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Review Article

A Systematic Review of Natural and Synthetic Fiber Reinforcement in Concrete: Mechanical Performance, Durability Mechanisms, and Sustainability Pathways

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Abstract *- The increased environmental impact of cement manufacturing has sparked interest in Fiber-Reinforced Concrete (FRC) as a long-term alternative capable of enhancing mechanical performance while lowering material consumption. This paper provides a thorough evaluation of natural and synthetic fibers used in concrete, assessing their mechanical properties, durability, and environmental impact. A comprehensive search was conducted using keywords and Boolean combinations in Scopus, Web of Science, and Google Scholar. From an initial pool of 512 papers, 146 full-text publications were screened, and 58 studies meeting the predefined inclusion criteria were analyzed. Natural fibers, including jute, coir, bamboo, hemp, and palm, show considerable benefits in fracture resistance, toughness, and early-age shrinkage management, all while having a low embodied energy and complete biodegradability. Their disadvantages include hydrophilicity, changeable shape, and low long-term durability, which frequently necessitate chemical treatment or hybridization. Synthetic fibers such as polypropylene, polyethylene, carbon, and glass have excellent tensile strength, heat resistance, and durability, suitable for structural and high-performance applications. The synthesis indicates that hybrid fiber systems provide synergistic benefits by combining the environmental benefits of natural fibers with the mechanical strength of synthetic fibers. A rigorous study identifies research gaps in fiber dispersion, interfacial bonding, long-term durability under environmental cycles, and the lack of consistent testing methodologies. A conceptual framework is proposed to assist optimal fiber selection based on mechanical needs, sustainability goals, and durability concerns. This analysis indicates how engineered hybrid FRC may improve structural performance while reducing environmental impact, hence supporting the transition to more sustainable construction materials.*

Keywords - *Polypropylene Fiber Reinforced Concrete, Mechanical Performance, Crack Resistance, Durability Enhancement, Construction Applications.*

1. Introduction

Concrete remains the dominant construction material globally. However, its production negatively impacts the environment and complicates the path to sustainability. For each kilogram of concrete produced, approximately 0.95 Megajoules (MJ) of energy is consumed, and 0.35 kg of Carbon Dioxide (CO_2) is emitted from the manufacturing process [1]. Cement is the primary cementing agent for concrete, producing nearly 7% of global CO_2 emissions from energy-intensive calcium carbonate calcination and the fossil fuels consumed during its manufacturing process [2-4]. Due to these factors, alternate reinforcement strategies and sustainable materials need to be developed to enhance mechanical properties and lower cement usage, thereby reducing embodied carbon.

For the last 5 decades, researchers have studied fiber reinforcement to improve tensile capacity, crack control, and durability. Although conventional concrete exhibits high compressive strength, its low tensile capacity makes it prone to brittle cracking under dynamic, seismic, and flexural loading. [8, 11]. Steel, natural fibers, and synthetic polymer fibers can assist in distributing tension stresses throughout the concrete, mitigating cracking associated with shrinkage (due to changes in moisture content), and providing enhanced ductility, toughness, and long-term durability of the concrete. [11, 12]

Natural fibers such as jute, coir, hemp, bamboo, palm, and sisal offer advantages over synthetic fibers due to their biodegradability, low embodied energy, and wide availability at low cost. [12, 15]. Additionally, they enhance toughness and early-age performance by bridging cracks and slowing crack propagation. A key limitation of natural fiber reinforcement is its hydrophilic nature, irregular geometry, and susceptibility to microbial degradation, which challenge long-term concrete durability and necessitate chemical treatment, coatings, or hybrid reinforcement [16-18].

Synthetic fibers such as polypropylene, polyethylene, carbon, and glass exhibit higher tensile strength, uniform geometry, superior chemical resistance, and enhanced long-term durability compared to natural fibers. Synthetic fibers will also improve post-cracking performance, impact resistance, and thermal stability, particularly in the case of high-performance or industrial concrete applications [38, 47].

However, there are some disadvantages associated with using synthetic fiber in concrete, including higher costs than natural fiber, the non-biodegradability of synthetic fiber, and environmental issues related to the manufacture and disposal of synthetic fiber.

Research into Fiber-Reinforced Concrete (FRC) is continuing to progress; however, the literature currently available remains scattered with varying results based on fiber type, treatment methods, dosage, mixture design, and exposure conditions, as previously mentioned. Numerous published reviews assess specific categories of fiber; however, there does not appear to be a published review that provides a fully comprehensive systematic assessment of both natural and synthetic fibers. In addition, research into the use of hybrid reinforcement systems has mostly been overlooked, although they may provide a positive synergistic effect when natural and synthetic fibers are used together, since natural fibers can provide a more sustainable alternative while synthetic fibers offer greater mechanical strength. In Figure 1, the typical fiber matrix interaction mechanisms in concrete reinforced with fiber are shown, including fiber pullout, fiber rupture, fiber debonding, and fiber bridging.

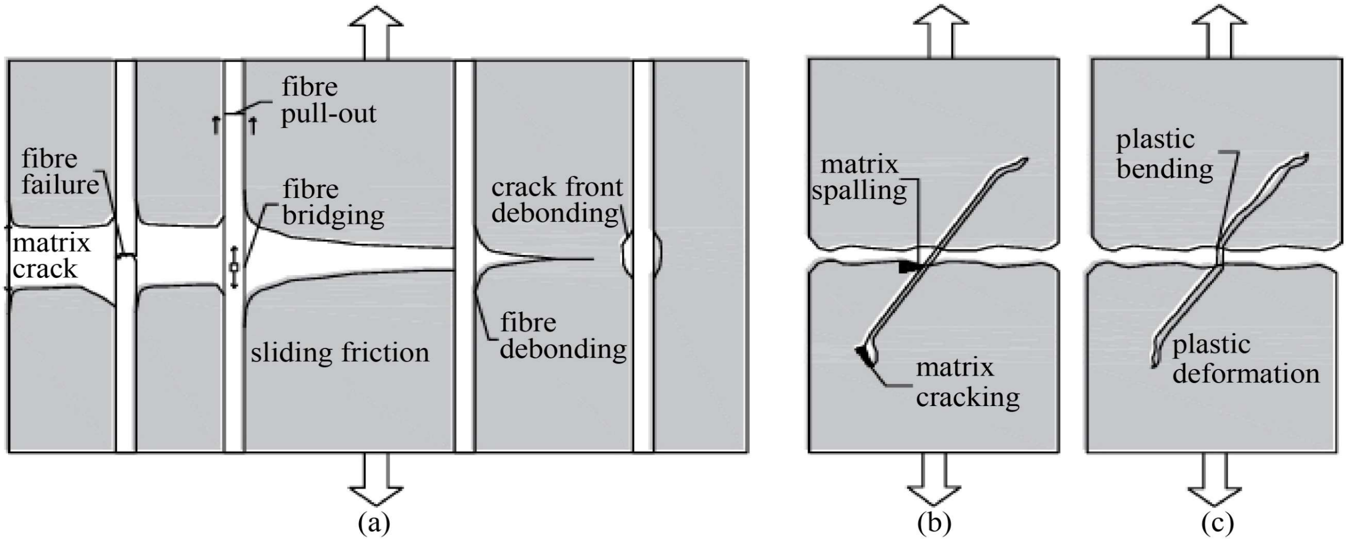

Fig. 1 Failure pattern in FRC

Source: https://www.mdpi.com/1996-1944/14/20/6090

This research project fills gaps in the literature through a systematic review of studies looking at how both natural (e.g., kenaf) and synthetic (e.g, polypropylene) fibers perform in concrete structurally (mechanical strength) and durably (how established durability mechanisms/processes are used in concrete with both types of fibers). By employing a systematic approach (structured database search, defined inclusion/exclusion criteria, and PRISMA-based screening), this review aims to provide a comprehensive synthesis of available evidence, identify gaps in the literature, and develop a conceptual framework to help guide future research toward creating optimized and sustainable fiber-reinforced concrete systems.

2. Research Methodology

The study followed the PRISMA guidelines to perform a systematic review of research publications from the years 2000 through 2024, conducted using Scopus, Web of Science, and Google Scholar, using predetermined keywords to search each database combined with Boolean operators. A total of 512 results were identified across these three databases, before removal of duplicates, and consideration for ineligible studies left 58 total studies that met the eligibility criteria after conducting study eligibility and assessment.

2.1. Search Strings and Boolean Combinations

The following keyword combinations were used:

- “Natural fibers” AND “Concrete Reinforcement.”
- “Synthetic fibers” AND “Fiber Reinforced Concrete.”
- “Hybrid fibers” AND “Mechanical Properties of Concrete.”
- “Bamboo/coir/jute/hemp” AND “Concrete Performance.”
- “Polypropylene/Polyethylene/Carbon/Glass Fibers” AND “Durability.”
- “Sustainable Concrete” AND “Fiber Reinforcement.”

- “Environmental Impact” AND “Fiber-Reinforced Composites.”

A total of 512 records were retrieved in the initial search for the study.

2.2. Criteria for Inclusion and Exclusion

In order to be eligible for selection, studies needed to meet the following criteria:

1. Experimental submissions on concrete reinforced with fibers must have been documented.
2. The effects of fiber reinforcement on concrete's mechanical properties, durability, or sustainability must have been assessed, using acceptable types of fiber, and must have had measurable results
3. Studies should have been presented at peer-reviewed journals or conferences during the period from 2000 through 2024.

2.3. Criteria for Exclusion

Studies were excluded if they:

1. Reported numerical or theoretical modeling with no experimental data in the study.
2. Focused solely on mortar without consideration of concrete composites.
3. Lacked clarity in methodology or did not have full or incomplete test data.
4. Duplicate records originated from multiple databases.
5. Publications that were not published in English.

2.4. Study Screening Process

The three stages of screening helped to select the articles for the study. Of the 512 records initially identified, 128 duplicates and other records were removed. Of the remaining 384 titles/abstracts screened, 238 did not meet the inclusion criteria. The remaining 146 articles underwent full-text review, and 58 of those 146 did not meet the required level of methodological quality, reported no results, or had a modeling study design. Thus, there were 54 studies that fulfilled all requirements and were included in the final synthesis.

2.5. Quality Assessment of Included Studies

Each study was evaluated using a five-point quality checklist:

Table 1. Five-point quality checklist

Sr No.	Criterion	Assessment Focus
1	Experimental Design	Clarity of mix design, fiber properties, and testing protocol
2	Sample Size & Replication	An adequate number of specimens for statistical reliability
3	Data Transparency	Availability of raw and comparative results
4	Methodological Rigor	Use of standardized testing procedures (ASTM/IS/EN)
5	Relevance to Review Objectives	Alignment with mechanical, durability, or sustainability outcomes

Table 1 consists of the five important points in the form of a checklist, which can be used to evaluate the methodological strength of the selected studies. The criteria ensure reliability, transparency, and relevance of experimental evidence included in the review. Only studies achieving a quality assessment score of four or higher out of five were considered eligible and included in the final analysis, ensuring methodological rigor and reliability of the synthesized findings.

The study selection procedure is summed up in the PRISMA flow diagram (Figure 2). Database searches yielded 512 entries in total. Following the removal of duplicates and other reasons, 146 full-text papers were evaluated for eligibility after 384 research papers were screened using titles and abstracts. Following the exclusion of 54 studies due to insufficient data or methodological limitations, 58 studies were included in the final systematic review.

3. Fiber Classification and Characteristics

In an overall sense, the fibers can be differentiated into natural and synthetic categories. Generally, the outer layer of natural materials like straws and carp is taken as natural fibers that are encountered in the natural ecosystem. In contrast, fibers produced using chemical processes and synthetic materials are classified as synthetic fibers.

3.1. Natural Fibers

Natural fibers are not only abundant but also widely available across the globe due to their growth in all types of conditions. Common examples include coir, palm, jute, flax, straw, sisal, bamboo, and cane. Natural fibers are further classified into categories such as wood fibers, basalt fibers, palm-based fibers, leaf fibers, and cereal straw. The characteristics of natural fibers have been influenced by various environmental factors like harvesting, soil quality, temperature, and other geographical conditions. The combination of multiple variables affects the performance and potential applications of Fibers/Composite Materials. Although Fibers are made of organic materials, in comparison to other Natural Fiber types, Natural Fibers have poor durability (usually diminishing over time). Another disadvantage is the absorbing/attracting nature; therefore, this characteristic has a negative impact on the overall performance of Natural Fiber in Composite Materials. Researchers are currently trying to find ways to enhance the durability of Fibers through different techniques, including chemical treatments / coatings and modifying / blocking / substituting the hydroxyl groups of Natural Fibers. More research is still needed to determine whether the techniques currently being investigated to extend the durability of Fibers will produce permanent (sustainable) or temporary (transient) results. Moreover, the methods of extending the durability of Fibers can be expensive and may present a risk, since the consequences associated with leaching due to biological, chemical, thermal, or UV-related degradation have not yet been thoroughly investigated [16].

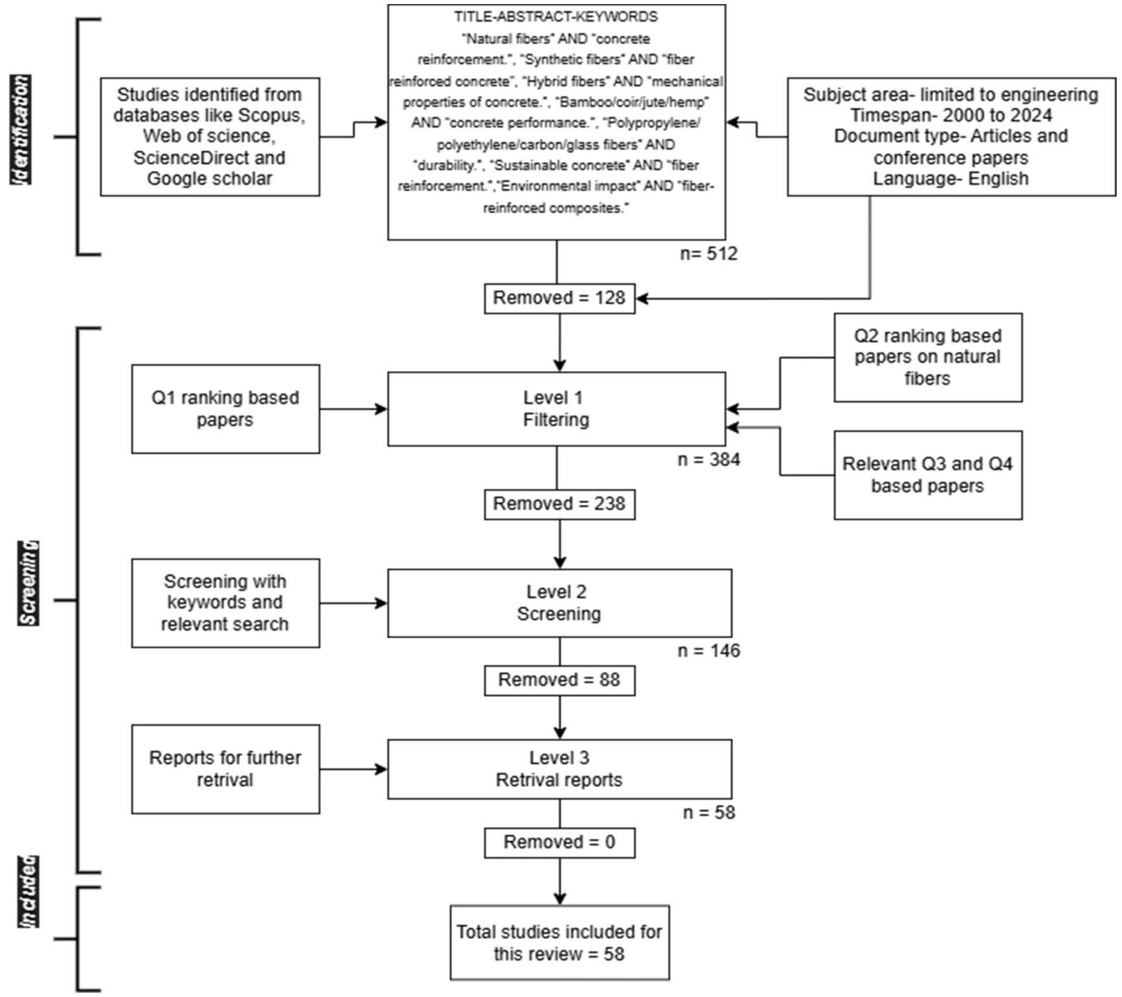

Fig. 2 PRISMA flow diagram adopted in the study

Thus, the use of natural fiber and recycled industrial waste will be key strategies for fostering sustainable building practices. Natural materials may provide good solutions for thermal use, such as in passive houses and energy-efficient greenhouses. The fundamental thermal insulation qualities of these natural materials result in improved control of temperature and humidity, leading to reduced need for additional climate regulation and improved overall energy efficiency [17].

The following is a discussion of various natural fibers and their properties.

3.1.1. Palm Fibers

Palm fibers such as those from date palms (Phoenix Dactylifera) and Coconut Palms (Cocos Nucifera) are cost-effective, abundant in different regions worldwide, and have many advantages. They are known for their lightweight, high strength, and excellent water absorption; additionally, they are somewhat resistant to the effects of the environment and can be used in numerous applications, making them sustainable materials. While palm fibers provide these benefits, they typically exhibit low modulus of elasticity and low tensile strength, which may limit their ability to provide good structural performance in load-bearing applications [18]. However, they are useful for insulation, building, and the creation of composite materials due to their abundance and environmentally favorable qualities.

The Aceraceae family of palms includes the coconut tree (Cocos Nucifera). Coir is a lightweight fiber derived from the fibrous coconut husk using mechanical or water-based extraction methods [19]. Compared to smoother, weaker white fibers, mature fibers are brown, stronger, and more abrasion-resistant. The elevated lignin with a high air porosity (95%) and a low cellulose content is extremely resilient, strong, stiff, and long-lasting [20].

Coconut (Coir) fibers are derived from the mesocarp of the coconut and are categorized into short and long types when the effective length is less than 130 mm [21]. These fibers are agricultural waste products that are continuously generated globally. Coconut trash is often burned or disposed of, but it can also be used effectively. Coir fibers are strong, resilient, durable, cost-effective, resistant to rot and fungi, fire-resistant, and exhibit high elongation [22]. Numerous studies have investigated the mechanical and physical properties of coconut fiber–reinforced soil, highlighting its potential for construction applications. By reducing visible fissures and boosting ductility, adding 4% coir fibers to soil blocks greatly improves their performance [23]. Coir fibers are long-term durable for up to four to ten years, and hence, this fiber makes an excellent alternative for temporary reinforcement in construction. Moreover, research has demonstrated that incorporating coir fiber enhances the engineering properties of various composite materials. Specifically, coir fiber addition enhances tensile and compressive strength, durability, and resistance to water absorption. [24]. Coconut fibers become stiffer and more rigid after boiling and then washing, and their fiber-matrix bond strength increases. Fiber tensile strength increased by 34% and 55% for pre-boiled and washed fibers, respectively [25]. Studies have found that fiber-reinforced concrete had a 42 MPa as average compressive strength and has shown a fractured energy of 17.2 N/m [26]. Concrete's workability might drastically decrease if coconut fibers are added. Although slump decreased by 100%, workability increased by 41% with the addition of 2% w/w coconut fibers and 1% w/w superplasticizer. Another study reported improved concrete strength with a mix containing 15% w/w silica fume, 2% w/w coconut fiber, and 1% cement superplasticizer [4]. Date palm fibers serve as an effective reinforcement material for composite construction uses due to their lightweight nature, natural hydrophilicity, and strong mechanical properties. These fibers are readily available and simple to obtain in areas where date palms are grown because of their noteworthy properties, which include durability, tensile strength, and affordability. Hence, the fibers of date and palm have good durability, resulting in an enhanced engineering industrial application. Improving the compressive strength and overall structural stability of composite materials is one of their primary advantages. This improvement is made possible by the fibers' interlocking mechanism, which holds aggregates and individual particles together and improves stability and load distribution.

3.1.2. Bast Fibers

Fibers that fall within this category and definition include flax, jute, hemp, sisal, and kenaf [27]. Various plant exteriors are used to remove these fibers. These bast fibers' high tensile strength is a frequent mechanical characteristic; additionally, they have the capacity to act as an effective thermal insulator. Since the fibers are found in the phloem, a mechanical and/or retting procedure is required to separate them from the woody core. They have good thermal insulating qualities and a high tensile strength [28]. Figure 3 shows the types of bast fibers. Flax fibers have been used as reinforcement in building materials to enhance stability and ductility in composite construction. In tropical and subtropical regions like Malaysia, kenaf, a cellulose fiber, is widely accessible [18]. Few studies have also shown the creation of natural fiber-based insulating materials, especially for use on plant façades [18].

Fig. 3 Types of bast fibers

Source: https://textileengineering.net/vegetable-fibres-properties-types-and-application/

Thermal binding was used to create the samples, and hemp, flax, and jute fibers were combined with a waste product known as Shive. All the components were bound together using polyester fiber. According to the results, the samples that contained 48% and 49% technical hemp fibers performed the best [17]. The new material's thermal insulation qualities were on par with those of other natural fiber insulation products on the market.

The raw jute fiber concrete exhibited a 7.14% reduction in bulk density compared to the control. Water absorption and apparent porosity increased by 57.7% and 47.39%, respectively. Further mechanical properties, like compressive strength, improved by 6%, and the concrete sample showed an increase of 10.64% in flexural strength. The ultimate load-bearing capacity of fiber-reinforced concrete pipes was 34.85% higher than that of the control.

Additionally, incorporating 5% w/w jute fibers in the tension zone with steel reinforcement enabled a 28% reduction in slab reinforcement. Few studies have also shown that there is an increase in dynamic elastic modulus by 68%, and an increase of 95% is seen in the Damping ratio post usage of Jute fibers [29]. The addition of 1%–2% fibers increased drying shrinkage while reducing water absorptivity and chloride penetration [30].

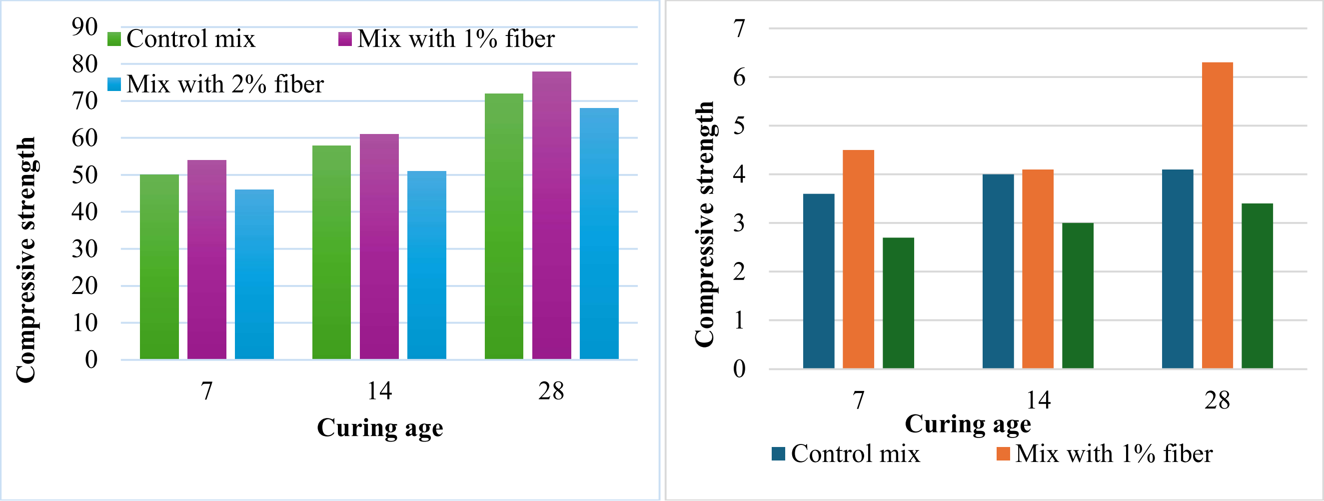

Fig. 4 Compressive and Split tensile strength graphs after adding jute fibers to concrete [30]

Source: https://www.sciencedirect.com/science/article/pii/S2214785320379505?via%3Dihub)

Figure 4 shows the variation in compressive and split tensile strength with jute fiber addition, while dynamic stiffness results indicate potential for floorboard applications. When materials are designed, the insulation materials have the potential to serve as effective cladding material for buildings. Proper construction ensures its durability, thermal efficiency, and overall performance in enhancing the building's energy efficiency and protection.

3.1.3. Bamboo Fibers

As an environmentally friendly building material, bamboo is considered a natural, renewable resource that has tremendous sustainability potential. As a biodegradable material, its decomposition at the end of its service life has minimal environmental impact [32]. Bamboo helps reduce dependence on non-renewable resources, improves energy efficiency, and supports sustainable construction practices. Its use aligns with the principles of sustainable development.

Life Cycle Assessments indicate that bamboo has the lowest carbon footprint of any renewable building resource; therefore, bamboo is among the best solutions for sustainable development [33].

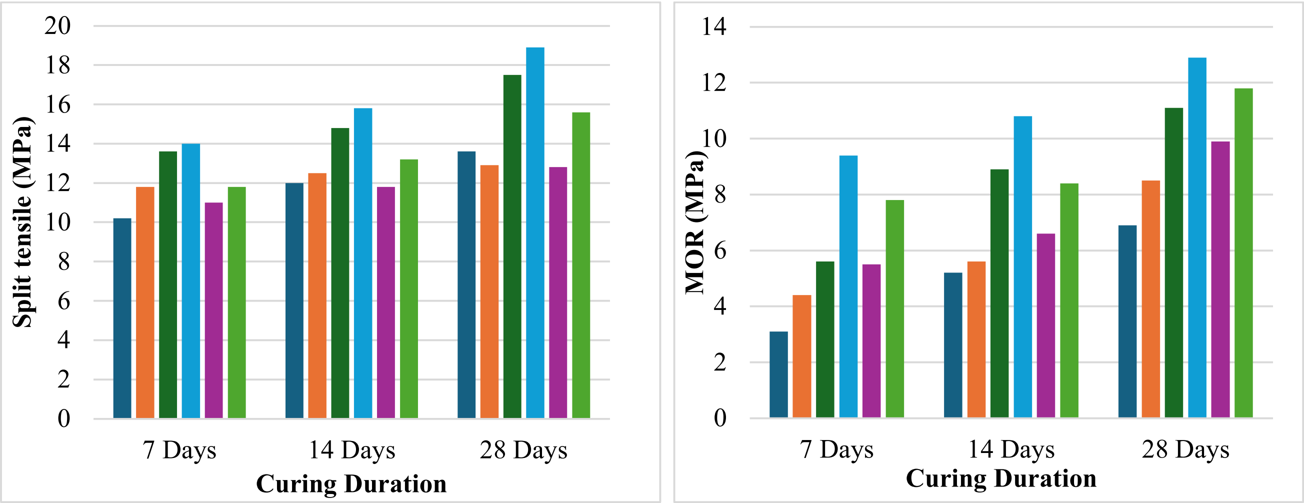

Fig. 5 Bamboo fiber reinforced concrete's compressive and flexural strengths across various time periods

Source:https://doi.org/10.1016/j.conbuildmat.2020.118405

When bamboo is combined with any concrete members, they provide 22% more strength in compression and 17% more strength in tension [34]. This is accomplished by using the bamboo fibers as reinforcing agents that help distribute evenly throughout the matrix, thereby improving durability and increasing fracture resistance. Strengthening a composite will help it last longer, perform better, and maintain its structural integrity. Furthermore, not only can bamboo be a viable option as a replacement for traditional steel-reinforced concrete, but it also has many other benefits that would support these claims. When tested, bamboo reinforced concrete slabs displayed 82% greater strength and 93% greater ductility than conventional steel reinforced concrete slabs. Adding 1%-1.5% bamboo fiber to concrete added 24.32% to its tensile strength, 54.5%-97% to its modulus of rigidity, and 16.00%-59.1% to its modulus of elasticity.

Alkali treatment enhances the thermal stability and surface area of bamboo fibers. The incorporation of 0.5% bamboo fiber in cement-based composites significantly improves the modulus of elasticity and toughness. Furthermore, as shown in Figure 5, bamboo fiber–reinforced concrete exhibits increased compressive and flexural strength at different curing ages. These results indicate that bamboo fiber has the potential to be an economically and environmentally sustainable alternative to traditional steel reinforcement in "green" construction methods, and should be studied further to fully understand and improve the mechanical properties of bamboo fibers. Infusing natural fibers, such as bamboo, into brittle thermosetting plastics such as polyester and epoxy has been shown to improve toughness [37]. Combining bamboo with other synthetic polymers can produce new materials, such as polyester-reinforced bamboo fiber composites.

3.1.4. Wheat Straws

The study focuses on the early phases of wheat straw-reinforced concrete. It was discovered that WSRC substantially decreased the frequency and severity of shrinkage cracks, which contribute to increased pavement durability and performance. The inclusion of WS enhanced the flexural, tensile, and compressive strengths of the mix while reducing its slump [37]. A study showed a significant increase by 108% in flexure toughness when wheat straw was used in a concrete mix, when compared to plain concrete under climatic conditions. The wheat straw's sewing action in the concrete will help to resist cracks and eventually boost its absorption capacity.

Table 2. Characteristics of natural fibers [10, 38]

Fibers	Fiber length(mm)	Tensile strength (MPa)	Density(g/cm3)
Sugar can	0.7-2.8	20-290	1.2-1.5
Coconut coir	0.3-1.0	100-600	1.1-1.6
Sisal	0.8-8.0	80-840	1.3-1.5
Jute	0.8-6.0	385-850	1.3-1.5
Palm			0.7-1.55
Bamboo	2.0-3.0	140-230	0.6-11
Areaca	10--60		1.5

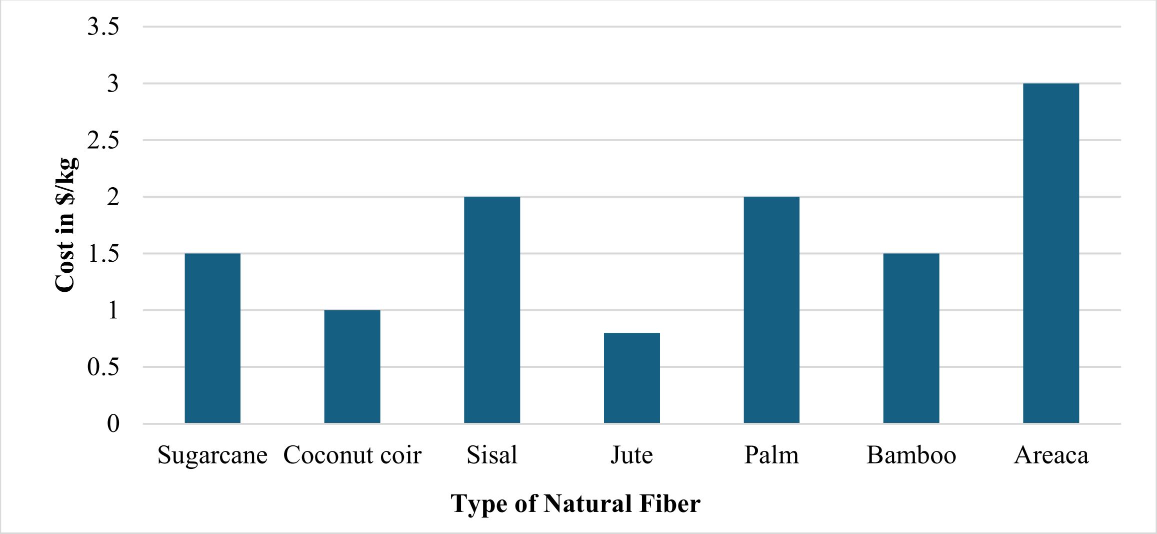

Fig. 6 Cost comparison of various natural fibers

3.1.5. Cost of Natural Fibers

Many variables play a role in determining how much you will pay for natural fibers. These factors include how easily available they are, how well they are made mechanically, how they will be processed, and how much demand there is for them by the industry. Areca fiber is the most expensive of all the natural fibers ($3.00/kilogram), but it has excellent mechanical properties and works best with high-performance composites as compared to other types of natural fibers because it takes a long time and labor to extract from its source and has limited availability. Although the processing costs associated with producing sisal and palm fibers ($2.00/kilogram) are also relatively high, they tend to add to the overall cost of production. Therefore, they are ideal materials for making ropes and textiles, as well as reinforced composites, because they have good tensile properties and durability. Bamboo ($1.50/kilogram) and sugar cane ($1.50/kilogram) fibers are less expensive due to their abundance and being renewable, but their durability is not as good as that of Sisal. In addition, coir (the fibrous husk of coconuts), which is generated as a byproduct of the coconut, costs about $1.00/kilogram, making it affordable; however, coir has low tensile strength (as well as type) and high-density value, which limits its capability and usefulness in certain end-use applications. One example is jute fiber, which is grown extensively throughout the world and has the lowest processing costs of all natural fibers ($0.75/kilogram); therefore, jute fibers are considered to be very cost-effective. Figure 6 presents a comparative cost analysis of various natural fibers used in concrete.

Table 3. Summary of key natural fibers used in concrete and their characteristics

Natural Fiber	Key Properties	Benefits of Concrete	Limitations	Typical Dosage (%)
Coir	High lignin content, good ductility	Crack bridging, toughness improvement, and impact resistance	Absorbs water, reduces workability if untreated	0.5–2.0
Jute	Moderate tensile strength, biodegradable	Improves tensile and flexural strength, early-age crack resistance	Increases porosity; degrades in an alkaline environment	0.5–1.5
Bamboo	High tensile strength, renewable	Enhances tensile capacity, ductility, and impact resistance	Requires treatment to prevent degradation	0.5–2.0
Hemp/Flax	Good insulation, low density	Reduces shrinkage cracking, improves thermal behavior	Highly hydrophilic; variable quality	0.25–1.0
Agricultural waste (straw, bagasse)	Low-cost, lightweight	Improves toughness and energy absorption	Weak durability unless treated	0.25–1.5

Table 3 summarizes the key natural fibers used in concrete and their characteristics. Fibers such as coir, jute, bamboo, hemp, flax, and agricultural residues enhance crack control, toughness, and ductility even at low dosages. They also provide significant sustainability benefits, albeit issues like water absorption, material variability, and limited durability frequently necessitate correct treatment. Typical doses vary from 0.25% to 2%.

3.2. Synthetic Fibers

Examples of synthetic fibers being utilized in multiple-strand matrix systems can be found with the addition of reinforcing volleyballs made from synthetic fibers to reinforce concrete via different types of fibers, including metal, Polymer, and other synthetic/natural materials. Although nylon is now the most common polymer fiber type, polypropylene fiber is still used in great numbers in concrete. By using polypropylene fibers, the potential for fracture development as well as slippage is reduced. The use of these fibers enhances mechanical properties (compressive, flexural, and tensile strength) and provides fewer instances of plastic shrinkage cracking and lower potential to resist impact forces. These benefits ultimately create an increase in the durability of concrete and the overall structural integrity. However, after cracks appeared after the loads were maintained, nylon fibers improved performance. Table 4 distinguishes between micro and macro-synthetic fibers based on their key characteristics, functional roles, and performance in concrete applications.

Table 4. Distinguishing between micro and macro synthetic fibers [39]

Geometry Micro Synthetic Fiber	Synthetic Fiber	Macro Synthetic Fiber
Diameter /cross-section	5–100 m	0.6–1 mm2
Length	5–30 m	30-60 mm

3.2.1. Polyethylene

Since the adoption of Polyethylene (PE), it has been recognized as a significant material and has been widely incorporated into composite mixes and formulations [40]. It belongs to the significant family of polyolefin resins and is created by the polymerization of ethylene. PE is an inexpensive thermoplastic polymer with exceptional characteristics like good toughness, impact resistance, abrasion resistance, and low water absorption. PE is the second most widely used Polymer when compared to other commercial polymeric compounds [41]. Figure 7 illustrates the basic molecular structure of PE.

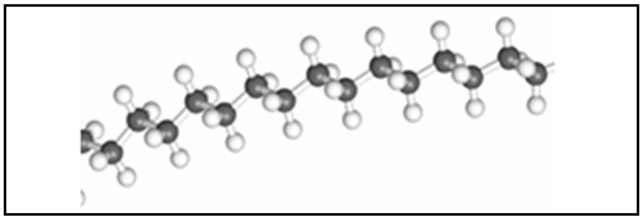

Fig. 7 Molecular structure of polyethylene

Because it is flexible, durable, and resistant to chemicals, it is being used extensively in civil engineering applications. The development of dual-layered PE coatings and textile-reinforced concrete has led to wider utilization in tunnel construction, pressure and non-pressure piping systems, and steel pipe corrosion prevention. These developments increase resistance to severe weather conditions, decrease maintenance requirements, and extend the lifespan of the matrix structures [42]. Furthermore, improvements in 3D printing of building materials have been made possible by the addition of PE fibers to cementitious composites. This advancement makes it a viable material for contemporary construction methods since it enables the creation of printed structures that are lightweight, strong, and long-lasting with improved flexibility and resistance to cracking. PE fibers have numerous great qualities, including tensile strength, chemical resistance, and ease of manufacture. The physical characteristics are based on the degree of branching and the molecular weight. These PE fibers show low- and high-density fibers of polyethylene. Li and his associates were the first to produce Engineered Cementitious Composites (ECC). 1% to 1.5% of bamboo fibers when adopted in concrete resulted in an increase in tensile strength by 24.32%, a rise in modulus of rigidity by 54.5% to 97%, and a boost in modulus of elasticity by 16% to 59.1%. Further addition of 0.5% bamboo fibers enhanced the toughness of the cement composite but resulted in a reduction in elastic modulus. The ability of ECC to survive many microcracks under tensile stress while retaining load-bearing capability is a result of its strain-hardening tendency. This special quality contributes towards material durability and structural performance, along with an increase in resistance to cracking. ECC is the best option for applications needing improved mechanical qualities and resistance to brittle failure because it integrates PE fibers, which give it greater flexibility and toughness than traditional concrete [44]. PE fibers reduced the slump of cementitious materials, according to earlier studies. Uneven fiber distribution resulted from the slump being lessened by PE fibers. The cementitious composites struggled with workability and uniformity [45].

3.2.2. Carbon Fibers

To create composites with better qualities, carbon fibers have been incorporated into other materials. When carbon fibers are added, a composite is produced with exceptional mechanical qualities, good performance in hot conditions, and the added advantage of durability [46]. Even though carbon fibers are quite brittle, carbon fiber-reinforced composites have great qualities when carefully considered throughout the design phase. Carbon fibers' drawbacks include the high cost of production resulting from their superior qualities and the potential difficulty of achieving a link between the fibers and the material matrix [47]. Like Glass Fibers, Carbon Fibers have many advantages, but their production raises environmental problems and raises doubts about their sustainability. The issue of carbon fiber composites disposal at the end of their useful lives is also widely recognized. Recycling may be an option for most of the carbon fiber composites, although most goods are either burned or buried [48].

When it comes to fatigue strength and elastic modulus, carbon fiber outperforms glass fiber. Research highlights that CFRPs outperform both glass and aramid fibers in long-term durability and mechanical reliability. These fibers are ideal for structural applications that require good strength and stability. An Experimental study has shown that adding 1% of the dosage of Carbon fiber has increased the concrete strength by 15% when compared to plain cement concrete [49]. A few studies have also reported that when 0.25% and 1% dosages of milled recycled CFs were added to cement paste, the fracture toughness increased by 168% and 325%, respectively. Also, when 1% dosage of RCF was added, the fracture energy increased 14 times.

The physical properties of carbon fiber are primarily determined by two main key factors, i.e., the degree of carbonization and the structural composition. Carbonization degree typically exceeding 92% carbon by weight strongly influences the fiber's mechanical strength, rigidity, and also the resistance to heat. Additionally, the specific manufacturing processes and any modifications introduced during production further influence the overall performance characteristics of the carbon fiber, making it suitable for various high-performance applications.

3.2.3. Glass Fibers

Glass fibers are available in a variety of characteristic properties and have excellent mechanical properties that play a crucial role in their performance. This glass has properties that adhere to composites and play a crucial role in their performance. Continuous basalt fibers are produced by processes like those used to create glass fibers in the spinneret process. In most processes, thermal converters between the fibers are equipped with overhead gas burners that provide energy to melt raw materials and assist in producing the glass strands. Glass melting will occur between 1400 and 1600 degrees Celsius, which will ensure maximum quality for fiber production and the strength of the resulting strands. Compared to basalt, glass fibers outperform basalt in acidic environments but are less resistant to alkali [50]. An experimental study on strength parameter by using glass fiber reinforced concrete has shown that there is an 20% increase in compressive strength for M20 Grade concrete, and an increase of 25%-30% when compared to plain concrete. Glass fiber composites, when properly thought out and developed, have outstanding qualities. Utilizing glass fibers has several advantages, but there are drawbacks as well because their production raises environmental issues and raises doubts about their sustainability. Boric acid, or Boron Trioxide B_2O_3, is needed for manufacturing at proportions that would not be sustainable due to the compound's limited supply. It is also common knowledge that glass products and glass fiber composites present a disposal challenge at the end of their useful lives [51]. Figure 8 shows glass fibers used as reinforcement in concrete.

Fig. 8 Glass fibers

Source: https://www.indiamart.com/proddetail/concrete-fiber-strand-21532216873.html

3.2.4. Various Characteristics of Synthetic Fibers

Table 5 summarizes the key characteristics of commonly used synthetic fibers in concrete, including fiber length, tensile strength, and density. The data provide a basis for comparing performance potential and selecting appropriate fibers for specific applications.

Table 5. Characteristics of synthetic fibers

Fibers	Fiber length(mm)	Tensile strength (MPa)	Density(g/cm3)
Polypropene	5-100	2500-6000	1.6-2.0
Carbon Fibers	3-50	150-600	0.9-0.95
Glass Fibers	3-50	2000-4500	2.4-2.6

3.2.5. Cost of Synthetic Fiber

The price of synthetic fibers is influenced by the cost of the raw materials, the complexity of the manufacturing process, and how well they perform. For example, carbon fiber is the most expensive choice ($40.00 per kilogram) due to its high strength-to-weight ratio, as well as its ability to withstand harsh manufacturing processes. Because of its strength and durability, carbon fiber is a good choice for both aerospace and commercial applications. In comparison, glass fiber is much cheaper ($6.00 per kg), has decent strength and corrosion resistance due to the availability of silica (the main component), and a relatively straightforward manufacturing process, which makes it an excellent alternative material for building construction and composite materials. At the other end of the spectrum, polypropylene fiber ($2.00 per kilogram) is the least expensive material on the list because of its low-cost polymer base (less expensive than both carbon and glass) and energy-efficient production, as well as being widely used in textiles, packaging, and reinforcing concrete. Figure 9 represents a cost comparison of synthetic fibers.

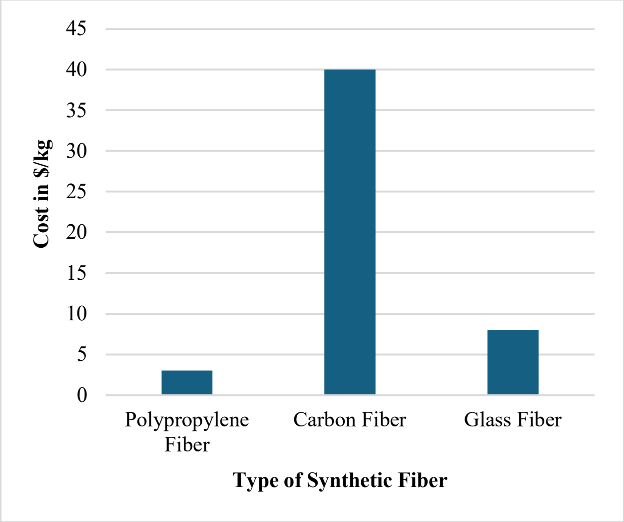

Fig. 9 Cost comparison of synthetic fibers

Table 6 summarizes the main synthetic fibers used in concrete and their performance characteristics. Polypropylene, Polyethylene, Carbon, and Glass Fibers improve toughness, tensile behavior, shrinkage control, and overall durability at relatively low dosages. Their limitations include reduced workability, dispersion challenges, cost, and sensitivity to alkaline environments, depending on the fiber type. Typical usage ranges from 0.1 to 1 percent.

Table 6. Summary of synthetic fibers and their performance characteristics

Synthetic Fiber	Key Properties	Benefits of Concrete	Limitations	Typical Dosage (%)
Polypropylene (PP)	Chemically inert, lightweight	Excellent plastic shrinkage control; improves toughness	Low stiffness; marginal compressive strength improvement	0.1–1.0
Polyethylene (PE)	High ductility, strong bonding	Strain-hardening behavior; microcrack control	Reduces workability at high contents	0.1–1.0
Carbon Fiber	Very high tensile strength	Enhances tensile capacity, fatigue resistance	Expensive; difficult to disperse	0.25–1.0
Glass Fiber	High stiffness, good tensile strength	Increases flexural and tensile capacity	Prone to alkali attack without treatment	0.25–1.0

3.3. Waste Materials as Fiber

A well-known problem that is getting worse as the population grows is the increase in waste materials, while landfill space is limited. The amount of waste that gets dumped in landfills can be significantly decreased by using waste materials and fibers, and the energy required for them. It is also possible to save the landfill's combustion process. The varieties and potential of waste materials and fibers are covered in this section. Because they are recycled, waste materials are categorized as secondary materials; nonetheless, for some applications, they may be able to replace primary virgin fibers. This can reduce the amount of raw energy, resources, and extraction procedures needed to obtain primary materials and fibers [52].

Various studies have covered a wide range of waste products, including tires, carpets, natural hair, glass, steel slag, coconut fiber, plastic, and cigarette butts. It was found through several studies that using waste resources to make construction materials had advantages as a cost-effective and sustainable alternative for applications.

Waste Tire and carpet components improved the toughness and tensile strength of SMA mixtures, prevented downspouts, and gave the mixture stability. It exhibits sustainable value and offers a cost-effective substitute [53]. Prior research has confirmed that recycling crumb rubber into concrete slabs increased the slab's fire resistance and decreased the spalling deficiencies caused by fire [45]. To enhance clay soils' engineering qualities and provide notable advantages for soil stability, waste carpet fibers have been used. These fibers help to improve deviator stress capacity, effective cohesiveness, and shear strength. Their addition also increases the soil's Unconfined Compressive Strength (UCS) and effective stress ratio, which increases its resistance to deformation. Discarded carpet fibers can be used in soil to improve the stability of the soil and its possible uses for supporting construction/development. There are many risks to the environment when using waste products in construction, due to potential chemical leaks and runoff associated with the use of certain materials (e.g., asphalt pavements); many of these would also negatively affect soils and water quality. For example, industrial waste such as steel slag may contain heavy metals (e.g., chromium) and will conduct electricity very well; this presents a large potential risk to both the safety of the environment and the integrity of the structure. The cost associated with using waste products is another major hurdle. The cost of processing, treating, and recycling waste products generally exceeds the cost of using new (or virgin) products due to the fact that they require special methods of processing and use many more resources. This increased expense, along with possible legal limitations and the requirement for quality assurance, restricts appeal and broad acceptance [45].

4. Comparative Analysis of Natural and Synthetic Fibers

According to Table 7, natural fibers, while less durable than synthetic fibers, have the benefits of efficiency, sustainability, and superior insulation properties. Similarly, while synthetic fibers have a higher cost and do not break down in the environment, they provide good strength, durability, and heat resistance when using these types of products in concrete structures. Industrial reinforcement applications typically use synthetic fibers, while natural fibers lend themselves to green building construction applications.

Table 7. Comparative analysis of natural and synthetic fibers

Criteria	Natural Fibers	Synthetic Fiber
Source	Extracted from plants, trees, and straw	Manufactured using polymers, steel, or glass
Sustainability	Renewable, biodegradable, and environmentally friendly	Non-biodegradable, difficult to recycle.
Mechanical Properties	Lower durability, high tensile strength, but prone to degradation	High strength, stiffness, and durability
Thermal Properties	Good insulation, but variable thermal stability	High thermal resistance and insulation
Economic Viability	Low-cost, energy-efficient production	Higher cost due to manufacturing processes
Processing & Workability	Requires minimal processing but varies in quality based on environmental conditions	Consistent quality but requires specialized manufacturing and handling.
Applications	Used in eco-friendly construction, insulation, reinforcement, and composites	Widely used in concrete reinforcement, high-performance composites, and industrial applications.

5. Mechanical and Durability Performance of Fiber-Reinforced Concrete

The use of fibers to reinforce concrete can improve the mechanical performance of concrete. The degree of this improvement can differ depending on which type of fiber is being used and how they are combined. Natural fibers, including jute, coir, and bamboo, give approximately 10 to 25 percent greater tensile strength than concrete, and at optimum dosages, provide good results for flexural toughness. The success of results may vary based on how well the fibers have been treated and disbursed into the concrete mix. The use of synthetic fibers generally provides a more predictable improvement in mechanical properties with increases of 15 to 30 percent in the tensile strength of concrete, as well as significantly better post-cracking behavior; this is especially true for polyethylene synthetic fibers, whose mechanical properties exhibit an increase in strength after the fiber reaches its elastic limit (strain hardening). Hybrid fiber systems provide the highest overall benefits, delivering synergistic improvements in tensile and flexural performance, enhanced toughness, multiple cracking, and improved ductility through complementary crack-bridging mechanisms.

Durability performance also varies with fiber category. Natural fibers significantly decrease shrinkage cracking at an early age, but they absorb more water and deteriorate in alkaline conditions unless treated. Synthetic fibers help control how much plastic shrinks and allow less permeation of water because they limit the size of the cracks. They also provide better resistance to freeze/thaw and chemical exposure. Combining these two types of synthetic fibers can create a hybrid system that will ultimately allow greater long-term durability and tolerance to environmental exposure. Furthermore, synthetic fibers increase fire performance by reducing explosive spalling, and natural fibers contribute to enhanced thermal insulation, making hybrid systems the most effective alternative for balanced mechanical and durability performance.

6. Sustainability Assessment and Environmental Impact

Sustainability is an important factor in the creation of fiber-reinforced concrete since fibers affect embodied energy, carbon emissions, durability, and end-of-life outcomes. Natural fibers such as coir, jute, bamboo, and agricultural leftovers have apparent environmental benefits since they are renewable, low-energy materials that require little processing. Their capacity to divert biomass from combustion and retain carbon promotes low-carbon building, while durability issues and the requirement for chemical treatments might raise environmental concerns. Synthetic fibers, such as polypropylene, polyethylene, glass, and carbon, have a greater embodied energy since they are manufactured using fossil fuels, but their better durability and crack-control capabilities help decrease maintenance and life-cycle emissions.

Recycled and waste-derived fibers help to achieve circular economy goals by recovering resources like plastic shreds, carpet fibers, and agricultural wastes that would otherwise end up in landfills or burned openly. These fibers reduce environmental impact and increase toughness, but quality discrepancies and microplastic problems persist. Overall, durability is critical to sustainability; fibers with increased resistance to breaking and degradation lengthen service life and minimize resource use over time. Hybrid fiber systems provide the best-balanced sustainability profile. By blending natural and synthetic fibers, they lessen dependency on high-carbon materials while preserving the durability necessary for long-term operation. This synergy can increase mechanical performance at lower fiber doses, reduce cement usage, and lessen overall life-cycle effects.

Table 8. Sustainability summary

Fiber Type	Embodied Energy	Carbon Footprint	Circular Economy Potential	Long-Term Sustainability
Natural fibers	Low	Low	High	Moderate (needs treatment)
Synthetic fibers	High	High	Moderate–Low	High
Hybrid fibers	Moderate	Moderate	High	Very high

Table 8 presents a comparative sustainability summary of natural, synthetic, and hybrid fibers used in concrete. The table highlights differences in embodied energy, carbon footprint, circular economy potential, and long-term sustainability to support informed material selection. Hybrid systems demonstrate the strongest sustainability potential, combining renewability with mechanical and durability performance.

7. Hybrid Fiber Synergy and Optimization

Hybrid fiber systems combine natural fibers microcrack control capabilities with synthetic fibers macrocrack resistance and post-cracking stability, resulting in improved overall performance of fiber-reinforced concrete. Considerable improvements in both the mechanical and durability properties, such as 20%-60% increase in flexural strength and over 100% increase in toughness compared to traditional or single fiber systems, can occur from this synergistic interaction of fiber types in a composite. Hybrid composites also exhibit greater resistance to shrinkage, improved long-term durability, and produce a lower environmental impact than concrete that is solely reinforced with synthetic fiber. The literature shows that the optimized performance of hybrid composites is most often observed when there are natural fibre contents of 0.5%-2% by volume (Volume Fraction) of the total composite and synthetic fibre contents of 0.1%-1% by volume (Volume Fraction) of the total composite; effective hybrid combinations are often found at a combination of 1.0% volume fraction of natural fibre and between 0.25%-0.50% volume fraction of synthetic fibre.

8. Study Limitations

- The review relies primarily on published experimental investigations, resulting in diversity in mix design, fiber type, dose, curing conditions, and testing methodologies, limiting direct comparison of findings.
- Most research focuses on short-term mechanical performance, but long-term durability under environmental exposures such as freeze-thaw, wet-dry cycles, chemical assault, and UV radiation is not well explored.
- Insufficient life-cycle assessment data exist for natural, synthetic, and hybrid fiber systems, leading to qualitative sustainability evaluations.
- Experiments are often undertaken at the laboratory scale with tiny specimens, with minimal validation in large-scale or field applications.
- The lack of established testing protocols for fiber treatment, dispersion, and durability evaluation limits the generalizability of findings.

9. Future Research Directions

- Developed standardized testing protocols for fiber-reinforced concrete to ensure consistency and reproducibility across studies.
- Investigated long-term durability of natural and waste-derived fibers under environmental and mechanical loads.
- Performance-based design of hybrid fiber systems, including fiber type combinations, dose ratios, and length distributions.
- Incorporate quantitative life-cycle evaluation into future experimental investigations to analyze embodied carbon, energy consumption, durability benefits, and end-of-life consequences.
- Emphasis on large-scale structural elements and real-world applications to validate laboratory findings and guide code development.
- Conducted microstructural and numerical modeling studies to understand fiber-matrix interactions and degradation behavior.

10. Discussion

The research demonstrates substantial advances in the use of natural, synthetic, and hybrid fibers, but various barriers prevent widespread acceptance. Natural fibers provide excellent sustainability benefits and effective crack control, but their hydrophilic nature, unpredictability, and low durability result in significant variations among research. These variables result from changes in environment, harvesting, treatment, and fiber shape, making comparison difficult and slowing industry acceptance. Synthetic fibers provide dependable mechanical and durability performance, but their high carbon content and end-of-life problems are important downsides. Hybrid systems exhibit the best-balanced behavior, but research lacks a systematic strategy for discovering ideal fiber combinations for various performance goals. Fiber handling and processing have emerged as another major concern. Chemical treatments increase the bonding and durability of natural fibers, although the processes vary greatly between research, lowering repeatability. The environmental impacts and costs of these products have also been underestimated. More research is needed into low-energy, environmentally friendly methods of improving durability without compromising sustainability benefits. The literature has many methodological constraints. There is great variation between mix designs, curing conditions, and methods of testing, while there are few long-term studies on durability, as well as a lack of microstructural analysis in the literature. Most studies are based on small-scale specimens and do not have sufficient statistical validation for their findings to be applicable at the field or structural size. The lack of adequate data limits the ability to generalize findings and hinders the development of code. All in all, fiber-reinforced concrete will produce substantial gains in mechanical properties and durability; however, the field requires standardization, performance-based optimization of hybrid systems, ultimately more rigorous durability and microstructural research, and quantitative life-cycle analysis. It is imperative that advances be made in these areas so that fiber reinforcement can be included in common structural design practice, as well as improving the sustainability profile of fiber-reinforced concrete products.

11. Conclusion

Using a systematic review, this research compiled data from 92 empirical studies to evaluate the effect of different types of fibers (including both natural and synthetic or a mix of the two) on the mechanical, durability, and sustainability performance of concrete. All of the reviewed studies show that fiber reinforcement can be used as a way to improve control of cracks, provide serviceability after cracking, increase toughness, and enhance overall performance in concrete. However, these improvements depend largely on the specific type of fiber used, the amount of fiber used, how that fiber has been treated or processed prior to incorporation into concrete, and the effectiveness with which the fiber has been dispersed throughout the cement matrix.

Natural fibers such as jute, coir, bamboo, and hemp, along with leftover materials from other agricultural products, are bio-based and therefore provide excellent sustainability benefits due to their being renewable, low in embodied energy, biodegradable (compared with many synthetic materials), and widely available. When incorporated into concrete, natural fibers have been shown to increase the fracture resistance of concrete at an early age, reduce the amount of shrinkage occurring during curing, and increase the energy absorption capacity of the concrete, making natural fibers attractive for use in environmentally friendly, low-carbon construction projects.

Hydrophilic nature, variable mechanical properties, and vulnerability to alkaline cement environments impact long-term behavior. Inappropriate treatment may result in high porosity and moisture ingress, resulting in degradation of durability, which limits structural application of these materials.

Synthetic fibers, such as polypropylene, polyethylene, glass fibers, and carbon fibers, provide consistent, predictable improvements in strength under tension, flexural performance, impact resistance, and crack width control. The excellent post-cracking performance, durability, and endurance of these materials make them suitable for structural and high-performance applications. While these materials offer many performance advantages, they have a higher embodied energy, greater emissions of carbon, and challenges with recyclability and disposal at the end of service life; thus, diminishing their overall sustainability advantages.

Hybrid fiber-reinforced concrete offers the best balance of the environmental benefits of natural fibers with the mechanical reliability and durability of synthetic fibers. The synergistic action of micro- and macro-cracking bridging creates improved toughness, ductility, and resistance to long-term failure while reducing the dependence on high-carbon reinforcing material. Improving durability translates to longer service lives and lower life cycle environmental impacts.

In conclusion, fiber reinforcement is a viable means for producing durable and sustainable concrete. Amongst available options, hybrid fiber systems provide the most opportunity to align mechanical performance with sustainability goals, while synthetic fibers are still the preferred choice for performance-enhanced structural applications, and treated natural fibers create benefits through low-carbon, resource-efficient construction.

Conflicts of Interest

The author(s) declare that there are no conflicts of interest associated with this publication.

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