2 and 4	12 cylinders of 50 Ø*100	+24%	ND	[40]
8	Coffee residues	Food waste	Pyrolysis	Portland cement CEM I 42.5N (PC)	Structural green concrete	0, 2, 4, 6, 8, and 10	18 prisms of 40*40*160 18 cubes of 100*100*100	58	4.1	[41]
9	Algae of chlorella with Zn and Ca	Marine biomass	Pyrolysis	Portland type I/II	Modified conventional concrete	0, 1, 3, 5, and 7	30 cylinders of 12.5 Ø*25	26.2	ND	[42]
10	Wood dust	Forest residue	Pyrolysis	Cement	NE	1–3	NE	50.23	ND	[43]

(Continues)

TABLE 2 | (Continued)

No.	Biodegradable material	Origin	Biochar production and time	Type of cement	Specification of the use of concrete	Percentage of biochar additive (blends) (%)	Type and quantity of specimens (mm)	Maximum strength (MPa) Compression	Flexural	Reference
11	Vetiver grass roots	Agricultural waste	Pyrolysis	Portland type I	UHPC	0.5, 1, 1.5, and 2	NE cubes of 50 * 50 * 50 NE beams of 13 * 76 * 280	18	28.7	[44]
12	Palm rachis	Forest residue	Pyrolysis	CEM II/AS 42.5N type cement	Bio-mortars	0, 1, 2, 3, 4, and 5	NE cylinders of 50 Ø 50	63.81	ND	[45]
13	Wood chips	Forest residue	Pyrolysis	Portland limestone CEM II/A-LL 42.5 R	Structural concrete	2.5, 5, 7.5, and 10	NE cubes of 150 * 150 * 150, NE cylinders of 100 Ø 200 NE prisms of 100 * 100 * 400 Total of 200 pieces	44	+29%	[46]
14	Corn stalks	Agricultural waste	Slow pyrolysis	Portland Ordinary Grade 42.5	Cement pastes for CO_2 storage.	5, 10, 20, and 25	24 cubes of 40 * 40 * 40.	+14.3%	ND	[47]
15	Bamboo	Forest residue	Pyrolysis	Portland type I	NE	1, 2.5, 5, 7.5, and 10	NE beams of 40 * 40 * 160	+8.6%	ND	[48]
16	Wood	Forest residue	Slow pyrolysis	Ordinary Portland Cement (OPC)	Carbon-negative cement paste	23 and 30	NE cubes of 50 * 50 * 50	54	ND	[49]

Addition percentages vary from a minimum value of 0.5 to a maximum of 20%, depending on the type of residue and the objective of the study. Portland cement was used (75%). The concrete specimens tested were cubes, cylinders, prisms, and beams. Results of compressive strength test were reported in whole on studies instead of only three cases of flexural tests. The mechanical properties evaluated show increases mainly in compressive strength and flexural strength in some specific cases. The results show variability due to differences in proportions, methods of obtaining biochar, dimensions, specimen types, and test conditions, aspects that will be analyzed in later sections.

3.3 | Origin, Production, Availability, and Sustainability

3.3.1 | Agave Fibers

The use of agave fibers in concrete represents a solid strategy from an environmental sustainability perspective, primarily because they are renewable natural materials that are biodegradable and, in most cases, agricultural residues. In the total number of articles reviewed, according to [7], note that Agave sisalana, commonly known as sisal, was the most frequently used fiber, present in more than two-thirds of the studies. Similarly, [8] used Agave americana fiber, known as maguey; both fibers achieved an increase in the mechanical tests to which they were subjected.

A key characteristic of these fibers is that their use in the concrete industry is secondary: They are byproducts of crops originally intended for the extraction of juices, syrups, or textile fibers. In many cases, the leftover fibrous material is discarded as organic waste, potentially contaminating the environment through decomposition or incineration. The possibility of incorporating it as structural reinforcement in construction materials allows adding a new value to an input that is considered waste, turning it into a technical resource with a positive economic and environmental impact [12, 15].

In environmental terms, agave fibers do not require intensive industrial processes to obtain them, nor do they generate relevant emissions during processing [10]. When subjected to thermal or chemical treatments to improve their adhesion to the concrete matrix, the processes involve temperatures and reagents with low environmental impact compared to those used in the manufacture of synthetic additives or polymeric reinforcements. In addition, their biodegradable condition ensures that, at the end of their useful life, the materials will not contribute microplastics or toxic residues to the environment, as is the case with industrial fibers, such as polypropylene or glass.

There is a high availability of agave fibers, especially in countries that are large producers of the food or textile industry [12]. This practice optimizes costs and promotes local circular economies, assigning value to industrial waste by reusing raw materials for new processes. This local valorization is also relevant from a social perspective, offering opportunities for innovation and the generation of added value in agricultural or rural communities.

3.3.2 | Biochar

The biochar used in the reviewed studies was obtained from a wide variety of organic wastes, including peanut shells, wood, palm, coffee residues, algae, and fruit pits, such as apricot and date pits. These wastes were transformed into biochar through pyrolysis, a thermochemical process that heats biomass in the absence or limited presence of oxygen and promotes conversion to a porous, chemically stable carbonaceous material.

In general, slow pyrolysis (between 300°C and 500°C, lasting 2–6 h) was the most common method among the studies, resulting in a biochar with high porosity, high water absorption capacity, and greater thermal stability-ideal characteristics for its application in concrete matrices. For example, it was observed that biochar obtained at 500°C and used in mortars improved the compressive strength by 10% with only a 1% addition [46].

Some works employed pyrolysis at higher temperatures (600°C–800°C), as in the case of algal biochar doping with zinc and calcium investigated or wood waste biochar evaluated by [46]. At these temperatures, the biochar acquired a highly carbonized and more chemically stable structure, which favored the secondary nucleation of C-S-H products during cement hydration, thus improving the compressive strength. However, both studies caution that excessively high temperatures can reduce the amount of surface functional groups (such as carboxyl and hydroxyl) on hydrated cement products, thereby decreasing their ability to chemically interact with other substances.

In comparative terms, the studies conclude that medium pyrolysis temperatures (around 500°C) offer the best balance between porosity, structural stability, and surface functionality, favoring both internal curing and reaction with the concrete matrix. In addition, chemical characterization using techniques, such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and energy-dispersive X-ray spectroscopy (EDS), confirmed that the biochar's obtained under these conditions exhibited a stable aromatic structure and capacity to integrate into the cement without causing detrimental reactions [35, 44].

3.4 | Treatments Applied and Performance

3.4.1 | Agave Fiber

Before being incorporated into concrete mixes, agave fibers require treatment to enhance their interaction with the mix. These treatments are aimed at eliminating natural impurities present in the fiber (such as waxes, lignin, and hemicellulose), reducing its water absorption capacity, and increasing its adherence to the concrete matrix. Without these modifications, the fibers tend to weaken the composite material, as they absorb moisture from the mix and generate failure zones due to poor structural compatibility [24]. The most frequently identified methods in the reviewed studies [5, 6, 8–13, 18–21, 27, 29, 32, 35] include alkaline, thermal, surface chemical, bioactivation, and pozzolanic treatments.

In addition to conventional alkaline and chemical surface treatments, recent studies have highlighted the effectiveness of alkaline-pozzolanic and pozzolanic treatments in improving durability and the fiber–matrix interface in cementitious composites. They have been shown to reduce water absorption, mitigate fiber degradation, and improve mechanical performance by promoting better adhesion and microstructural stability [50, 51].

The studies reviewed agree that the application of pretreatments to agave fibers is essential to improve their compatibility with the concrete matrix and ensure effective reinforcement. One of the most common methods was alkaline treatment with sodium hydroxide (NaOH), which removes impurities, such as lignin, hemicellulose, and surface waxes from the fiber. This increases its roughness and improves cement adhesion. In the study by [8], treatment with 2% NaOH significantly improved the tensile strength of the agave/mortar composite.

Reference [15] mentioned that the use of calcium oxide (CaO), used on maguey fibers by immersion in a CaO–water solution (3: 1) for 24 h, modifies the surface of the fibers, favoring their adhesion to the cementitious matrix. As a result, a significant improvement in the mechanical resistance to compression, tension, and modulus of elasticity was observed, especially with a dosage of 0.9% of fiber.

Chemical surface treatments were also employed, such as the one performed by [23] who used a Na_2CO_3 solution to modify the surface of the sisal fiber. This treatment generated calcium carbonate deposits at the fiber–matrix interfaces, which enhanced the compressive and tensile strength of the concrete, in addition to increasing the stability of the fibers in alkaline environments. The accumulation of Na^+ and CO_3^{2-} ions on the fiber surface promoted reactions with the Ca^{2+} of the cement, reducing the dissolution of components, such as hemicellulose and lignin, thereby improving the durability of the composite.

In general, the chemical treatments applied promoted better adhesion between the fibers and the concrete, which was reflected in improvements in postcrack strength, ductility, and durability of the composite. In contrast, studies, such as those by [8], observed that untreated fibers tend to absorb more water, which negatively affects the performance of the composite, and may lead to early cracking or lower mechanical strength.

3.5 | Assessment of Carbon Contribution and Capture

3.5.1 | Biochar

According to [47], it offers an environmental advantage, particularly in terms of sustainability and emissions reduction. It is produced from agricultural waste or discarded biomass, such as peanut shells, wood residues, coffee, or algae, and its incorporation into concrete represents an efficient strategy for the valorization of organic waste, as it becomes an additive, closing the life cycle of biomass within a circular economy logic.

Although pyrolysis requires temperatures between 400°C and 600°C, the process is more energy efficient than Portland cement production, whose clinker requires temperatures of up to 1450°C. Additionally, biochar can be produced using adaptable technologies on a small scale in rural areas, utilizing controlled kilns and local biomass, which reduces the transportation footprint and allows for decentralized production.

A highlight is its high capacity to capture and store carbon. Unlike other materials, biochar does not degrade easily in alkaline media, nor does it emit gases during its useful life. On the contrary, studies have shown that each kilogram of biochar can encapsulate up to 1.3 kg of CO_2, acting as a carbon-stable sink in the concrete matrix [49]. This behavior is explained by its resistant, aromatic carbonaceous structure and its low reactivity to oxidation.

Environmental optimization models developed by [43] estimate that, depending on the raw material used, the efficient use of biochar can contribute to reducing up to 870 kg of CO_2 per ton of processed agricultural waste, without compromising the mechanical properties of the concrete or its economic viability. Moreover, its high fixed carbon content (above 60%) is what makes it a key material versus other mineral admixtures. While Portland cement contains a significant fraction of carbonates that release CO_2 upon decomposition during calcination, biochar acts in the opposite direction, storing carbon instead of releasing it.

3.6 | Evaluation and Microstructural Performance of Modified Cementitious Matrices

3.6.1 | Agave Fibers

Studies evaluating the use of agave fibers as reinforcement in cement mortars employed various physical conditioning and structural characterization procedures to ensure their compatibility with the matrix. In the study by [8], the effect of varying fiber lengths (5, 10, 25, 40, and 50 mm) on the interlocking capacity and crack bridging in concrete mixtures was evaluated. The results showed that fibers of intermediate length, averaging 25 mm, offered the best mechanical performance, with increases in both tensile and flexural strength. In contrast, the shorter and longer fibers at this value presented limitations: The former provided minor improvements, while the latter exhibited dispersion and agglomeration problems, which negatively affected their structural contribution. The morphological characteristics of agave fibers, including their longitudinal and transverse structure, as well as the effect of fiber cutting on length uniformity, are illustrated in Figure 3, which helps to contextualize the influence of fiber length on dispersion behavior and interlocking efficiency within the cementitious matrix.

Additionally, the fibers were dried (at temperatures up to 150°C for 8 h) to eliminate impurities, reduce their water absorption capacity, and improve their stability against the alkaline environments of the concrete. Report by [24] and [10], through SEM analysis, determined that thermally or chemically treated fibers present a higher surface roughness and a more exposed structure, which facilitates mechanical anchorage with the concrete matrix. This enhanced fiber–matrix interaction is evidenced in Figure 4, where SEM images show chemically treated agave fibers well embedded within the cementitious matrix, surrounded by C–S–H gels and reduced interfacial voids, indicating improved mechanical anchorage.

XRD analysis was used to study the crystallinity of cellulose; as reported by [8], it has been mentioned that higher crystallinity is related to stronger fibers which favor the mechanical properties of concrete.

In addition, other studies have examined the structural and thermal responses of fiber-reinforced concrete under high-temperature conditions. George and Selvan [52] reported that hollow columns filled with lightweight steel exhibited greater ductility and delayed local buckling when filled with fiber-reinforced concrete exposed to high temperatures, highlighting

FIGURE 3 | Morphology and preparation of agave fibers: (a) raw agave fibers and (b) agave fibers cut to a controlled length for incorporation into cementitious matrices. Adapted from [17]. The figure used is available under the Creative Commons license at https://doi.org/10.1177/15589250241265701.

the role of confinement in preserving residual strength. In further research, the same authors [53] showed that steel fiber-reinforced concrete beams retained up to 90% of their load-bearing capacity after exposure to 1000°C, demonstrating the contribution of fibers to reinforcing stiffness and strength under severe heating. A subsequent study [54] confirmed up to 32% higher load-bearing capacity for similar configurations and the potential of fiber-reinforced systems to maintain structural integrity and mitigate thermal degradation in cementitious composites.
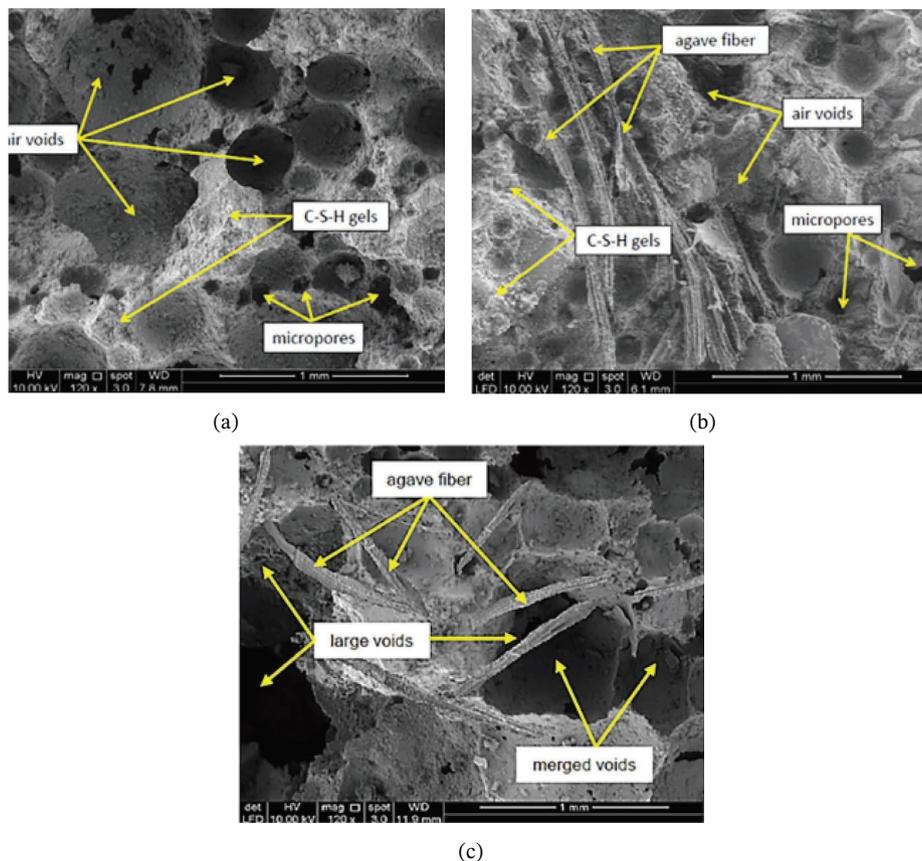
FIGURE 4 | SEM images of cementitious composites: (a) control specimen without fibers, (b) agave fiber–reinforced composite showing improved fiber–matrix interaction, and (c) composite with higher fiber content exhibiting fiber agglomeration and voids. Adapted from [17]. The figure used is available under the Creative Commons license at https://doi.org/10.1177/15589250241265701.

(a)   (b)
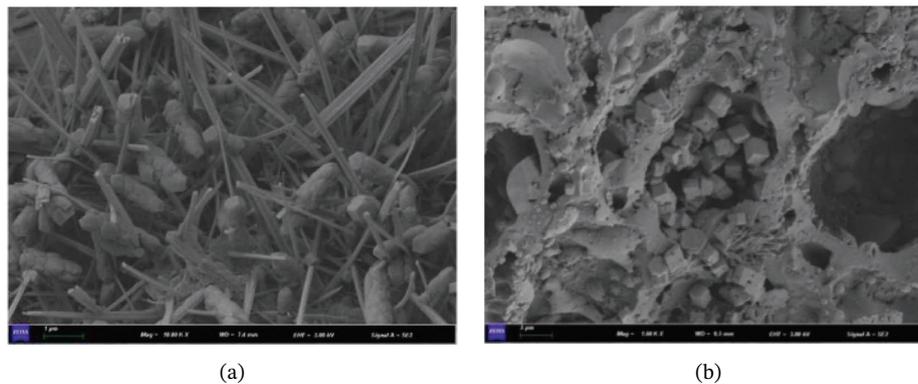
FIGURE 5 | SEM microstructure of biochar-modified cementitious matrix: (a) cementitious matrix with abundant hydration products and (b) porous biochar particles embedded within the matrix. Adapted from [38]. The figure used is available under the Creative Commons license at https://doi.org/10.1016/j.cscm.2024.e03595.

3.6.2 | Biochar

According to studies by [42], biochar enhances the mechanical properties of concrete, including compressive strength. Also, it serves as an internal curing agent due to its high porosity and water-holding capacity. It can store moisture during the mixing stage and gradually release it during hydration. This sustained release of water contributes to a more complete hydration of the cement silicates, especially tricalcium silicate (C_3S), which promotes the formation of hydrated products, such as C-S-H (hydrated calcium silicate), responsible for the development of strength in concrete. Figure 5 shows SEM images of the porous biochar structure, which acts as an internal reservoir for water and promotes the formation of hydration products within the cementitious matrix.

From the chemical point of view, [42] demonstrated that metal (Zn/Ca)-doped biochar enhances C-S-H nucleation through its metal nanoparticles, which provide active sites for the growth of hydrated phases. Additionally, the porosity of the biochar allows for internal curing, gradually releasing water for more complete hydration. This results in a dense microstructure and higher compressive strength; however, its effect on the interfacial transition zone (ITZ) was not studied because pure pastes were used.

Reference [44] also reported that biochar, when presaturated before its incorporation into UHPC (first UHPC) mixes, acts as an internal curing material, decreasing autogenous shrinkage by up to 15% (for biochar used at 2%) and promoting better hydration, which leads to a denser microstructure. Through nano-indentation analysis by atomic force microscopy (AFM), it was determined that the addition of 1% biochar optimizes the concrete matrix, while higher doses (2%) generate "micro defects" that reduce the mechanical properties. However, thermogravimetry (TGA) data confirmed a reduction in harmful porosity by improving the degree of hydration by 14%.

The beneficial effect of biochar strongly depends on its dosage. Several studies agree that amounts of 5–7.5 wt. % of cement increase the overall porosity of the system (due to the internal pores of BC) and decrease the mechanical strength, as its internal pores start to behave as structural voids that weaken the matrix [48]. As illustrated in Figure 6, excessive biochar content leads to an increased number of pores and micro-cracks, suggesting that biochar pores may act as structural voids at high dosages.

3.7 | Improved Mechanical Properties

3.7.1 | Agave Fibers

The performance of agave fibers in concrete depends on several key parameters, including fiber treatment, fiber length, percentage, and the type of mechanical test performed. To consolidate this information (see Table 3), the technical parameters
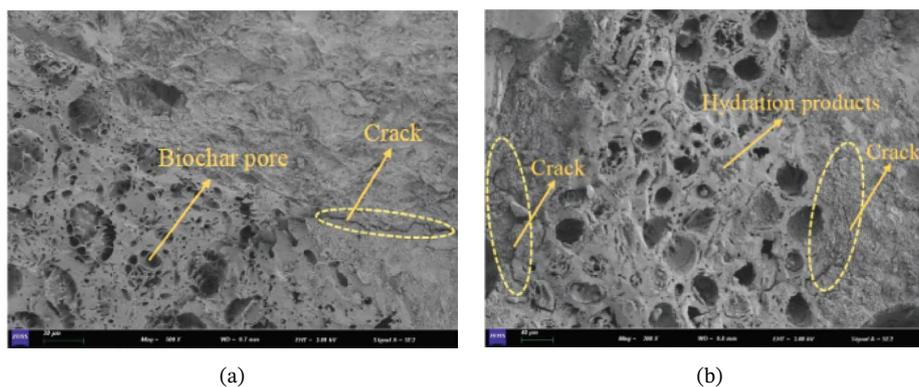

(a)   (b)

FIGURE 6 | SEM microstructural features of cementitious matrix with high biochar content (a-b). Adapted from [38]. The figure used is available under the Creative Commons license at https://doi.org/10.1016/j.cscm.2024.e03595.

and results collected from 29 studies that incorporated agave fibers into concrete matrices are summarized.

The table includes essential variables of the fibers that show the best results obtained from different addition percentages, such as the type of pretreatment applied to the fibers (e.g., alkaline immersion, silane treatment, or surface modifications), the length of the fibers (between 5 and 50 mm), fiber dosage (0.25%–9.3% by volume), water–cement ratio (w/c), and the geometry and dimensions of the test samples. Also noteworthy are the age of the tests (7–90 days), the mechanical property evaluated (compression and flexural strength), the maximum strength obtained (in MPa), and the percentage improvement relative to the control mixtures.

The experimental data in Table 3 show that the mechanical response of agave fiber-reinforced concrete depends directly on three parameters: fiber length, treatment, and dosage. The best performance was obtained with fibers 25 mm in length and dosages between 0.25% and 1.0% by volume. Under these conditions, alkaline-treated and CaO-treated fibers increased flexural strength by 34.42%, compressive strength by 54%, and tensile strength by 39.13% compared with control specimens. Mixtures containing untreated fibers (0.5%–1.5% by volume) showed no measurable improvement and, in some cases, a 5%–10% reduction in compressive strength due to poor interfacial bonding and high water absorption that produced internal porosity and early microcracking. These results identify 25 mm fibers chemically treated and 0.9% by volume as the most effective combination for mechanical enhancement.

3.7.2 | Biochar

The included articles indicate that incorporating biochar in controlled proportions can significantly improve the mechanical properties of concrete, provided that it is kept within optimal ranges (between 1% and 4% by weight of cement for standard particles and up to 7.5% for fine particles). These improvements are primarily attributed to the internal curing capacity of biochar, as it gradually releases the moisture retained during hydration and enhances the nucleation of hydrated phases [23, 35],

To consolidate the results, Table 4 summarizes the production parameters and mechanical improvements described in 16 studies using biochar as an additive in concrete mixtures. This table includes the type of biomass source (wood, coffee, algae, rice husks, palm rachis, peanut shells, etc.), pyrolysis conditions (temperature, duration, and atmosphere), water–cement ratio, biochar dosage, sample type and size, curing age, and maximum compressive strength achieved (MPa). It also highlights the percentage improvement over control mixtures.

3.8 | Limitations and Technical Considerations

3.8.1 | Agave Fibers

Despite the growing interest in incorporating agave fibers into concrete mixtures, there are technical limitations that still restrict their direct application in construction practice, especially in major structural elements. Several studies agree that the addition of vegetable fibers should be done with caution, as their excess can negatively affect the cohesion of the mix, increase porosity, and reduce compressive strength. Experimental evidence summarized in Tables 1 and 3 indicates that when fiber

content exceeds 1.5% by volume, the mixture exhibits a 10%–18% reduction in compressive strength, increased porosity, and poor workability due to excessive water absorption and fiber agglomeration. These effects are associated with irregular dispersion and entrapped air voids that weaken the cement matrix. For this reason, it is recommended to maintain fiber content below 1.5%, limiting its use mainly to nonstructural elements, such as blocks, prefabricated panels, dividing walls, pedestrian pavements, or low-load concrete where mechanical safety is not compromised. Therefore, it is recommended to limit its use mainly to nonstructural elements, such as blocks, prefabricated panels, dividing walls, pedestrian pavements or low-load concrete, where mechanical reinforcement does not compromise the main structural safety.

Another relevant aspect is that, unlike other admixtures, agave fibers do not directly replace basic concrete materials, such as cement, gravel, or sand. Their function is that of dispersed-phase reinforcement, which means that they do not replace aggregates or reduce the amount of cement; instead, they act as tension bridges in the hardened matrix, improving flexural or tensile strength. However, their incorporation does require adjustments in the mix design, particularly in the water/cement ratio, due to the high water absorption of the fibers, and in the mixing time to ensure uniform distribution.

It was also identified that the type of cement most commonly used in these mixtures is Portland cement, which has a highly alkaline environment.

It is worth noting that there are currently no industrial standards for the dosage, preparation, and application of agave fibers, which represents a barrier to their adoption in real-world projects. The absence of clear regulations generates uncertainty regarding the quality of the reinforcement, long-term performance, and its behavior in different environmental conditions. Therefore, for these fibers to be a realistic and reliable option, it is essential to advance the standardization of their use and quality control from their origin to their on-site placement.

3.8.2 | Biochar

Although biochar has shown remarkable potential as a sustainable admixture in concrete mixtures, the reviewed studies agree that there are still relevant technical limitations that hinder its implementation on a real construction scale. One of the main challenges is the generalized absence of tensile strength evaluations. None of the analyzed articles reported concrete values of maximum tensile strength in biochar blends, which represents a gap, considering that this property is important for the performance of elements subjected to tensile stresses. This lack of information limits the possibility of applying biochar in structural elements. Moreover, as already mentioned, the effect of biochar on concrete depends strongly on its type, origin, pyrolysis temperature, and dosage. There is no standardization on its production or on the properties it must meet as an admixture, which generates a high variability among studies. This represents an important barrier to its scalability as it prevents the establishment of clear rules for its dosage, its expected behavior, or its interaction with other concrete components. Another critical aspect is the feasibility of large-scale production; although biochar is made from low-cost organic waste, such as coffee grounds, wood, vegetable shells, or algae, the amount of waste required to

TABLE 3 | Technical parameter optimization of concrete mixtures with agave fibers.

No.	Fiber treatment	Length (mm)	Ratio (w/c)	Fiber (%)	Specimen type and dimension (mm)	Age and type of essay	Maximum strength (MPa)	Improvement (%)	Reference
1	NaOH 4% 30 min → rinse → dry at 60°C; → silane hydrolysate → ultrasonic immersion 30 min → dry at 120°C	20	0.30	2	Beams of 40 * 40× * 160	28 days Flexural	5.5	ND	[7]
2	NaOH 2% at 60°C for 120 min	19	0.50	2	Beams of 40 * 10 * 150	28 days Flexural	13.54	40.6	[8]
3	ND	ND	ND	ND	ND	ND	ND	ND	[9]
4	Immersion in NaHCO$_3$ (2.5%, 5%, 10%) for 120 h (5 days) → washing with distilled water → drying at 40°C for 24 h	25	1:05:2	2	Beams of 40 * 40 * 160	28 days Flexural	3.3	64	[10]
5	Mercerization NaOH 5%–10%	20	0.50	0.75	Slabs of 300 * 300 * 25	28 days Compression	37	48	[11]
6	Immersion in 10% NaOH for 24 h → rinse with water → neutralization with acetic acid	25	0.45	2	Cubes	28 days Compression	32.67	45.5	[12]
7	Immersion in water at 27°C for 3 h → draining excess water, hanging for 30 min → drying at 80°C for 16 h → cooling in the oven (avoid thermal shock) 4 h 30 min → repeating the cycle 10 times in 24 h	ND	0.35	9.3	Plates (thin beam) of 400 * 100 * 10	Flexural	25.9	ND	[13]
8	2% NaOH immersion	5	0.5	0.5	Beams of 40 * 40 * 160	28 days Flexural	8.27	16.54	[14]
9	Immersion in Cao = 3:1 for 24 h → washing → air drying at 27°C–29°C	50	0.64	0.9	Cylinders of 150 Ø * 300	28 days Compression	27.33	13.41	[15]
10	None	30	NE	3	Blocks of 200 * 100 * 80	28 days Compression	14.7	48	[16]
11	None	19	0.45	4.5	Cubes of 100 * 100 * 100	28 days Compression	ND	23.6	[17]
12	Immersion in 5% NaOH (in a borosilicate glass) for 5 min → microwave exposure of the suspension at 640 W for 10 min → rinse with distilled water → drying for 24 h at room temperature → drying after 12 h at 80°C in an oven	NE	NE	NE	NE	Flexural	47.93	65	[18]
13	None	10	ND	1	Cubes of 50 * 50 * 50	28 days Compression	2.55	ND	[19]
14	None	25	ND	0.25	Cubes of 100 * 100 * 100	28 days Compression	2.54	13.39	[3]

(Continues)

TABLE 3 | (Continued)

No.	Fiber treatment	Length (mm)	Ratio (w/c)	Fiber (%)	Specimen type and dimension (mm)	Age and type of essay	Maximum strength (MPa)	Improvement (%)	Reference
15	Immersion in water and lime (NE) $\longrightarrow$ drying at room temperature at 27°C for 1 week	50	0.48	NE	Cylinders of 150 Ø * 300	28 days Compression	33.29	4.4	[20]
16	Immersion in hot water (70 ± 5°C) for 1 h $\longrightarrow$ air drying for 48 h $\longrightarrow$ immersion in tannic acid (10 g/L) in 200 mL of water, pH adjusted to 8 with NaOH, for 12 h $\longrightarrow$ immersion in octadecylamine (3.75 g/L) with 120 mL of isopropanol + 80 mL of water, for 12 h $\longrightarrow$ washing with deionized water $\longrightarrow$ air drying for 24 h	NE	1.29	NE	NE	NE	ND	ND	[21]
17	Initial wash $\longrightarrow$ 2 with drinking water, 1 with tap water $\longrightarrow$ immersion in 2% NaOH for 4 h $\longrightarrow$ immersion in 1 mL H_2SO_4 for 2 h $\longrightarrow$ wash and dry for 2 h	10–20	0.54	1.5	Cubes of 150 * 150 * 150	28 days Compression	37.37	20	[22]
18	Immersion in Na_2CO_3 (sodium carbonate), for 10 days	35–40	0.42	1	Cubes of 150 * 150 * 150	28 days Compression	37.17	7.4	[23]
19	None	20	0.35	1	Beams of 40 * 40 * 160	28 days Flexural	NE	150.71	[24]
20	None	12	NE	1.5	Cubes of 150 * 150 * 150	90 days Compression	44.91	5.62	[25]
21	None	30 ± 2	0.56	1	Cubes	15 days Compression	59.5	22	[26]
22	Immersion in water for 15–20 min $\longrightarrow$ air drying for 24 h $\longrightarrow$ drying at 150°C for 8 h	20	0.50	0.5	Cylinders of 100 Ø * 200	28 days Compression	NE	35.98	[27]
23	None	10	NE	NE	Cubes of 150 * 150 * 150	28 days Compression	49.74	16.5	[28]
24	Dried at 150°C for 8 h	NE	0.39	1.5	Cubes of 100 * 100 * 100	28 days Compression	54.3	9.7	[29]
25	Washing with detergent	NE	NE	1.5	Cubes of 150 * 150 * 150	28 days Compression	NE	34.48	[30]
26	None	30–50	NE	1	Cubes of 150 * 150 * 150	7 days Compression	24	5.2	[31]
27	Dried at 80°C for 48 h	NE	0.5	NE	Beams	28 days Flexural	35	11.2	[32]
28	None	2.30	NE	3	Beams of 165 * 40 * 5	28 days Flexural	NE	60	[33]

(Continues)

TABLE 3 | (Continued)

No.	Fiber treatment	Length (mm)	Ratio (w/c)	Fiber (%)	Specimen type and dimension (mm)	Age and type of essay	Maximum strength (MPa)	Improvement (%)	Reference
29	60-min immersion in Bacillus subtilis	25	0.45	1	Cylinders of 100 Ø * 200	28 days Strain	NE	36.8	[34]

obtain a useful mass of biochar applicable in construction is considerable. For example, to produce a beam or a standard volume of concrete with 1% biochar, it would be necessary to collect large quantities of waste. This limitation of residual biomass availability represents a challenge for regions with low agricultural waste generation or where the available biomass has very variable compositions. Biochar does not replace major components, such as cement or aggregates. On the contrary, its inclusion requires fine adjustments in the dosage and in the water/cement ratio due to its high porosity and absorption capacity. If these factors are not adequately compensated for, the workability and homogeneity of the mix can be negatively affected. In addition, the porosity of biochar can compromise compaction and increase air content, reducing the density of the final concrete. From a practical perspective, there are still no normative regulations or official technical guidelines for its use in structural concrete, which limits its acceptance in conventional works; the chemical characterization conditions have not been sufficiently studied in mixtures with biochar, which leaves unanswered key questions about its long-term durability.

4 | Discussion

4.1 | Use of Agave Fibers

A viable strategy to transfer the laboratory findings to real applications on site is the development of standardized protocols that contemplate the type of fiber, its treatment, length, and proportion, as well as the adaptation of the cementitious mixture. Based on the studies reviewed, Agave sisalana and Agave americana fibers have shown a more favorable behavior as vegetal reinforcement in concrete. Ordinary Portland cement (type I) was the most used binder in more than 90% of the studies analyzed, which supports its compatibility with these treated fibers.

Therefore, from the studies analyzed, a fiber dosage between 0.5% and 1.5% by volume of the total concrete, with lengths of 25 mm, is recommended as this range has shown average increases of 20%–40% in flexural strength and improvements of more than 30% in tensile strength.

To improve the density of the concrete mix and minimize water absorption, it is suggested to pretreat the fibers by alkaline immersion (NaOH 1%-2%) for 12–24 h or thermal drying at 150°C for 6–8 h and keep the fiber in a dry environment. After mixing the aggregates (cement, sand, gravel, and water), the fiber should be incorporated completely dry into the mix, and it is advisable to check the slump of the mix and adjust the water content so as not to interfere with the design strength of the project.

These fibers should not be used as a substitute for aggregates or cement but as an additional functional component to improve strength and ductility. Therefore, the design of the mix should be slightly adapted, considering that the fiber volume takes up space in the mix. It is recommended to slightly increase the final mixing time (1-2 additional minutes) to achieve homogeneous dispersion.

In nonstructural elements, such as blocks, prefabricated panels, walkways, finishes, simple concrete pieces, or low-traffic pavements, the use of agave fibers represents a technically and ecologically viable alternative. For critical structural elements

TABLE 4 | Production parameter optimization and the effect of biochar in concrete mixtures.

No.	Pyrolysis process	Ratio (w/c)	Biochar (%)	Specimen type and dimension (mm)	Age and type of essay	Maximum strength (MPa)	Improvement (%)	Reference
1	Pine nut shell → washing and drying (60°C) → mixing with urea (ratio 0.2) → immersion (12 h) → drying → addition of KOH solution → stirring (0.5 h) → immersion (12 h) → drying → pyrolysis in a vacuum oven (600°C–800°C, 1.5 h, 5°C/min) → washing with HCl and deionized water until pH 7 → final drying → modified biochar (M3)	0.35	4	Cubes of 40 * 40 * 40	28 days Compression	NE	24.6	[35]
2	Wood sawdust → slow pyrolysis at 500°C under anoxic conditions	2.5	5	Cylinders of 50 Ø * 100	28 days Compression	0.42	15	[36]
3	NE	NE	20	Cubes of 100 * 100 * 100	28 days Compression	29.37	17.81	[5]
4	Wood sawdust → typical pyrolysis at 400°C under low oxygen conditions	0.48	2.5	Cylinders of 100 Ø * 200	28 days Compression	46	23	[37]
5	NE	0.24	1	Cubes of 40 * 40 * 40	28 days Compression	75.56	NE	[38]
6	Rice husk → pyrolysis at 500°C for 60 min (muffle furnace)	0.5	6	Cubes of 100 * 100 * 100	28 days Compression	53.2	44.6	[39]
7	Peanut shells → pyrolysis at 600°C–800°C under hypoxic conditions	0.44	2	Cubes of 100 * 100 * 100	28 days Compression	NE	24	[40]
8	Coffee waste → pyrolysis at 400°C for 2 h (in a tray sealed with perforated aluminum)	0.55	4	Cubes of 100 * 100 * 100	28 days Compression	59	5.85	[41]
9	Chlorella algae → mixture with $Zn(NO_3)_2 \cdot 6H_2O$ or $Ca(NO_3)_2 \cdot 4H_2O$ → stirring for 24 h at room temperature → drying for 24 h at 80°C → pyrolysis increasing the temperature from 21°C to 500°C at a rate of 5°C/min, holding for 1 h → cooling to 21°C at 5°C/min	0.40	3	Cylinders of 12.5 Ø * 25	28 days Compression	26.2	22.6	[42]
10	Wood powder → pyrolysis at 480°C–620°C for 160–280 min under oxygen-restricted conditions	0.4–0.6	1–3	NE	NE	50.23	9.68	[43]
11	Grass roots → pyrolysis at 500°C for 1 h in the absence of oxygen	0.23	1	Cubes of 50 * 50 * 50	28 days Compression	128	10	[44]
12	Palm rachis → pyrolysis at 300°C–500°C for 30 min	0.5	1	Cylinders of 50 Ø * 50	28 days Compression	63.81	13	[45]
13	NE	0.5	5	Cubes of 150 * 150 * 150	28 days Compression	44	17	[46]
14	Corn stalks → slow pyrolysis at 500°C–600°C	0.5	10	Cubes of 40 * 40 * 40	28 days Compression	NE	14.3	[47]

(Continues)

TABLE 4 | (Continued)

No.	Pyrolysis process	Ratio (w/c)	Biochar (%)	Specimen type and dimension (mm)	Age and type of essay	Maximum strength (MPa)	Improvement (%)	Reference
15	Bamboo ⟶ pyrolysis at 700°C	0.5	1	Beams of 40 * 40 * 160	28 days Compression	NE	8.6	[48]
16	Wood ⟶ slow pyrolysis at 677°C for 10 h in an oxygen-free atmosphere	0.55	23	Cubes of 50 * 50 * 50	56 days Compression	54	22	[49]

(beams, columns, and load-bearing slabs), its use still requires validation at full scale through protocols that ensure uniformity of reinforcement and long-term durability control.

4.2 | Use of Biochar

Based on the findings, it is proposed to establish a controlled application range between 1% and 5% by weight of cement as a conservative measure to take advantage of its benefits without compromising structural safety, especially in the absence of specific regulations. Although several studies report significant improvements in mechanical properties with proportions of up to 7.5% in controlled experimental conditions, these results are not always extrapolated to real construction contexts, where the variability in the biomass, the lack of standardization in the pyrolysis process, and the sensitivity of the mixture can generate inconsistencies in the performance of the material. Therefore, its use is recommended in nonstructural or semistructural elements, such as blocks, pavers, prefabricated elements, or ecological pavements, where its properties as an internal curing agent and microstructural modifier can be exploited with less risk. Also, it is necessary to implement standardized protocols for its production, specifying optimal pyrolysis temperatures (approximately 500°C), types of biomass admitted, degree of activation, and any previous treatments. This would facilitate the development of a certified biochar industry capable of offering products with predictable properties and safely applicable in concrete. These actions will allow progress toward a responsible technical adoption of biochar as a sustainable additive in the construction sector.

5 | Conclusions

From an environmental perspective, the incorporation of materials, such as agave fibers and biochar into concrete, contributes to reducing the carbon footprint associated with cement production. As cement manufacturing accounts for nearly 7% of global CO_2 emissions, replacing a portion of cement or synthetic additives with agricultural byproducts reduces clinker demand and, consequently, lowers greenhouse gas emissions throughout the material's life cycle. This approach aligns with sustainable construction objectives and supports the transition toward low-carbon concrete technologies.

The use of agave fibers and biochar as partial additives in concrete represents two distinct approaches to achieving sustainability, each addressing different aspects of material performance and environmental impact. Agave fibers improve the mechanical performance of concrete primarily at the macrostructural level, functioning as dispersed reinforcement elements that bridge microcracks and enhance tensile and flexural strength. Their inclusion increases ductility and postcracking behavior, which are key to extending service life and reducing maintenance in structural and nonstructural elements.

Biochar, in contrast, acts at the microstructural level by refining the pore network, increasing the nucleation sites for calcium silicate hydrate (C–S–H), and improving hydration efficiency through its internal water retention capacity. These effects result in higher compressive strength, reduced permeability, and enhanced durability under long-term exposure.

Both materials therefore contribute to sustainability through different mechanisms and scales of action: Agave fibers enhance mechanical resilience, while biochar improves matrix compactness and longevity, each promoting the reuse of agricultural residues and the reduction of cement-related carbon emissions. From an economic perspective, the studies reviewed provide limited quantitative information on the actual cost implications of incorporating agave fibers and biochar. Most of the literature analyzed focuses primarily on environmental benefits and mechanical performance, while cost breakdowns, such as raw material procurement, processing, labor, and equipment, are rarely included. In this regard, the economic value proposition of using agave fibers and biochar depends on factors, such as transport distance, local availability of agricultural waste, the complexity of required treatment, and the volume of material needed to achieve the desired mechanical improvement. Consequently, the viability of these materials varies, favoring especially areas where agave fibers or residues for biochar are abundant.

In general, the studies reviewed focus on long-term environmental benefits and gains rather than overall economic terms. This is an important opportunity for future research to incorporate economic analyses that quantify the real costs of using biodegradable materials in concrete.

From a territorial sustainability perspective, the use of biochar derived from local agricultural waste (such as agave bagasse, coffee husks, or fruit peels) improves territorial viability by reducing transportation costs, strengthening local circular economies, and allowing the additive's properties to be adapted to regional concrete production conditions and practices. This approach minimizes the environmental footprint associated with long-distance material transport and also generates value chains that directly benefit rural communities.

However, the application of biogenic materials, such as biochar in nonstructural concrete elements, faces significant practical challenges, including the logistical difficulty of collecting and processing sufficient volumes of biomass, variability in the composition and pyrolysis conditions of the raw material, and the absence of consistent quality controls, which leads to inconsistent performance in concrete mixes. It should also be remembered that an excess of either additive can be detrimental to the mix.

These problems can be addressed by developing regional biochar production centers capable of processing local biomass and creating standardized protocols that regulate pyrolysis temperature, moisture content, and particle size, ensuring uniformity and reproducibility. It is therefore important to establish clear regulations that define safe application ranges and guide producers in the rational use of these materials.

5.1 | Optimal Conditions Identified

From the literature reviewed, optimal conditions for concrete improvement using these reinforcements were identified:

- Agave Fibers (Preferably Agave Sisalana or Americana): doses between 0.25% and 1.5% by volume, lengths of 25 mm, and heat treated or treated with NaOH/CaO to improve adherence.

- Biochar Derived from Vegetable Residues (Coffee, Peanuts, and Algae): additions between 1% and 5% by weight of the cement, obtained by slow pyrolysis ($\sim$500°C), and preferably presaturated or doped to improve its performance.

- Both materials should be considered complementary admixtures, not substitutes for aggregates or cement. Therefore, the mix design should be adjusted to consider water content, mixing time, and slump control.

5.2 | Future Prospects

It is necessary to promote research that explores the effect of using plant fibers and biochar simultaneously in a single mixture, as well as to analyze new natural fibers with properties similar to those of agave. There is also the possibility of studying biochar derived from more local and diverse waste (such as agave itself or agricultural pruning residues), which could broaden its territorial viability. In addition, it is recommended to evaluate the application of these materials not only in conventional structural elements but also in less mechanically demanding components, such as partition walls, floors, dividing walls, or nonbearing prefabricated systems. Finally, this approach to concrete reinforced with biogenic materials represents a technical means to enhance structural performance. It is a strategic tool to reduce the carbon footprint of the construction sector, promote rural circular economies, and improve the competitiveness of the industry through cheaper, renewable, and responsible solutions.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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