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REVIEW ARTICLE

A review on contemporary developments in biofiber and its prospective applications in civil engineering

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Abstract: In recent years, there has been a growing focus among researchers on exploring the viability of biobased fibers as sustainable alternatives to conventional building materials. This review article provides a comprehensive overview of the current research landscape concerning the utilization of biofibers in civil engineering. It offers insights into the existing and potential applications of biofibers across various domains within civil engineering, encompassing structural, geotechnical, transportation, and environmental engineering. The article delves into the fundamental properties of biofibers, including their mechanical and chemical characteristics, shedding light on their potential for diverse engineering applications. Additionally, it addresses both the challenges and potential advantages associated with integrating biofibers into civil engineering practices. Through an in-depth examination of the current state of research, this review aims to contribute to the ongoing discourse surrounding sustainable materials in the field of civil engineering.

Keywords: Biocomposites, natural fibers, biobased resins, civil engineering, sustainable development

1 Introduction

Civil engineering is a field that is concerned with the design, construction, and maintenance of the built environment. Civil engineering professionals supervise the use of substantial amounts of raw and processed materials in the construction of structures including buildings, transportation hubs, water resource facilities, and environmental applications. The extraction, processing, and transportation of these minerals require significant amounts of energy and natural resources [1]. The materials used in civil engineering applications must meet a variety of requirements, including strength, durability, and sustainability. Owing to its myriad advantages, the concept of sustainability has ascended to a position of paramount importance within the construction sector. Given the increasing global emphasis on sustainability, the industry is prioritizing the development of eco-friendly structures. The relentless pace of urbanization is precipitating a spectrum of environmental challenges. The adoption of sustainable

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construction materials offers a viable pathway to mitigate pollution and ameliorate prevailing environmental conditions [2]. Because of their remarkable mechanical qualities and lightweight nature, composite materials have proven helpful in different industries like sports, automotive, aerospace, aeronautics, and the military. However, the usage of products sourced from fossil fuels has decreased due to environmental concerns. Natural fiber composites are crucial because attempts to minimize greenhouse gas emissions and increase fuel economy also call for lightweight materials with a smaller carbon impact [3]. Composite materials that contain one or more phases that have a biological origin are known as biocomposites. Plant fibers like cotton, flax, hemp, and the like, as well as fibers from wastepaper or reclaimed wood, and even byproducts from food crops, might be used as reinforcement. Natural "nanofibrils" of cellulose and chitin, as well as regenerated cellulose fibers (viscose/rayon), are ultimately derived from a renewable resource [4]. Polymers, preferably sourced from sustainable sources like vegetable oils or starches, can also serve as matrices. On the other hand, synthetic, fossil-derived polymers are more common. These can be recycled or "virgin" thermoplastics like polyethylene, polypropylene, polystyrene, and polyvinyl chloride, or virgin thermosets like isocyanates, epoxies, unsaturated polyesters, and phenol formaldehyde [5]. Biocomposites surpass traditional materials with their notable advantages, including superior mechanical strength-to-weight ratio, effective thermal insulation, and CO_2 neutrality [6]. They excel in vibration damping, exhibit high fatigue resistance, and are safer for health, enhancing their desirability across applications. Their raw materials are readily available and renewable, contributing to their appeal [7]. Furthermore, biocomposites are characterized by excellent resistance to abrasion and corrosion, low density, reduced energy requirements for production, and overall lightness, making them a compelling alternative in a wide range of industries [8]. A number of surface modifications and chemical treatment techniques can be used to tackle some of the problems of natural fibers, including hydrophilic qualities and inherent brittleness in order to reach adequate usage [9]. The main limitations associated with employing natural fibers as reinforcement in composite materials stem from their tendency to absorb moisture and their suboptimal compatibility with the matrix. To enhance the bond between the fibers and various matrices, modifications of the natural fibers are explored, aiming to alter their surface characteristics. Achieving a robust yet highly brittle interface can lead to significant improvements in strength and stiffness by facilitating fracture propagation through both matrix and fiber. Conversely, a weaker bond might impede efficient stress transfer from the matrix to the fiber, compromising the composite's performance [10]. Considering the surge in interest and growing demand, biofibers have been extensively used in various fields of civil engineering domain.

This review article employs a systematic and comprehensive methodology to analyze the applications of biofibers in civil engineering, ensuring a thorough exploration of the topic. The study is structured into several key sections: Introduction, Bibliometric Analysis, Classification of natural fibers and their properties and challenges, Applications in Civil Engineering, Conclusions and future perspectives, and Conclusion. Each section is designed to provide a detailed understanding of the role of biofibers in sustainable construction, from their fundamental properties to their practical applications and future potential. The structure of the paper is carefully designed to align with the title and theme, "Applications of Biofibers in Civil Engineering," ensuring a logical flow from theoretical concepts to real-world applications.

This review article distinguishes itself from previous works through its comprehensive and interdisciplinary approach, focusing specifically on the applications of biofibers in civil engineering while integrating bibliometric analysis to identify emerging trends and research gaps. Unlike earlier reviews that primarily explore mechanical properties and surface treatments, this article provides a holistic view by linking material science with civil engineering practices, covering domains such as structural, geotechnical, transportation, and environmental engineering. It emphasizes environmental sustainability, including carbon footprint and life cycle assessment, which is often underrepresented in existing literature. The inclusion of real-world case studies and practical applications, such as biofiber-reinforced composites in bridge decking and erosion control, adds a unique dimension. Additionally, the article critically examines challenges like moisture sensitivity and flammability, proposing innovative solutions such as nanotechnology and advanced surface treatments. By outlining future research directions, such as fire-resistant biocomposites and smart materials, and offering practical recommendations for fiber selection and treatment, this review advances the field beyond existing works. Its data-driven insights, focus on sustainability, and integration of recent advancements make it a valuable resource for researchers, engineers, and policymakers, contributing to the ongoing discourse on sustainable construction practices and paving the way for innovative solutions in civil engineering.

2 Bibliometric analysis

To understand the evolution and current state of research in this field, a bibliometric analysis was conducted, focusing on the use of biofibers in civil engineering applications over the past five decades. The selection of articles for this review was based on their relevance to the theme of biofiber applications in civil engineering. Articles published within the last 10–15 years were prioritized to ensure the inclusion of the latest advancements and trends. Studies focusing on the mechanical properties, surface treatments, and environmental benefits of biofibers were given particular emphasis, as these aspects are critical to their performance in civil engineering applications. Additionally, articles addressing challenges such as moisture absorption, flammability, and variability in fiber properties were included to provide a balanced perspective on the limitations and opportunities associated with biofiber usage. The inclusion of studies from diverse domains of civil engineering, such as structural engineering, geotechnical engineering, transportation engineering, and environmental engineering, ensures that the review covers a wide range of applications, from biofiber-reinforced concrete in structural panels to the use of biofibers in soil stabilization and erosion control.

While humans have historically utilized natural fibers since ancient times, the 20th century witnessed an unprecedented surge in the utilization of synthetic fibers, far surpassing the use of their natural counterparts. However, growing environmental apprehensions and concerns over fossil fuel depletion have catalyzed renewed interest in natural fiber composite research over the past two decades. This surge is evident in the exponential increase in the number of patents and scholarly articles focusing on natural fiber composite (biocomposite) materials [11,12]. From our review of the literature, it became apparent that biofibers have found applications in four primary domains of civil engineering: structural engineering, geotechnical engineering, highway engineering, and environmental engineering. In this study, we delve into the utilization of biofibers within these fields and explore their various applications.

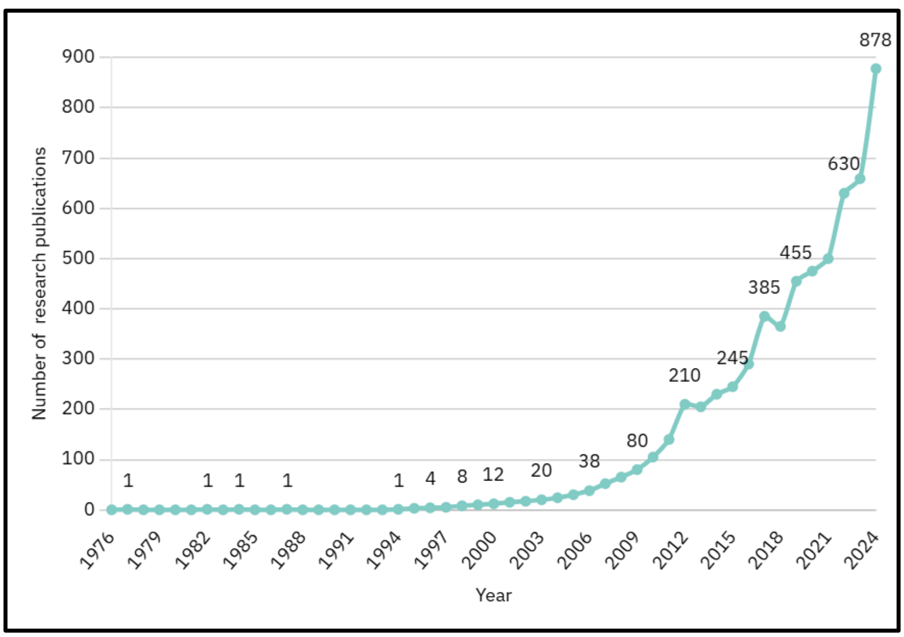

Fig. 1. Research articles by year from 1976 to 2024 (source – scopus.com)

The Scopus database was searched between the years 1976 and 2024 for the terms "biofiber," "biobased fiber," "natural fibers," "biocomposites," and "civil engineering" in the article, abstracts, and keywords. The articles were evaluated in terms of documents per year, articles published in top journals, documents by country, documents by subject area, and documents by type. In total 6,262 articles were published in Scopus-indexed journals, books and conference proceedings. **Fig. 1** The year-wise research publication trend from 1976 to 2024 shows a clear progression from negligible activity to a phase of rapid growth. In the initial years, from 1976 until the mid-1990s, research output was minimal, with fewer than five publications per year. A gradual rise began in the late 1990s, and by 2005, the annual count reached around 30 publications. The pace of growth increased notably after 2008, with the period from 2010 to 2016 witnessing a sharp climb from about 105 to 290 publications annually. From 2017 onwards, the momentum remained strong, crossing 500 publications in 2021. The most dramatic surge occurred in recent years, with 630 publications in 2022 and an all-time peak of 878 in 2024, indicating an exponential growth pattern that reflects expanding research capacity, greater funding opportunities, and stronger collaborations.

There are publications from 105 different nations, except those whose nationality is not specified. The majority of publications come from a small number of nations. **Fig. 2** displays the geographical dispersion of the number of publications. The country-wise publication distribution for the same period (1976–2024) reveals a highly uneven landscape dominated by a few nations. India leads by a significant margin with 1,322 publications, followed by China with 858 and the United States with 663, together contributing a substantial share of the total output. Several other countries, including Malaysia, France, Italy, Canada, the United Kingdom, and Germany, each recorded more than 200 publications, highlighting their active engagement in this research area. In contrast, countries such as Turkey, Poland, Saudi Arabia, South Korea, Brazil, and Spain contributed fewer than 200 publications each but still maintain a visible presence. At the lower end of the spectrum, nations like Singapore, Norway, and Ethiopia have only around ten publications. This distribution reflects a concentration of research activity in a handful of high-output countries, with a long tail of nations contributing smaller yet meaningful numbersExcept for unidentified publications, around 90% of all publications are produced by the top 15 nations in terms of quantity of publications.

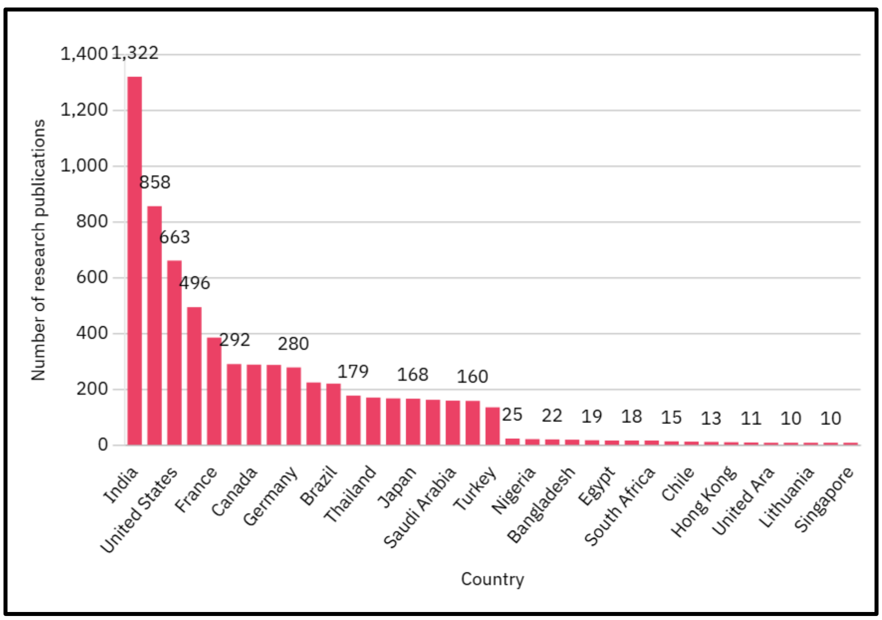

Fig. 2. Documents by country from 1976 to 2024 (source – scopus.com)

The bibliometric analysis also revealed that biofibers have been studied across four primary domains of civil engineering: structural engineering, geotechnical engineering, transportation engineering, and environmental engineering. This aligns with the overarching theme of the paper, which seeks to explore the diverse applications of biofibers in these fields. The increasing volume of research, particularly in the last decade, reflects the recognition of biofibers as viable alternatives to traditional materials, driven by their renewable nature, low environmental impact, and potential to enhance the mechanical and thermal properties of composites.

By examining the trends and patterns in biofiber research, this bibliometric analysis sets the stage for a deeper exploration of their applications in civil engineering. The following sections delve into the classification, properties, and surface modification techniques of natural fibers, providing a comprehensive understanding of their potential to revolutionize sustainable construction practices.

3 Classification of natural fibers and their properties and challenges

The applications of natural fibers in civil engineering are vast and varied. They can be used in structural components such as beams, columns, and walls, as well as in non-structural applications such as cladding, roofing, and insulation. Natural fibers are categorized into three distinct subgroups based on their origin either from plant, animal, or mineral sources. Among these classifications, plant-based fibers, alternatively referred to as botanical or cellulose-based fibers, hold significant prominence as they constitute the primary source of natural fibers utilized in engineering applications [13,14]. The second-largest source of naturally occurring fibers that are used is derived from animal sources. The primary factors thought to prevent animal fibers from being widely used instead of plant fibers are their high prices and limited availability. Therefore, it is thought that because animal fibers are more coveted, they are used in more advanced industries like electronics and biomedicine [15]. The least common form of fiber in this category is mineral-based fiber since it is linked to serious health risks from a number of illnesses that mostly affect the lungs [16–18]. There are broadly two types of plants that produce natural fibers based on how they are used: main and secondary. The purpose of primary plants is to produce fiber, whereas secondary plants are produced for other purposes and produce fiber as a byproduct. The primary plants utilized for natural fibers encompass jute, hemp, kenaf, sisal, and cotton, while secondary species comprise pineapple, cereal stalks, agave, oil palm, and coir. Plant species represent the predominant categorization system for natural fibers. Accordingly, plant fibers are commonly classified into six fundamental categories: bast fibers, leaf fibers, seed fibers, core fibers, grass and reed fibers, and miscellaneous types such as wood and roots [19,20]. **Fig. 3** shows the classification of natural fibers.

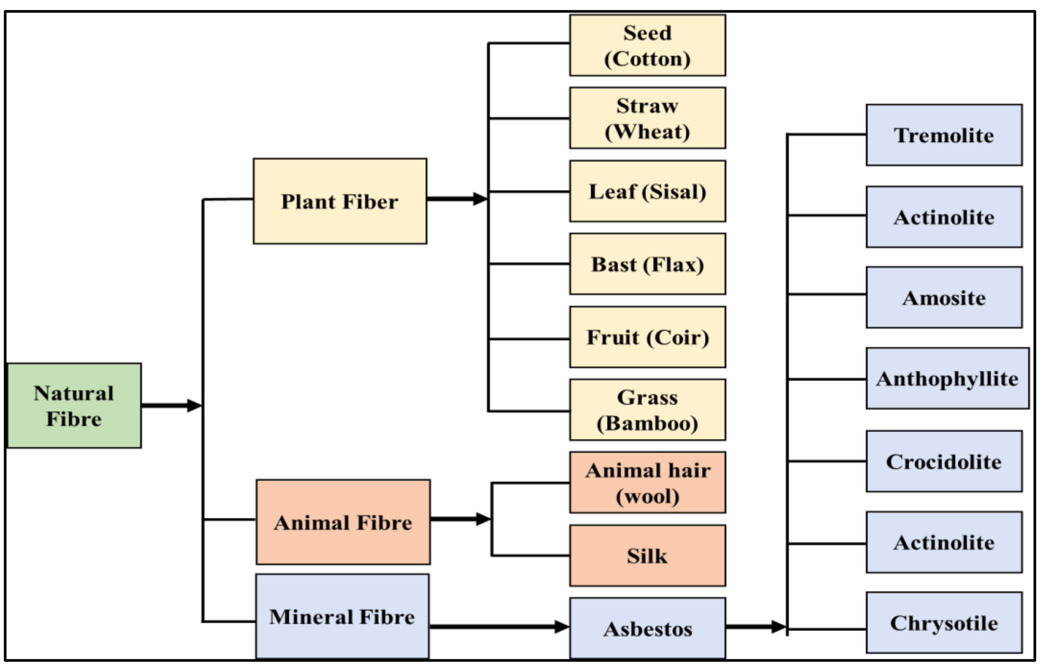

Fig. 3. Classification of natural fibers [19–21]

The applications of bio fibers in civil engineering are vast and varied. They can be used in structural components such as beams, columns, and walls, as well as in non-structural applications such as cladding, roofing, and insulation. It was found from the literature survey that flax, jute, hemp, sisal, coir, wheat straw, cotton, alfa, banana, date palm, and bamboo are the plant-based fiber that have been used in civil engineering applications [22–25].

Understanding the classification of natural fibers sets the stage for exploring their chemical composition, which plays a critical role in determining their mechanical properties and suitability for civil engineering applications.

3.1 Chemical composition

Various natural fibers (*NF*s) exhibit diverse chemical compositions, comprising components such as cellulose, hemicellulose, lignin, wax, ash, pectin, and moisture content. The distribution of these chemical constituents within the fiber is influenced by factors such as the plant's location, growth rate, and tissue structure. Of particular significance, the proportion of cellulose present in a plant fiber significantly influences its strength and stiffness characteristics [26]. The strength and durability of fibers are predominantly contingent upon the presence of cellulose, with the quantity of cellulose directly dictating these key properties [27,28]. **Tab. 1** displays the chemical composition of commonly used natural plant fibers across diverse civil engineering applications.

Table 1. Correlation between cellulose content and mechanical properties of biofibers [29–48]

Biofiber	Cellulose Content (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Ramie	68–85	400–938	44–128	1.2–3.8
Flax	70–80	800–1500	50–70	1.2–1.6
Hemp	68–74	550–900	30–70	1.6–2.0
Jute	61–71	393–773	26.5–55.0	1.5–1.8
Sisal	60–78	468–640	9.4–22.0	2.0–2.5
Banana	60–65	529–754	27–32	1.0–3.5
Kenaf	53–64	223–930	14.5–53.0	1.5–2.7
Coir	32–43	131–220	4.0–6.0	15.0–25.0

Higher cellulose content generally correlates with higher tensile strength and Young's modulus, as seen in flax, hemp, and ramie. Fibers with lower cellulose content, like coir and bamboo, tend to have lower tensile strength but higher elongation at break, making them more flexible. Fibers with intermediate cellulose content, like jute and sisal, show a balance between strength and flexibility.

3.2 Mechanical Properties

Natural fibers such as bamboo, hemp, and flax are frequently employed as reinforcement in biocomposites, offering exceptional strength and stiffness while maintaining a low weight. Various plant biofibers are combined with thermoplastics or thermosets to fabricate biocomposites. Notably, commonly utilized natural fibers also known as biofibers like hemp and flax can exhibit Young's modulus exceeding 50 GPa, positioning them as viable alternatives to glass fibers across numerous applications. The mechanical properties of these composites are significantly influenced by the robust mechanical characteristics of the biofibers when reinforced with polymers [49]. The robust mechanical attributes of biofibers play a pivotal role in shaping the mechanical performance of composites when they are reinforced with polymers. Mechanical properties of the most widely used biofibers and synthetic fibers are listed in **Tab. 2.** Synthetic fibers, such as aramid, carbon, and glass fibers, are widely recognized for their superior mechanical properties, including high tensile strength, stiffness, and durability. These fibers are engineered to meet specific performance requirements, making them indispensable in high-performance applications such as aerospace, automotive, and ballistic protection. For instance, carbon fibers exhibit an exceptionally high Young's modulus (230-240 GPa) and tensile strength (4000 MPa), while aramid fibers like Kevlar offer remarkable toughness and impact resistance. E-glass and S-glass fibers, though less stiff than carbon fibers, provide excellent strength-to-weight ratios and are commonly used in composite materials for structural applications. However, the production of synthetic fibers often involves high energy consumption and environmental concerns, which has spurred interest in exploring sustainable alternatives like natural fibers. Despite this, synthetic fibers remain critical in industries where performance under extreme conditions is paramount.

Table 2. Mechanical properties of natural fiber [50–59]

Types of fibers	Density (g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)
Flax	1.5	30-60	300-800	2-4
Jute	1.23	20-55	187-773	1.5-3.1
Hemp	1.35	30-60	580 - 1110	1.6 - 4.5
Sisal	1.20	9-22	507- 855	1.9 - 3
Coir	1.20	6	175	15 -25
Wheat straw	1.20	6.6	32	-
Cotton	1.5 – 1.6	5.25 - 8	287–597	3 - 10
Alfa fiber	1.4	58	1327	2.4
Banana fiber	1.50	27 -32	529 - 914	5 - 6
Date palm fiber	1.3 - 1.45	4.74 $\pm$2	170$\pm$40	16 $\pm$3
Bamboo fiber	0.66	20.1	206.2	-
Aramid	1.4	63-67	3000-3150	3.3-3.7
Carbon	1.4	230-240	4000	1.4-1.8
E-glass	2.5	70	2000-3000	0.5
S-glass	2.5	86	4570	2.8

While natural fibers offer numerous advantages, their use in composites is not without challenges. The next section explores these challenges and the surface modification techniques employed to overcome them.

4 Challenges and surface modification of biofibers

When natural fibers are used in polymeric composites, several problems arise, including poor mechanical qualities, weak matrix-fiber interfacial adhesion, moisture absorption, and durability [60–62]. The limited thermal stability and other deficiencies, including inadequate interfacial adhesion between fibers and matrix, irregular and inconsistent fiber surfaces, and finite fiber length, pose challenges for utilizing them in harsh or demanding environments [27,63–65]. Improving the interfacial interaction between natural fibers and the polymer matrix is essential for enhancing performance. This enhancement facilitates more efficient load and stress transmission from the matrix to the fibers, thereby leading to enhanced mechanical and thermal properties [66-68]. Employing appropriate surface modification or treatment represents an effective approach to enhancing the adherence of natural fibers in composite materials [69]. These surface treatments are two types physical treatments and chemical treatments. The following subsections provide an in-depth look at the physical and chemical treatments used to enhance the properties of natural fibers and their compatibility with polymer matrices.

4.1 Physical modification

Fibers are given physical treatment primarily for two purposes. Initially, to divide the fiber bundles into separate filaments. This approach helps prevent the agglomeration issue, thereby mitigating the formation of stress concentration sites within the matrix region. The second is the alteration of the fiber surface to improve compatibility with applications using composite reinforcement [70–72]. Various kinds of physical treatments are presented in **Fig. 4.**

4.1.1 Corona treatment

A special technique for promoting surface oxidation and altering the surface energy of cellulose fibers is corona treatment. The purpose of this treatment is to improve the compatibility of hydrophilic fibers with a hydrophobic matrix. In particular, it has been found that the application of corona discharge treatment to cellulose fibers and a hydrophobic matrix enhances the interaction between the two elements [73]. The purpose of the study was to determine how various corona treatment settings affected the mechanical characteristics of composites made of cellulose and polypropylene fibers. Both the polypropylene and cellulose fibers were altered by applying different corona treatment doses and oxygen concentrations. The mechanical properties of composites made from various mixes of treated or untreated cellulose fibers and polypropylene were evaluated using tensile stress-strain measurements. The results showed that treating either the cellulose fibers alone or both components together significantly improved their mechanical qualities. For composites made of treated polypropylene and untreated cellulose fibers, the improvement was, however, negligible [74]. Studies have investigated the influence of corona treatment on the tensile properties of wood fiber-linear low-density polyethylene (LLDPE) composites. The research indicates that corona treatment substantially enhances the strength characteristics of the composites. Upon treatment of either one or both components of the composite, there is an increase in yield stress. Notably, composites containing 15–30% corona-treated fibers exhibit a noteworthy improvement in ductility [75]. The study examined the influence of corona-treated hemp fibers on the mechanical properties of polypropylene biocomposites. Reports on the effect of fiber content indicate that regardless of treatment, a 20% concentration yields the highest values of tensile strength and Young's modulus. Furthermore, treating either the fibers or the matrix significantly enhances tensile strength. Cellulosic reinforcements contribute to a more substantial improvement in the composites' characteristics, with a 30% increase in the modulus of elasticity compared to polypropylene reinforcements [76].

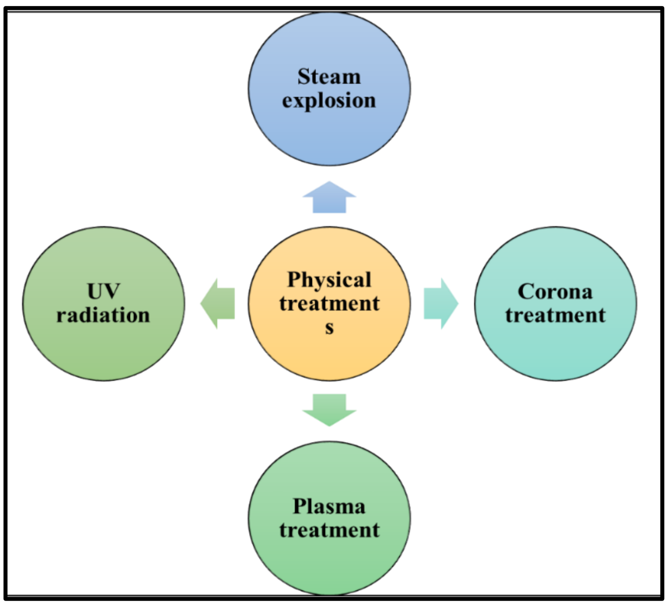

Fig. 4. Types of physical treatments [70–72]

4.1.2 Plasma treatment

By roughening the fiber's surface through the sputtering effect, plasma treatment modifies the physical surface of the fiber and increases the friction between the fiber and the polymer by expanding the contact area [77,78]. By roughening the fiber's surface through the sputtering effect, plasma treatment modifies the physical surface of the fiber and increases the friction between the fiber and the polymer by expanding the contact area. The composites' substantial improvements in mechanical characteristics during characterization suggest that plasma treatment enhances fiber/matrix adhesion. The resin clings to treated fibers more readily than it does to untreated ones, as seen by SEM micrographs [79,80]. The purpose of this work is to investigate how low-pressure plasma treatment affects cellulose fibers in order to enhance the adherence of natural fibers utilized as reinforcement to a polymeric matrix. When the power and treatment duration of the plasma are just right in the chamber, the flax fiber surface is altered by low-pressure plasma (LPP) treatment, making it more wettable. A better fiber–matrix interface interaction is the outcome of improved adherence between the polyethylene matrix and the flax fiber reinforcement. As a result, the mechanical qualities get better, particularly when the fiber content is close to 20% [81]. In order to alter the fiber surface, jute fibers were treated with low temperature oxygen plasma in this investigation. It was looked at how plasma powers affected the mechanical characteristics of composites made of jute fiber and high-density polyethylene (HDPE). The untreated jute fiber/HDPE composite was found to have a flexural strength of 31.4 MPa. The flexural strength of the jute cloth increased to 39.7 MPa after it was treated with 30 W of plasma power. In this investigation, the highest value of flexural strength (45.6 MPa) was obtained by increasing the plasma power to 60 W. This translates into a 45% gain in flexural strength. In particular, jute fiber's surface may be altered without causing the fiber to deteriorate at 60 W [82,83].

4.1.3 Ultra-violet treatment

Due to its simplicity of use and inexpensive experimental setup, UV radiation has been shown to be a clean and economical method for altering the surfaces of cellulose fibers. With wavelengths ranging from 10 to 400 nm, ultraviolet light is a kind of electromagnetic energy that reacts chemically with different organic molecules to produce effects that are more intricate than basic heating. One potential energy source that affects the mechanical characteristics of cellulose fibers is UV light, which causes photochemical reactions in the fiber's molecular structures [84]. Researchers utilized unsaturated polyester as the matrix and pulp derived from empty fruit bunches (EFB) as the reinforcing agent to fabricate biofiber composites, subsequently cured using ultraviolet (UV) radiation. EFB pulp serves as the reinforcing fiber, while unsaturated polyester resin acts as the polymer matrix, facilitating the creation of UV-curable biofiber-based polymer matrix composites. Notably, the presence of lignin in EFB pulp significantly influences the degree of cure and penetration depth in the submerged layers of the composite, owing to its extensive absorption of UV light. These factors ultimately impact the mechanical characteristics and degree of cure of the composite material [85].

4.1.4 Steam treatment

Steam explosion is a procedure that chemically breaks down cellulose and other adhesive-like compounds that bind fibers together. Conversely, the conventional technique for separating hemp fibers involves cutting the hemp stems and leaving them in the field. Here, they undergo cycles of being soaked by dew at night and dried by the sun during the day, facilitating the natural separation of fibers from the plant [86]. Research conducted on hemp fiber, employing steam explosion treatment, indicates that the enhanced adherence of fibers to the matrix post-treatment may have resulted in improvements in both the tensile strength and tensile modulus of the hemp/polypropylene composite [87]. Superheated steam (SHS) was used in this work to treat oil palm mesocarp fiber (OPMF) to change its properties for use in biocomposite applications. The temperature range for the treatment was 190 ℃ – 230 ℃ for one, two, or three hours. Overall, the data presented here indicated that surface modification by SHS is a successful treatment technique that enhances the natural fiber's properties. Most significantly, using innovative, environmentally friendly SHS might help with surface modification of natural fiber sustainably and ecologically [88,89].

4.2 Chemical modifications

While physical treatments are effective, chemical modifications offer additional avenues for enhancing fiber-matrix interactions. Chemical reagents or compounds are frequently employed in modifying biofibers. These compounds play a crucial role in facilitating the bonding of the hydroxyl groups within the fibers with the resin present in the composite. They achieve this by either activating or removing specific components within the biofiber structure [90]. Lignocellulosic fibers primarily consist of cellulose, hemicelluloses, and lignin, with cellulose being the principal component responsible for providing strength to the fibers. Natural fibers (NF) are treated with a diverse range of chemicals with the main objective of augmenting the cellulose content while eliminating undesirable impurities such as oil and wax. The various chemical treatments for natural fiber are depicted in **Fig. 5.**

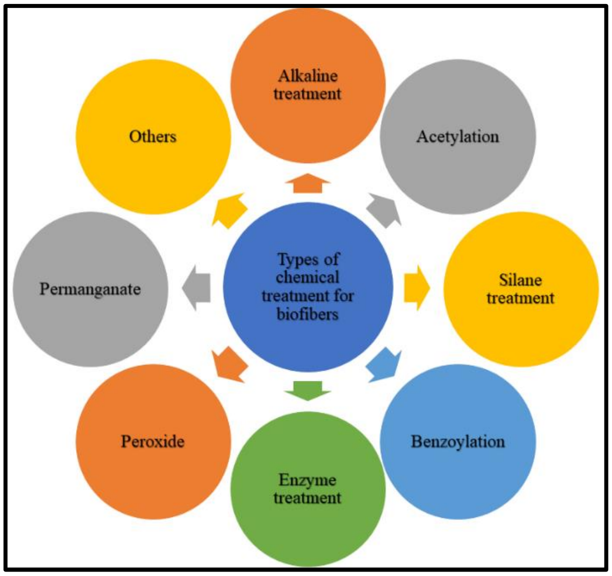

Fig. 5. Types of chemical treatment for biofibers [90]

4.2.1 Alkaline treatment

The commonly utilized chemical process, known as "alkali treatment" or "mercerization," alters the structure of the fiber surface by subjecting it to treatment with potassium hydroxide (KOH) or sodium hydroxide (NaOH). Since hydroxyl groups are present in the amorphous regions of cellulose, hemicellulose, and lignin components, natural fibers tend to absorb moisture. However, when natural fibers are treated with alkali, they lose some of their moisture-related hydroxyl groups, leading to a reduction in their hydrophilic properties [91]. In literature flax fibers were first treated for an hour at room temperature with solutions of sodium hydroxide (NaOH) in concentrations of 2.5,5, and 7%. Fibers treated with a 2.5% alkali solution had the best qualities among the other treatments. Comparing composites with treated fibers to those without, it was found that the treated fiber composites exhibited less moisture absorption. The effects of chemical treatment were linked to the increase in flexural characteristics and storage modulus seen in composites containing fibers treated with alkali [92]. In an investigation, coir fibers were subjected to different concentrations of sodium hydroxide (NaOH) solutions, ranging from 3% to 5%, for varying durations of 2, 4, and 6 hours at room temperature. Following treatment, coir fibers with 10% and 30% weight percent were extruded alongside untreated fibers, which measured between 160 to 250 μm, using polypropylene (PP). The results showed that the treated samples exhibited enhanced hydrophobicity, demonstrated by their higher thermal stability and increased residue percentage compared to the untreated fibers. Additionally, when comparing the tensile characteristics of biocomposites made from treated fibers with 5% weight percent NaOH to untreated coir/PP composites, the former showed a significant improvement of 28%. This study highlights the superiority of alkali-treated coir fibers over untreated ones, showcasing enhanced properties that contribute to greater tensile strength in resulting biocomposites [93–95].

4.2.2 Acetylation

The process of adding an acetyl group to an organic substance is known as acetylation. This might entail replacing an active hydrogen atom with an acetyl group [96,97]. Researchers utilized compression molding to successfully produce nonwoven, unidirectional matted banana empty fruit bunch fiber (BBF)-reinforced polypropylene (PP) composites. The study investigated the characteristics of PP/BBF composites concerning fiber composition, mercerization, and the incorporation of acetylation as a coupling agent. The findings revealed that BBFs acted as reinforcing fillers, enhancing the mechanical properties of the composites, including tensile strength, modulus, and Charpy impact strength. Compared to composites with alkali-treated and untreated fibers, PP/BBF composites subjected to acetylation following alkali pretreatment exhibited superior interfacial shear strength and mechanical characteristics [98]. Acetylation involves the conversion of the hydroxyl group in bagasse fiber to an acetyl group, leading to a reduction in the fiber's polarity and hydrophobicity. Bagasse serves as a valuable filler and reinforcing material for cement and plastic matrices. Acetylation treatment of bagasse fibers enhances adhesion and interaction between the fiber and matrix, consequently reducing the fibers' moisture absorption [99].

4.2.3 Silane treatment

The main drawback of using natural fibers as reinforcements in polymeric matrices stems from their hydrophilic nature, leading to inadequate interaction with the matrices. Surface treatments are necessary to increase their compatibility as composite reinforcement. It is common practice to treat natural fibers with silane to change their hygroscopic characteristics. This work has established a novel approach to silane treatment that does not require prehydrolysis or silanol group curing/dehydration. In order to do this, amino-silane was applied directly to flax fibers after 2,2,6,6-tetramethylpiperidine-1-oxy radical (TEMPO)-mediated oxidation. The oxidized silanized fiber composite showed better fiber/matrix adhesion, according to the data. Furthermore, when comparing the oxidized silanized fiber-reinforced composite to the one that was received, there was a notable 20% reduction in water absorption [100]. Natural fibers exhibit versatile properties that vary based on their physical and chemical composition. To enhance their compatibility with polymer matrices, researchers have investigated the effects of alkali, silane, and combined alkali and silane treatments on the mechanical (tensile), morphological, and structural characteristics of Pineapple Leaf Fibers (PALF) and Kenaf Fibers (KF). It was found that the tensile strength of PALF and KF treated with silane surpasses that of untreated, alkali-treated, and NaOH-silane treated samples. Results from the droplet test indicate that while silane-treated fibers exhibit the highest Interfacial Stress Strength (IFSS), alkali- and silane-treated PALF and KF show improved IFSS as well [101].

4.2.4 Benzoylation

A recent study explores the impact of alkaline and benzoylation treatments on the single fiber tensile strength and interfacial shear strength (IFSS) of sugar palm fibers. Both benzoylation and alkaline treatments result in enhanced tensile strength of sugar palm fibers. These treatments chemically alter the structure of sugar palm fibers, thereby improving their overall qualities. The tensile strength of the benzoylation-treated and alkaline fibers does not significantly differ, indicating that the benzoylation treatment can be utilized to enhance the fiber's characteristics. This is further supported by the high IFSS value that benzoylation-treated sugar palm fiber demonstrated, indicating that it has a greater potential for application as reinforcement in polymer composites [102]**.** This study's primary goal was to find out how benzoyl treatment affected the functionality of hybrid polypropylene composites reinforced with kenaf and sugar palm fibers. The study found that benzoyl treatment increased the tensile strength of polypropylene hybrid composites reinforced with sugar palm and kenaf, achieving a value of 19.41 MPa. Furthermore, an examination using scanning electron microscopy (SEM) revealed that the hybrid composites' mechanical qualities were enhanced by surface treatment. Overall, it is shown that benzoyl-treated composites with a larger percentage of kenaf fiber than sugar palm fiber are expected to improve the mechanical characteristics of the hybrid composites [103,104].

4.2.5 Enzyme treatment

In order to produce composites reinforced with natural fibers, enzyme treatment presents itself as a cost-effective, environmentally responsible, and efficient means of altering natural fibers. The impact of several enzyme treatments on the mechanical characteristics of polyester composites reinforced with jute fiber was examined in a published study. Before composites were made, jute textiles were treated with pectinase, laccase, cellulase, and xylanase enzyme solutions. Depending on the experimental design, different enzyme combinations and treatment times were used. The study also examined the differences between samples treated with enzymes and those treated with NaOH. The enzymes were found to break down pectin, hemicelluloses, and lignin components at the interface of the fiber bundles. This led to a reduction in the technical fiber diameter and an increase in the fiber aspect ratio. Consequently, enzymatic treatment resulted in a larger fiber-matrix interface area, promoting enhanced fiber-matrix adhesion and improving the mechanical properties of the composites [105]. The properties of composites reinforced with natural fibers were investigated regarding the utilization of enzymes as an alternative to dew retting for flax. Composites infused with fibers extracted following enzymatic treatments demonstrated enhanced mechanical performance compared to composites using dew-retted fibers. All enzymatic treatments yielded biocomposites with lower equilibrium moisture content and diffusion coefficient, as well as finer fibers compared to green fibers [106].

4.2.6 Peroxide treatment

Hydrogen peroxide is used in a bleaching process to alter fibers. Because of the increased fiber/matrix interfacial adhesion, bleached fiber composite exhibited better mechanical characteristics than untreated fiber composite [107]. Composites composed of untreated and dicumyl peroxide (DCP) treated sisal fibers were fabricated using polymer matrices consisting of three different types of polyethylene (PE): low-density PE (LDPE), linear low-density PE (LLDPE), and high-density PE (HDPE). In all composites, the elongation significantly decreased upon failure. While the treated HDPE samples exhibited a clear decline in Young's modulus compared to the untreated samples, the treated LDPE and LLDPE composites showed a noticeable increase in tensile strength and Young's modulus compared to the untreated composites [108]. Because of its excellent performance, ramie fiber—one of the natural cellulose fibers—has experienced fast development. This study shown that isopropyl alcohol and hydrogen peroxide are highly effective agents for removing non-cellulosic materials and enhancing the characteristics of ramie fibers at the same time. The majority of the gummy components were successfully removed, according to the results, by using the same bath solution for both the fiber preparation and chemical modification processes. When compared to the alkali or peroxide approach, the treated fibers showed better softness, elongation, and fineness qualities [109].

4.2.7 Permanganate treatment

Table 3. Summary of physical treatments

Name of Treatment	Effect of Treatment	Advantages	Disadvantages	References
UV Treatment	Modifies fiber polarity, enhances adhesion, and cleans fibers by breaking bonds (C-C, C-O, etc.).	•Improves fiber-matrix adhesion. • Environmentally friendly. • No chemical residues.	• Limited penetration depth. • May degrade fiber strength if overexposed.	[112]
Steam / Thermal	Raises fiber temperature (100–200 ℃), altering crystallinity, water content, and properties.	• Reduces moisture absorption. • Improves thermal stability. • Enhances fiber-matrix bonding.	• High energy consumption. • Risk of fiber degradation at high temperatures.	[113]
Corona Treatment	Introduces polar groups through oxidation, enhancing interfacial adhesion.	• Improves surface energy and wettability. • No chemical waste.	• Short-lived effect. • Requires specialized equipment.	[114]

Table 4: Summary of chemical treatments

Name of Treatment	Effect of Treatment	Advantages	Disadvantages	References
Alkaline (Mercerization)	Reduces hydrophilicity, removes impurities, and improves surface roughness.	• Enhances fiber-matrix adhesion. • Increases fiber strength. • Low cost.	• Generates chemical waste. • May reduce fiber flexibility if over-treated.	[115]
Acetylation	Uses acetic anhydride for superficial plasticization, improving interfacial bonding.	• Reduces moisture absorption. • Improves dimensional stability. • Enhances thermal stability.	• Requires toxic chemicals. • High cost of reagents.	[116]
Silane Treatment	Coats fiber surface with silane, improving adhesion and reducing hydrophilicity.	• Enhances fiber-matrix compatibility. • Improves mechanical properties.	• Requires pretreatment (e.g., alkalization). • Silane reagents are expensive.	[117]
Benzoylation	Reduces hydrophilicity using benzoyl chloride, improving thermal stability and adhesion.	• Enhances fiber-matrix bonding. • Improves thermal and mechanical properties.	• Uses toxic chemicals. • Complex process.	[118]
Enzyme Treatment	Uses enzymes (pectinase, laccase, etc.) to improve fiber-matrix adhesion.	• Environmentally friendly. • Enhances mechanical properties. • Selective and mild process.	• High cost of enzymes. • Requires precise control of reaction conditions.	[119]
Peroxide Treatment	Generates free radicals to improve fiber-matrix interface and reduce moisture absorption.	• Enhances interfacial bonding. • Reduces moisture sensitivity. • Improves thermal stability.	• Risk of fiber degradation. • Requires careful handling of peroxides.	[120]
Permanganate Treatment	Initiates graft copolymerization using potassium permanganate (KMnO4).	• Improves fiber-matrix adhesion. • Enhances mechanical properties.	• Uses toxic chemicals. • Complex process.	[29]

Heat-press molding was used to create polypropylene composites reinforced with jute textiles, sometimes known as Hessian cloth. Potassium permanganate treatment of jute fibers in oxalic acid medium was done to examine the oxidizing influence on the composites' characteristics. Oxalic acid solutions ranging from 1.0 to 10.0% w/v were made, with a 0.01% w/v potassium permanganate proportion. Potassium permanganate in jute composite treated with 5.0% oxalic acid performed best mechanically among the treatments. Jute fabric treatment increased the composite's thermal stability. The properties of the composites' degradation were examined in soil, water, and weathering simulation scenarios. The composites' water uptake was also investigated. In comparison to the control composite, treated jute composites were shown to be less water-sensitive and less biodegradable [110]. The use of the biodegradable substance Butea parviflora (BP) fiber in sustainable solutions is emphasized in this study. BP fiber is lightweight, biodegradable, and inexpensive to recycle, among its many other environmental advantages. This study explores the effects of potassium permanganate ($KMnO_4$) treatment on BP (banana pseudo-stem) fiber, examining both its chemical and physical characteristics. The findings highlight the favorable attributes of BP fiber, including its low density (1.40 g/cc) and high cellulose content (59.4%), which promote compatibility with resins and matrices. XRD analysis reveals notable crystalline behavior, characterized by a high crystallinity index (83.47%) and large crystallite size (6.4 nm). A comparison between treated and untreated fibers reveals significant improvements in mechanical properties for the former. Specifically, treated fibers exhibit higher tensile strength (198 MPa) and Young's modulus (4.40 GPa) compared to untreated fibers (tensile strength: 92 MPa, tensile modulus: 2.16 GPa) [111]. **Tab. 3** and **Tab. 4** describe about effects, advantages and disadvantages of physical and chemical treatments respectively.

Physical treatments are generally eco-friendly and do not involve chemicals, but may require specialized equipment and have limited effects on fiber properties. UV and corona treatments are effective for surface modification but may not penetrate deeply into the fiber. Thermal treatment improves thermal stability but consumes significant energy. Chemical treatments are more effective in modifying fiber properties but often involve toxic chemicals and complex processes. Alkaline treatment is widely used due to its low cost and effectiveness, but it generates chemical waste. Silane and enzyme treatments are environmentally friendly but expensive. Acetylation and benzoylation improve fiber-matrix bonding but require careful handling of toxic reagents [121-124].

Table 5. Comparison of mechanical properties of biofiber and synthetic fiber reinforced composites

Fiber Type	Matrix	Tensile Strength (MPa)	Flexural Strength (MPa)	Young's Modulus (GPa)	Density (g/cm³)	References
Flax	PP	50–100	70–120	5–10	1.2–1.4	[119,125]
Jute	PP	60–100	80–130	6–10	1.3–1.5	[29,126]
Bamboo	Epoxy	100–200	150–250	10–20	1.1–1.3	[127,128]
Ramie	PP	70–120	90–150	8–12	1.2–1.4	[30,31,129]
Glass	PP	1000–2000	300–600	40–70	1.8–2.0	[130]
Carbon	Epoxy	1500–3500	600–1200	70–200	1.5–1.7	[131,132]
Aramid	Polyester	2000–3000	500–800	60–120	1.4–1.5	[133]
Basalt	Epoxy	800–1500	400–600	30–50	1.7–1.9	[134,135]

Tab. 5 provides a comparative overview of the mechanical properties of natural and synthetic fiber composites, highlighting their tensile strength, flexural strength, Young's modulus, and density. Natural fibers such as flax, jute, bamboo, and ramie exhibit moderate mechanical properties, with tensile strengths ranging from 50 to 200 MPa, flexural strengths from 70 to 250 MPa, and Young's moduli between 5 and 20 GPa. These fibers are lightweight, with densities typically between 1.1 and 1.5 g/cm³, making them suitable for applications where weight reduction is critical. In contrast, synthetic fibers like glass, carbon, aramid, and basalt demonstrate significantly higher performance, with tensile strengths ranging from 800 to 3500 MPa, flexural strengths from 300 to 1200 MPa, and Young's moduli between 30 and 200 GPa. While synthetic fibers dominate high-performance applications due to their exceptional strength and stiffness, natural fibers offer a sustainable and eco-friendly alternative for lightweight, low-to-moderate load-bearing applications. The table underscores the trade-offs between performance and sustainability, providing a clear comparison for selecting appropriate materials based on specific engineering requirements.

4.3 Fire resistance behavior of biocomposites

The fire resistance behavior of biocomposites is a critical factor in their application in civil engineering and construction, where safety and durability are paramount. Biofibers, being organic materials, are inherently flammable due to their cellulose, hemicellulose, and lignin content. However, the fire resistance of biocomposites can be significantly improved through various strategies, such as the incorporation of flame retardants, surface treatments, and the use of fire-resistant matrices. For instance, the addition of inorganic flame retardants like aluminum trihydroxide (ATH) or magnesium hydroxide ($Mg(OH)_2$) can enhance the thermal stability of biocomposites by releasing water vapor during decomposition, which dilutes flammable gases and cools the material [136]. Additionally, the use of fire-resistant polymer matrices, such as epoxy or phenolic resins, further improves the fire performance of biocomposites [137]. Despite these advancements, challenges remain in balancing fire resistance with mechanical properties and environmental sustainability. Recent studies have explored the use of nanotechnology, such as nano-clays or carbon nanotubes, to enhance fire resistance without compromising the eco-friendly nature of biocomposites. For example, the incorporation of nano-clays has been shown to form a protective char layer during combustion, which acts as a barrier to heat and oxygen [138]. Overall, the development of fire-resistant biocomposites is an active area of research, with significant potential for applications in sustainable construction and infrastructure.

4.4 Concrete-Biofiber Adhesion

The adhesion between biofibers and concrete is a critical factor influencing the mechanical performance and durability of biofiber-reinforced composites. Biofibers, being hydrophilic in nature, often exhibit poor interfacial bonding with the hydrophobic cement matrix, leading to reduced load transfer efficiency and premature failure. To address this, surface treatments such as alkali treatment, silane coupling, and acetylation have been widely studied to enhance fiber-matrix adhesion. For instance, Xie et al. [139] demonstrated that alkali treatment of rice straw fibers significantly improved their adhesion to cement matrices by removing non-cellulosic components like lignin and hemicellulose, thereby enhancing mechanical properties. Similarly, Toledo Filho et al. [140] highlighted that chemical treatments, such as sodium hydroxide (NaOH) immersion, reduced the hydrophilic nature of sisal and coir fibers, improving their compatibility with cementitious matrices. Additionally, de Klerk et al. [39] proposed a combined alkaline and acetylation treatment to mitigate the degradation of sisal fibers in alkaline environments, further enhancing their long-term performance in concrete. These studies underscore the importance of surface modifications in optimizing the interfacial bonding between biofibers and concrete, which is essential for the development of durable and high-performance biofiber-reinforced composites in civil engineering applications.

4.5 Biofiber Usage and Environmental Sustainability

The use of biofibers in civil engineering contributes significantly to environmental sustainability by reducing reliance on non-renewable resources and minimizing carbon emissions. Biofibers, derived from renewable sources such as plants (e.g., jute, flax, hemp) and agricultural waste (e.g., coir, banana fibers), are biodegradable and have a lower environmental impact compared to synthetic fibers like glass or carbon [29]. The production of biofibers typically requires less energy and generates fewer greenhouse gases, making them a greener alternative for sustainable construction. For example, the cultivation of jute and hemp not only provides raw materials but also contributes to carbon sequestration, further reducing the carbon footprint of biofiber-based composites [141]. Additionally, the use of biofibers in composites can help reduce waste by utilizing agricultural by-products that would otherwise be discarded. However, challenges such as moisture absorption, flammability, and variability in fiber properties must be addressed through treatments and modifications to ensure long-term performance and durability. Despite these challenges, the integration of biofibers into civil engineering applications aligns with global sustainability goals, offering a promising pathway toward eco-friendly and resource-efficient construction practices [119].

5. Applications of biofiber in civil engineering applications

The growing emphasis on sustainability in civil engineering has spurred significant interest in the use of biofibers as eco-friendly alternatives to conventional construction materials. As highlighted in the introduction, the extraction and processing of traditional materials like steel and concrete are energy-intensive and contribute to environmental degradation. In contrast, biofibers, derived from renewable sources, offer a sustainable solution with the potential to reduce the carbon footprint of civil engineering projects.

5.1 Selection Criteria of Biofibers in Civil Engineering

The selection of biofibers for civil engineering applications is guided by several key criteria, including mechanical properties, cost-effectiveness, availability, and environmental impact. Biofibers such as jute, flax, and hemp are often preferred due to their high tensile strength, stiffness, and compatibility with polymer matrices, making them suitable for reinforcement in composites used in structural applications like bridge decking and building panels [29]. Cost and availability are also critical factors, as biofibers like coir and sisal are widely available in tropical regions and are relatively inexpensive compared to synthetic fibers. Additionally, the chemical composition of biofibers, particularly their cellulose content, plays a decisive role in determining their mechanical performance and durability. For instance, fibers with higher cellulose content, such as flax and ramie, exhibit superior strength and stiffness, making them ideal for high-performance applications [112]. Furthermore, the ease of processing and compatibility with surface treatments (e.g., alkali, silane, or acetylation) are considered to enhance fiber-matrix adhesion and overall composite performance. Finally, the environmental sustainability of biofibers, including their biodegradability and low carbon footprint, is a significant advantage over synthetic alternatives, aligning with the growing demand for eco-friendly construction materials [117]. Biofibers have found applications across various domains of civil engineering, including structural engineering, geotechnical engineering, transportation engineering, and environmental engineering. Their lightweight, renewable, and biodegradable nature makes them ideal for sustainable infrastructure development. The following subsections provide detailed insights into the specific applications of biofibers in each of these domains.

5.2 Structural engineering

Biocomposites hold promise for diverse structural applications such as bridges, buildings, and infrastructure due to their potential for providing high strength and stiffness at a reduced weight. This characteristic makes them well-suited for lightweight structural elements. Nonetheless, their utilization in such applications remains constrained by considerations of mechanical properties and durability, necessitating thorough evaluation to ensure safety and longevity [142,143]. The study investigated the feasibility of using banana fiber rebars (12–18 mm in diameter) as reinforcement in concrete beams. These rebars were derived from banana waste produced in Egypt and were used in 1 m-long concrete beams with reinforcement ratios ranging from 0.7% to 1.5%. The performance of these reinforced concrete beams was analyzed both numerically and experimentally. Furthermore, a comparative analysis was conducted on concrete beams reinforced with banana fiber bars, a hybrid of banana and glass fiber bars, and conventional steel bars. The results indicated that the inclusion of banana fiber reinforcement enhanced the beam’s strength by 25% compared to a plain concrete beam [144].

Structural engineering plays a pivotal role in the design and construction of buildings, bridges, and other infrastructure critical to modern society's functioning. Through careful planning, analysis, and implementation, structural engineers contribute to the creation of robust and resilient structures, incorporating innovative materials like biocomposites while upholding stringent safety and performance standards [145,146]. The field of structural engineering encompasses a wide range of applications, each addressing specific challenges and requirements. This article explores some of the key applications in structural engineering and their significance in creating safe, efficient, and sustainable structures.

5.3 Building construction

One of the most fundamental applications of structural engineering is in building construction. Structural engineers collaborate with architects and other professionals to design and analyze the structural systems of various types of buildings, such as residential, commercial, institutional, and industrial structures. Structural engineers are tasked with ensuring that buildings are capable of enduring diverse loads, including dead loads (the permanent weight of the structure), live loads (occupants and movable items), and environmental loads (such as wind, earthquake, and snow). The goal is to create durable, stable, and aesthetically pleasing structures that meet safety standards and local building codes [147]. **Fig. 6** presents a prototype of a newly developed panel designed for prefabricated buildings. The panel construction incorporates a lightweight lime-based biofiber composite, which replaces the inner layer. The full-sized sandwich hemp concrete wall panel consists of dense magnesium oxychloride cement (MOC)-hemp composite slabs on the outer sides, with a lightweight lime-hemp composite filling the internal layer. This system offers significant potential for practical applications in construction, as the lime composite is more accessible, cost-effective, and provides excellent vapor-buffering capacity [148].

Fig. 6. Sandwich hemp concrete wall full-sized panel: dense MOC-hemp composite slabs on the outer sides; light-weight lime-hemp composite to be filled in internal layer (reproduced under the creative commons attribution license) [148]

Experimental research demonstrated that the thermal characteristics and behavior of a hemp-lime wall material closely resembled those of a commonly used lightweight concrete insulating material with a similar density [149]. Research investigations were carried out to assess the impact of date palm fibers (DPF) sourced from the Biskra oasis in Algeria (Phoenix dactylifera L.) on the mechanical properties, water absorption capacity, and thermal conductivity of gypsum-based composites. This study aimed to assess the effectiveness of hemp fiber (HF) and flax fiber (FF) as dispersed reinforcement in concrete and to evaluate their comparative performance and practical applicability in the construction industry. Prior to use, HF and FF were treated with a NaOH solution and stearic acid to enhance their resistance to the aggressive alkaline environment of concrete. The incorporation of HF and FF helped mitigate the brittle failure of concrete, ensuring that during the destruction process, concrete cubes did not shatter into multiple fragments but instead maintained structural integrity with a network of cracks (**Fig. 7b** and **Fig. 8b**). This behavior is attributed to HF and FF, which provide additional binding within the cement matrix [150].

These findings revealed that this novel biocomposite exhibits robust mechanical and thermal characteristics, rendering it suitable for applications as thermal insulation materials [151]. The thermomechanical characterization of composite materials composed of Date Palm Fibers mesh (DPF) and mortar is the focus of this investigation. The findings demonstrate that the thermomechanical characteristics of the composite material are positively impacted by the DPF mesh. In fact, it makes mortar lighter, raises the heat diffusion damping rate, and greatly improves the mortar's insulating ability [152]. The laboratory findings of an optimized flax fiber reinforced concrete (FFRC) are presented in this research. The mechanical outcomes are meant to serve as an example of how natural fiber reinforced concretes, or NFRCs, might be used to construct structures in underdeveloped nations where there are abundant sources of cellulose fibers and small-scale industrial facilities to handle them. Enhancing the shear strength of structural elements made of flax fiber reinforced concrete presents opportunities for cost-effective methods of reducing building materials, particularly steel. According to the investigation, hemp may be utilized as a building material (hemp bast and concrete mix) as well as for the production of insulating panels (hemp fibers alone). This biocomposite has demonstrated moderate mechanical resilience and strong insulating qualities [153]. In order to lower building material costs, minimize pollution, and enhance concrete quality, bamboo fiber was substituted for aggregate. For every percentage of bamboo fiber used to substitute aggregate in concrete—0%, 5%, 12.5%, 10%, 12.5%, 15%, and 17.5%—four cube examples were produced. The results demonstrated that replacing 5% of the concrete with bamboo fiber produced the best strength (27.77 N/mm2), with the conventional concrete showing a strength decrease of just around 2.38%. Based on the findings, the ideal proportion of bamboo fiber to substitute aggregate in concrete is indicated to be 5% in bamboo fiber concrete [154].

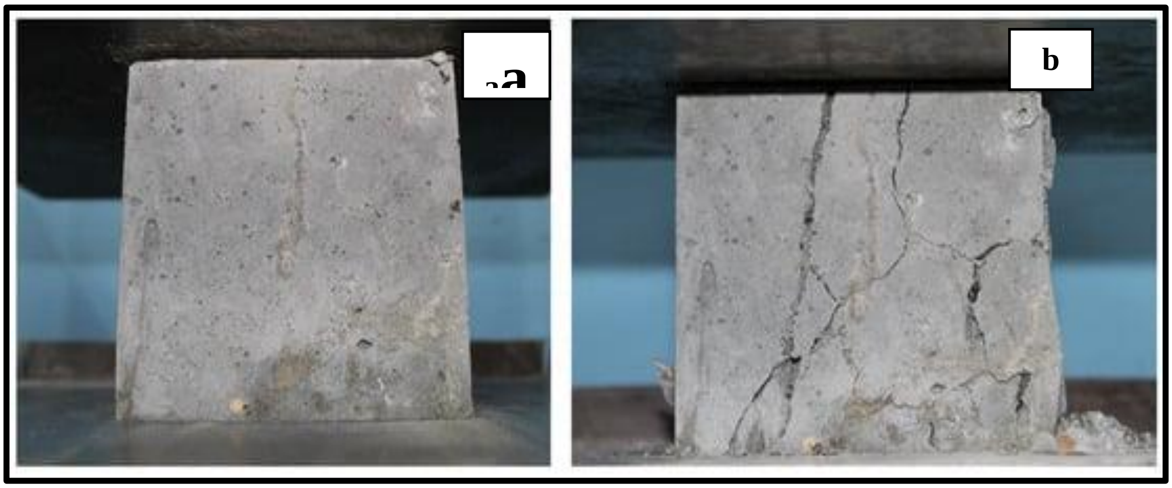

Fig 7. Image showing cube specimens of concrete with HF during compression testing: (**a**) before failure; (**b**) after failure (reproduced under the creative commons attribution license) [150]

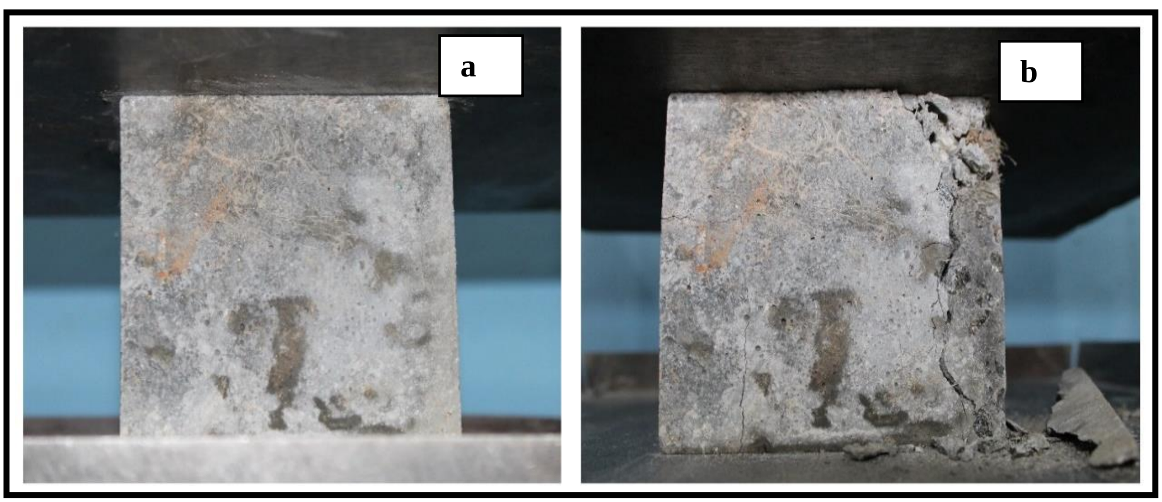

Fig. 8. Image showing the cubic concrete samples with FF during compression examination **(a)** before failure & **(b)** after failure (reproduced under the creative commons attribution license) [150]

In terms of concrete strength, bamboo fibers demonstrate promising outcomes and mitigate inherent brittleness. Research findings indicate that, akin to other fiber types such as steel fibers, the incorporation of bamboo fibers reduces the workability of concrete. Nevertheless, the inclusion of bamboo fibers also enhances the compressive strength of concrete. Furthermore, bamboo fibers augment the tensile strain capacity, thereby mitigating undesired brittle failure. The assessment underscores an optimal fiber-to-cement ratio ranging from 1 to 1.5% by weight [155]. This study examines a biocomposite building material composed of hemp shives mixed with a lime binder, specifically in the context of an arid environment.

Hemp-lime test cells after removal of formwork and before application of exterior finish and installation of roof. The physical properties and thermal performance of hemp-lime are evaluated through laboratory tests, temperature measurements in test cells, and thermal simulations, comparing them with conventional building materials. The findings indicate that hemp-lime offers a significant advantage over traditional materials, not only in terms of lower embodied energy but also in reducing net CO_2 emissions throughout the entire life cycle of a typical building [156].

Bamboo, a rapidly renewable resource, grows abundantly in both tropical and non-tropical regions worldwide, with particularly rich biodiversity in the Asia-Pacific region. In concrete construction, bamboo can serve as an alternative to steel reinforcement. Bamboo-reinforced concrete (BRC) beams exhibit superior performance under shear and flexural loads compared to conventional concrete beams.

A good substitute for current synthetic fiber-reinforced concrete, such steel and glass fibers, is bamboo fiber-reinforced concrete (BFRC). The utilization of current and upcoming research discoveries to develop standardized testing protocols and structural criteria will open the door to bamboo's widespread application in the building sector [157]. Fibers are commonly employed to reinforce concrete and mitigate crack formation. Concrete mixes typically incorporate various fibers to attain the desired strength and resistance. In order to understand the mechanical behavior of bamboo fiber-reinforced concrete members, researchers have conducted studies. Overall, the study has revealed that the addition of bamboo fibers to concrete enhances its strength, hardness, torsional resistance, and tensile stress. However, further research is necessary to ascertain the durability of bamboo fiber-reinforced concrete [158]. There is a lot of study on the toughening effects of cement concrete made from bamboo, but not enough on its durability. The two primary issues with cement concrete based on bamboo are inadequate durability and weak interfacial bonding. More research is required to be done to determine how to increase the mechanical and long-lasting qualities of cement concrete made from bamboo.

Biofibers are used to reinforce concrete, enhance the thermal insulation of building materials, and reduce the overall weight of structures. For example, hemp-lime composites have been shown to exhibit thermal properties comparable to conventional insulating materials, making them suitable for energy-efficient buildings. Beyond buildings, biofibers are also being explored for use in bridges, as discussed in the next subsection.

5.4 Bridge Engineering

Bridges stand as crucial components of infrastructure, fostering connectivity between communities and facilitating the seamless movement of goods and individuals. The intricate task of designing and analyzing these structures falls into the hands of structural engineers, who must carefully consider factors such as bridge type (e.g., beam, arch, suspension, cable-stayed), span length, soil conditions, and traffic loads. A paramount aspect of bridge engineering lies in the thoughtful selection of materials and construction methods to ensure the longevity and safety of these vital structures. In the contemporary landscape, architects and clients increasingly emphasize sustainability. Recent studies conducted in the Research conducted in the Netherlands has shown that footbridges built using Fiber-Reinforced Polymers (FRPs) have a smaller carbon footprint than footbridges built with more conventional materials like steel and concrete. It's crucial to remember that non-renewable resources still account for the bulk of FRPs. The present author is a researcher who is actively engaged in the study of biocomposites' application in load-bearing footbridges. This creative bridge demonstrates a sustainable approach to bridge building by using flax fibers, biobased resins, polylactic acid (PLA) foam, and natural cork in its construction [159].

The integration of natural fiber-reinforced composites in construction faces challenges due to the absence of standardized guidelines and building codes, uncertainties in static and dynamic performance post-production, and unknown long-term durability. To address these issues, a novel design approach is proposed, focusing on material properties and the underlying elastic strain limit. A mechanical model was developed and tested to validate the design assumptions. As a result, a 15-meter-span footbridge was constructed using flax fibers and a partially biobased resin. Following its production, a load test was conducted to evaluate its static performance. During its service life, strain threshold levels for bridge management are continuously monitored, with any exceedance of these values being recorded. This study provides a comprehensive framework for the successful application of natural fibers in footbridge construction, offering guidelines for material selection, design, production quality, and performance evaluation. Additionally, a periodic static test using four barrels at the center of the bridge (**Fig. 9**) will be conducted. This ongoing assessment aims to detect changes in the bridge's behavior and evaluate its load-carrying capacity by comparing strain values from periodic load tests with the initial loading phase [160].

Fig. 9. Static test with four barrels in the center (reproduced under the creative commons attribution license) [160]

The issue of progressive performance degradation due to steel-bar corrosion in reinforced concrete (RC) bridge decks has become increasingly critical. In response, fiber-reinforced polymer (FRP) composites have emerged as alternative structural materials to traditional RC, owing to their lightweight nature, high strength, and superior corrosion and fatigue resistance. However, it is essential to acknowledge that FRP composites have drawbacks, including high cost and potential environmental and health hazards. This article offers a comprehensive overview of various design methods and innovative research findings related to FRP bridge decks. The goal is to establish a foundation for the design of biocomposite bridge decks. The discussion addresses the challenge of insufficient mechanical properties of biocomposites when applied to bridge deck structures. Furthermore, advanced techniques for enhancing the performance of natural fiber composites are introduced, addressing the need for high-performance solutions in bridge construction [159]. Biofibers, particularly flax fibers, have been successfully used in the construction of footbridges, demonstrating their potential as sustainable alternatives to traditional materials like steel and concrete. These biocomposite bridges not only reduce the carbon footprint but also offer excellent mechanical performance. In addition to new construction, biofibers are also being used to retrofit and rehabilitate existing structures, as highlighted in the next subsection.

Currently, research is being conducted on the application of biocomposites in load-bearing footbridge structures (**Fig. 10**). The bridge is constructed using flax fibers, biobased resins, polylactic acid (PLA) foam, and natural cork, aiming to develop a sustainable and structurally efficient alternative to conventional materials. The findings of this study will contribute to the design and fabrication of a fully load-bearing biocomposite footbridge, offering insights into its mechanical behavior, durability, and feasibility for broader structural applications [161].

Fig. 10. The opening of the flax fiber biocomposite footbridge in Eindhoven (reproduced under the creative commons attribution license) [161]

Fig. 11. Modular Bamboo Space-Frame Structure with Metallic Connectors

The image **(Fig.11)** depicts an experimental bamboo structure assembled with metallic connectors, demonstrating the integration of traditional natural materials with modern engineering techniques. Bamboo, known for its high strength-to-weight ratio and sustainability, is used here as the primary structural element, while the metal joints provide reliable connections to overcome bamboo's natural limitations in joint formation. The arrangement resembles a space-frame system, where inclined and intersecting members distribute loads efficiently through axial compression and triangulation, ensuring stability and strength. Such prototypes are often explored in research and educational institutions to test the feasibility of bamboo-based modular construction for applications like temporary shelters, lightweight pavilions, and sustainable housing solutions, highlighting the potential of bamboo as an eco-friendly alternative to conventional construction materials.

5.5 Structural Retrofitting and Rehabilitation:

As existing infrastructure ages or faces new requirements, structural engineers are often tasked with retrofitting and rehabilitating structures to meet modern safety and performance standards. Retrofitting involves strengthening existing structures to improve their resilience against seismic events or other extreme conditions. Rehabilitation, on the other hand, addresses deterioration, corrosion, or other damages, restoring the structure's functionality and extending its service life [162].

In reinforcing existing reinforced concrete (RC) elements, natural fibers can be employed in externally bonded (EB) fiber-reinforced polymer (FRP) strips. Reinforced concrete (RC) wall specimens reinforced with fiber-reinforced polymer (FFRP) exhibited notable improvements in ductility, approximately 30%, and strength enhancements of up to 150% [163,164]. Moreover, experimental results demonstrate that walls reinforced with FFRP (flax-FRP) disperse energy more efficiently compared to walls strengthened with CFRP (carbon-FRP) [165]. Green retrofitting using green fiber-reinforced polymer (FRP) materials composed of natural biofibers such as sisal can contribute to sustainable development. In a study, reinforced concrete (RC) beams prone to shear failure were retrofitted with sisal FRP composites, derived from organic fibers sourced from non-fossil fuels. The objective was to evaluate the advantages of natural sisal FRP retrofitting over carbon and glass FRP retrofitting methods. Analysis of failure modes in the modified RC beams revealed that sisal fiber-reinforced polymer (FRP) performed comparably to carbon and glass FRP [166,167]. Unlike glass FRP, which exhibited sudden debonding, and carbon FRP, which demonstrated abrupt FRP rupture, sisal FRP facilitated ductile beam failure with noticeable warnings and significant deflections [168]. The necessity for environmental protection on a worldwide scale and new laws have spurred researchers to create more ecologically friendly fiber-reinforced polymers (FRP) to replace synthetic FRP [169]. The components that researchers in the study area have given the greatest thought to are concrete columns and RC beams. The most popular polymer is epoxy, while flax and jute are the main fibers employed in the development of biobased FRPs for reinforced concrete buildings [170,171]. Natural fiber-reinforced polymers (FRPs) are increasingly being used to strengthen and repair aging infrastructure. For instance, flax-FRP composites have been shown to improve the ductility and strength of reinforced concrete walls, offering a sustainable solution for structural rehabilitation. The use of biofibers is not limited to land-based structures; they are also being explored for offshore applications, as discussed next.

5.6 Offshore Structures

In recent years, green composites have drawn more attention as a sustainable substitute for conventional materials used in maritime constructions. The state of the art in green composites was examined in this review, which offers a range of biobased materials with promising mechanical and environmental properties that might make them appropriate for use in maritime applications. The majority of green composites are hydrophilic, which causes a reduction in mechanical strength when exposed to the maritime environment, and their mechanical qualities are still very different from those of high-performance synthetic FRPs. Furthermore, a thorough examination of the environmental impact is necessary for the responsible construction of structures made of green composite materials [172].

This review paper critically examines the long-term durability of biocomposites tailored for maritime conditions, along with insights from existing literature. The study delves into the effects of abiotic factors on the physical, mechanical, and thermal properties of biocomposites, including hygrothermal exposures such as temperature variations and UV light. Over the past decade, there has been significant attention on the use of sustainable materials derived from renewable resources in the maritime industry. However, addressing the limitations of these materials can be challenging despite their numerous appealing properties. These challenges include poorer mechanical performance compared to well-established glass fiber composites, which are already widely used in maritime applications, as well as limited long-term durability when exposed to harsh outdoor conditions such as temperature fluctuations, saltwater aging, mechanical loads, and UV radiation [173]. In contrast to synthetic fibers commonly utilized in the wind energy industry, our study focused on investigating the elastic behavior of a biocomposite composed of Alfa fibers and a polymer reinforced with carbon nanotubes (CNT) and graphene nanoplatelets (GNP). To assess the effects of aspect ratio, volume fraction, and agglomeration of the nanofillers on the effective mechanical properties of the polymer biocomposite containing randomly distributed CNTs and GNPs, we employed a multi-stage homogenization approach. The study comprised two main phases: firstly, evaluating the properties of the reinforced polymers using CNTs/GNPs, and secondly, incorporating various natural and manmade unidirectionally oriented fibers into the reinforced polymers. It was observed that agglomeration significantly impacted the mechanical properties of the composites [174].

While biofibers show promise for offshore applications, their performance in harsh marine environments remains a challenge. Research is ongoing to improve their performance. The next subsection explores the use of biofibers in geotechnical engineering.durability and mechanical properties of biocomposites for use in maritime structures.

5.7 Geotechnical Engineering

Geotechnical engineering is essential in the planning and development of civil infrastructure. Recently, there has been a notable interest in utilizing biocomposites in geotechnical applications owing to their sustainable characteristics and favorable mechanical properties. These biocomposites, comprising natural fibers and a biodegradable matrix, present an attractive alternative to conventional geotechnical materials. This article explores the advancements, applications, and challenges associated with the use of biocomposites in geotechnical engineering. Biocomposites exhibit several advantages that make them suitable for geotechnical applications [175]. First, they are renewable and biodegradable, reducing the environmental impact associated with conventional materials. Biocomposites also possess good mechanical properties, including high tensile strength, stiffness, and durability. Their lightweight nature simplifies transportation and installation processes, making them cost-effective alternatives. Additionally, the natural fibers in biocomposites enhance soil-structure interaction and contribute to improved sustainability in geotechnical projects.

Geosynthetics have been widely utilized in low-volume roads (LVRs); however, their high costs and non-biodegradability present significant challenges for budget-constrained LVR development and environmental sustainability. As a viable alternative, natural geotextiles made from coconut coir have gained attention due to their cost-effectiveness and eco-friendly nature. This study evaluates the suitability of coir geotextiles (CGTs) in LVRs, assessing their performance, economic feasibility, and environmental impact. The inclusion of CGTs enhanced road performance by increasing the subgrade modulus by 37–46%. As a result, the required aggregate layer thickness was reduced by 17.5–23.5% compared to unreinforced sections, leading to cost savings of 15.5–17.3% and a reduction in global warming potential by 15.0–21.0%. These findings demonstrate that coir geotextiles offer a sustainable alternative to geosynthetics in LVR applications, providing comparable performance while utilizing renewable and biodegradable resources [176].

Researchers have optimized the remediation of expansive clay by adding proportionate quantities of waste renewable wool-banana (WB) fiber composites. This addition aims to enhance the elastoplastic strain

($\mathcal{E}_{EP}$), peak strength (Sp), resilient modulus (MR), and California bearing ratio (CBR) of expansive clays. The findings demonstrate that incorporating appropriate amounts of waste renewable wool-banana (WB) fiber composites into expansive clay has improved its elastoplastic strain ($\mathcal{E}_{EP}$), peak strength (Sp), resilient modulus (MR), and California bearing ratio (CBR). The use of waste and recycled materials as a more environmentally friendly and sustainable method of soil reinforcement has been suggested by geotechnical and geoenvironmental researchers in response to the observed changes in climate over the past few decades and the unchecked release of greenhouse gases. Natural fibers are a viable option due to their cost-effectiveness and widespread availability, often obtained as waste from various agro-industrial operations. Sawdust, a by-product of wood manufacturing, possesses a rough texture that can substantially enhance the soil's bearing capacity and shearing strength. This enhancement is attributed to the high friction generated between the fiber and the matrix [177]. In geotechnical engineering, lightweight geomaterials have found extensive use as seismic dampers. One such material, lightweight sand-mycelium soil (LSMS), has been introduced. LSMS is a biobased lightweight geomaterial composed of hyphae, substrate material (such as wheat bran), and host soil. Due to its lightweight nature, LSMS exhibits dynamic properties that suggest its potential utility as an earthquake buffer. Traditional methods of stabilizing soil require the use of additions like cement and lime. However, these techniques pollute the environment significantly and consume a lot of energy. Bioadditives have gained attention recently as ecologically acceptable, economical, and sustainable development substitutes for chemical stabilizers in geo-environmental applications. These methods use biochemical processes to stabilize soil particles, such as biocementing, bioclogging, biocoating, and bioencapsulation. The purpose of this study is to investigate how the kind and quantity of biostabilizers affect the geotechnical properties of soil for soil stabilization [178]. Jute fiber (JF) and xanthan gum (XG) were used to stabilize the dredged soil from the Yellow River. Uniaxial compression and splitting tension experiments were used to examine the mechanical behavior of solidified dredging soil (SDS) at varying fiber lengths, XG and JF concentrations. Microanalysis reveals that the network structure created by JF with soil particles and the cementation of XG itself were the primary factors in the improvement of the strength of SDS samples. Dredged soil reinforced with XG and JF has superior mechanical performance and holds significant application potential [179]. This study examines how a unique zein biopolymer binder cements soil over sandy surfaces. Various concentrations of zein biopolymer, ranging from 0 to 5%, are combined with soil specimens. The findings demonstrate that when curing times and biopolymer contents increase, treated soils' compressive strength and elastic modulus consistently rise [180]. Natural fibers have become more and more popular as an environmentally acceptable substitute for soil reinforcement in a range of building applications in recent years. The use of fibers in soil reinforcement has several technical advantages, such as lowering heat conductivity and building material weight, brittleness of the soil, and the prevention of tensile fractures.

However, the primary benefits of using wool fibers rather than polypropylene in the production of construction materials are their reduced cost, reduced environmental effect, enhanced thermal behavior, and decreased density [181]. Coir deteriorates differently depending on the embedment medium and climate; after six months in clay, it still retains 80% of its tensile strength. Nowadays, a variety of features of coir geo-textiles are accessible, making them cost-effective for use as temporary reinforcement [182]. Due to its higher coefficient of friction compared to synthetic fibers, coir fiber exhibits a more robust response. For instance, research findings suggest that coir fiber (47.50%) enhances the resilient modulus or soil strength to a greater extent than synthetic fiber (40.0%) [183].

Ravishankar and Raghavan confirmed that in lateritic soils stabilized with coir, the addition of coir causes a decrease in the maximum dry density (MDD) of the soil, while an increase in the percentage of coir enhances the soil's optimum moisture content (OMC). Up to 1% more coir in the composite soil resulted in an increase in compressive strength; however, as coir amount increases, the values decrease. As the proportion of coir grows, so does the percentage of water absorption. As the amount of coir in the soil rises, the tensile strength of the soil reinforced with coir (oven dry samples) also increases [183,184]. The ductility behavior of black cotton soil demonstrates improvements both before and after failure when treated with 4% lime and reinforced with coir fiber. To effectively reinforce the black cotton soil, an optimal fiber content of 1% by weight, along with an aspect ratio of 20, was recommended [185]. In their study, Prabakar and Siridihar incorporated sisal fibers of four different lengths—10, 15, 20, and 25 mm—into the raw soil at varying weights of 0.25%, 0.5%, 0.75%, and 1%. They observed that the addition of sisal fibers led to a reduction in the soil's dry density. As the length and content of the fibers increased, the soil's dry density decreased accordingly. Additionally, they found that the shear stress exhibited a nonlinear increase with fiber length up to 20 mm and beyond, after which it decreased with length.. Shear strength is further enhanced by the fiber content %. However, the shear stress decreases when the fiber content increases over 0.75% [186]. According to Jamellodin et al., the addition of palm fibers can substantially improve the shear strength parameters (Φ and C) as well as the failure deviator stress of soft soil. They observed that the fibers serve to interconnect individual and groups of particles, forming a cohesive matrix, thereby enhancing the soil's strength characteristics [187].

Aggarwal and Sharma reinforced soil with jute fibers of varying lengths (5–20 mm) and percentages (0.2–1.0%). Fibers were coated with bitumen to prevent microbial assault and deterioration. They concluded that whereas jute fiber raises OMC, it decreases MDD. A 10 mm long and 0.8% jute fiber sample yields the maximum CBR value, which is more than 2.5 times higher than the CBR value of plain soil. Segetin et al. enhanced the ductility of soil-cement composite by incorporating flax fibers. To reinforce the interfacial connection between the fibers and the soil, they applied an enamel paint covering to the surface. The authors recommended a fiber length of 85 mm and a fiber content of 0.6% [188].

In geotechnical engineering, biofibers are used for soil stabilization, erosion control, and reinforcement. For example, coir fibers have been shown to enhance the bearing capacity and shear strength of soils, making them suitable for temporary reinforcement in construction projects. The versatility of biofibers extends to transportation engineering, where they are being used to improve the performance of pavements, as discussed in the next subsection.

5.8 Transportation engineering

5.7.1 Flexible pavement

The method described in this research, which has potential in the construction sector, particularly for pedestrian sidewalks, involves creating biocomposites from cement and tanned leather fibers. The potential of making Portland cement paving blocks out of leather fibers, or leather shavings, are discussed in the study. Using a method for making paving blocks, 10 m^2 of blocks were produced by substituting 1% of the weight in leather fibers for cement. Interest in utilizing agricultural wastes to produce sustainable composites for various applications has surged alongside increasing environmental consciousness and the imperative to utilize waste resources. The date palm tree, Phoenix dactylifera L., is notably the most prevalent crop in the Middle East and North Africa (MENA) region, generating an annual waste volume of 2.6–2.8 million tons, a substantial portion of which ends up in landfills. Several studies have explored the utilization of date palm fibers (DPF) in the fabrication of building materials employing diverse matrix systems. When DPF was employed as reinforcement in polymeric composites, incorporating fiber content of up to 60% led to enhancements in mechanical and physical characteristics [189]. Furthermore, Bellatrache et al. recently demonstrated the suitability of date palm fibers (DPF) for bitumen binder modification, citing several reasons. Given that bitumen melts at temperatures lower than 200 ℃ and DPF maintains thermal stability at production temperatures, it can be seamlessly incorporated into bituminous mixes without requiring special treatment or modification. Moreover, the addition of DPF was observed to enhance the thermomechanical behavior of the composite, rendering it more resistant to penetration and raising its softening point at service life temperatures. Additionally, DPF improved viscosity and resistance to rutting. This enhancement is attributed to the semi-amorphous fiber network serving as mechanical reinforcement for the bituminous matrix [190]. This study explores the potential application of natural fibers, particularly hemp fibers, as modifiers for asphalt paving materials. To assess their impact on fatigue behavior, the study investigates four different fiber lengths and three varying proportions. Test results reveal that fiber-modified asphalt mixes exhibit lower complex modulus and phase angle values compared to the control mixture. This suggests a decrease in stiffness but also an increase in flexibility of the modified mixes. Furthermore, the use of natural fibers reduces energy dissipation, as indicated by the study of ultrasonic measurements [191–193].

Jute stands out as a preferred raw material for asphalt overlay (A/O) fabric due to its commendable tensile qualities. This study delves into examining the thermal stability of jute during the asphalt overlaying process and assesses its compatibility with asphalt by subjecting jute-asphalt composites to mechanical and hydraulic stresses. The modulus of the jute-asphalt composite notably increased following a 6-month hydro treatment. Results indicate that despite a 10% decline in jute strength under asphalt overlaying conditions, the overall tensile behavior of the jute fabric–asphalt composite material surpasses that of pure jute fabric, particularly under biological and prolonged hygral loading conditions. This robust interface between jute and asphalt stems from their physical and chemical bonds. Additionally, the study highlights asphalt's protective role against the biodegradation of jute, underscoring the usefulness of jute as a material for asphalt overlays [194]. The escalation in traffic loads, characterized by increased axle counts and high tire pressure from heavy vehicles, has amplified pavement distress associated with traffic-induced wear. To combat this challenge, one approach involves modifying asphalt binders to augment pavement performance. This paper investigates the utilization of natural fibers and their composites in modifying asphalt concrete. The review encompasses various natural fibers (e.g., coir, sisal, hemp, jute, palm, and flax) as well as synthetic fibers (including PP, PE, nylon, glass, and steel) employed in asphalt concrete modification. Special emphasis is placed on natural fibers such as jute, sisal, coir, and hemp due to their potential to enhance the mechanical properties of bituminous mixtures. The literature surveyed suggests that natural fibers can effectively substitute synthetic fibers in stone matrix asphalt (SMA) mixtures, primarily owing to their strong adhesion with asphalt. Furthermore, it is observed that reinforcing with natural fibers not only enhances fatigue life but also bolsters stability, thereby exhibiting the capacity to fortify structural resistance against distress induced by traffic loads in flexible pavement [195].

The escalating demands of traffic necessitate the construction of pavements that boast enhanced durability and safety for users. A prevalent solution in developed nations involves utilizing Stone Matrix Asphalt (SMA) with a discontinuous gradation. This type of mixture requires a higher asphalt content to safeguard the pavement from damage by forming a thicker film around the aggregate, thereby resisting oxidation, moisture penetration, and preventing cracking and aggregate separation. To counter the increased asphalt content and potential drain down, fibers are incorporated. In this study, asphalt mixtures were formulated using four types of fibers: coconut, sisal, cellulose, and polyester. Mechanical assessments, including tensile strength and modulus of resilience, unveiled that blends containing natural fibers showcased remarkable resistance while effectively mitigating asphalt drain down issues. The drain down test findings highlighted the superior performance of asphalt mixtures incorporating natural fibers compared to those utilizing polyester and cellulose fibers, typically employed in discontinuous mixtures in Southern and Southeastern Brazil [196].

5.7.2 Rigid pavement

One of the main risks that concrete pavements face from temperature variations during the day is freeze-thaw. When building, certain precautions should be taken to shield concrete pavements from the effects of freezing and thawing. This study examines how various freeze-thaw cycles affect the mechanical and dynamic properties of plain and reinforced concrete using jute fibers. The results of using reinforced concrete with jute fibers appear to be favorable for applying stiff pavement in freeze-thaw situations [197]. Among natural fibers, coconut fiber (CF) offers the advantage of having the highest tenacity. Its cheap cost and wide availability make it more cost-effective for usage in concrete composites. The utilization of natural fibers can contribute to reducing the thickness of concrete roadways [198]. This study examines the mechanical properties of silica-fume plain concrete (S-PC) and silica-fume coconut fiber reinforced concrete (S-CFRC) incorporating varying silica-fume contents, namely 5%, 10%, 15%, and 20% by cement mass. These characteristics include energy absorption and toughness indices. With a 15% SF content, it is discovered that S-CFRC has mechanical characteristics that are typically better than those of S-PC. Therefore, S-CFRC's improved mechanical qualities make it more useful for reducing the thickness of concrete roadways. Concrete that has been roller-compacted (RCC) resembles regular concrete but has no slump [199,200].

The primary benefit of Roller Compacted Concrete Pavement (RCCP) over traditional concrete is its lower cost. Banana fiber is used as the natural fiber in this study. This work especially examines the viability of using banana fiber and nanosilica in the formulation of the RCCP. According to IS 519, compressive tests are performed on RCCP utilizing different Nano Silica compositions, including 0%, 0.25%, 0.5%, 0.75%, 1.0%, 1.25%, 1.50%, 1.75%, 2.0%, 2.25%, 2.50%, 2.75%, & 3.0%, as well as compositions of Banana Fiber, including 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%. According to the findings, banana fiber may make up to 1.5% and nanosilica can make up to 2% of the composition [201,202]. In this study, the effects of reinforcement fibers on the mechanical properties, chloride ion penetration properties, and abrasion resistance of roller-compacted latex-modified fiber-reinforced rapid-hardening-cement concrete (RCLMFRRHCC) were evaluated for emergency repair of concrete pavements. The reinforcement fibers examined included polyvinyl alcohol (PVA) and natural jute fibers (non-structural fibers), as well as macro synthetic fibers (structural fibers). Various tests, including abrasion resistance tests, impact resistance tests, splitting tensile strength, compressive strength, flexural strength, and chloride ion penetration characteristics, were conducted as part of the experiment [203,204].

Natural fibers are widely available worldwide, drawing interest from researchers in their possible application as building materials. It is imperative to investigate the structural integrity of cement concrete reinforced with various natural fibers. This study focuses on wheat straw and evaluates the structural stability of roads constructed with wheat straw reinforced cement concrete (WSRC). Results from the investigation demonstrate that the WSRC test section exhibited a load transfer efficiency 16% higher and an energy absorption capacity 34% greater than the controlled portion. Moreover, the structural performance of the WSRC road test section was found to be equivalent to that of the plain concrete road test section, despite having a design thickness 7% less [199,203,205]. This highlights the potential for creating cost-effective and sustainable concrete roadways through the utilization of natural fiber reinforcement. Pineapple stubble fibers from Costa Rican production waste were processed using low-cost methods (mechanical peeling, solar drying, and manual cutting) for use in asphalt mixtures. FTIR, TGA, and SEM analyses confirmed their suitability, enhancing stiffness and deformation resistance while reducing environmental impact by replacing synthetic fibers. The approach supports circular economy goals by creating jobs, promoting gender equity, and enabling technology transfer. This sustainable, scalable solution improves road material performance while repurposing agricultural waste [206].

Biofibers are increasingly being incorporated into flexible and rigid pavements to enhance their mechanical properties and resistance to environmental stressors. For instance, jute fibers have been used to modify asphalt binders, improving the fatigue life and stability of pavements. Biofibers are also making significant contributions to environmental engineering, particularly in wastewater treatment, as explored in the next subsection.

5.9 Environmental Engineering

Pollution and water shortage are major worldwide issues that call for creative solutions. In the field of water and wastewater treatment engineering, biocomposites—which are made of natural fibers and a biodegradable matrix—have gained recognition as sustainable materials. The uses, advantages, and difficulties of biocomposites in the treatment of water and wastewater are examined in this article. Furthermore, eco-friendly and biodegradable, biocomposites lessen the buildup of non-biodegradable elements in water treatment systems. Additionally, using biocomposites may lessen the carbon footprint that comes with using traditional materials, encouraging the development of more environmentally friendly techniques in water treatment [207,208].

Tab. 6 represents the summary of applications of biofibers in several domains of civil engineering.

Table 6. Summary of applications of biofibers in several domains of civil engineering

Structural Engineering	Building construction	• Biofibers can be used with lime, gypsum, and mortal to form building materials with good insulating properties • Biofibers can be used in concrete to increase shear strength of concrete which eventually reduces the overall steel requirement which ultimately is more economical • Biofibers can be used as a partial replacement of fine aggregate in concrete
	Bridge engineering	• Biofibers like flax fibers have been used successfully in the construction of bridge decks
	Structural Retrofitting and Rehabilitation	• Reinforced concrete (RC) wall specimens reinforced with fiber-reinforced polymer (FFRP) exhibited notable improvements in ductility and strength enhancements. • Unlike synthetic FRP, which exhibited sudden debonding and abrupt FRP rupture, biofiber-based FRP facilitated ductile beam failure with noticeable warnings and significant deflections
	Offshore Structures	• Despite numerous appealing properties of biofiber composites, their performance is poor in maritime applications because of exposure to harsh outdoor conditions such as temperature fluctuations, saltwater aging, mechanical loads, and UV radiation altogether.
Geotechnical engineering	Soil improvement	• remediation of expansive clay by adding proportionate quantities of waste renewable biobased fibers
	Soil strengthening	• Biofibers from industry waste can substantially enhance the soil's bearing capacity and shearing strength.
	Soil stabilization	• Biofibers can be used to stabilize dredged soil
	Geotextiles	• Bifiber-based geotextiles are cost-effective and can be used as a temporary reinforcement
Transportation Engineering	Flexible pavement	• Biofibers can be incorporated in bitumen mixes for binder modification. It decreases the stiffness but also increases the flexibility • Biofibers used in bituminous mixes not only increase the mechanical properties of the mixes but also enhance fatigue life and resistance against distress due to traffic loads.
	Rigid pavement	• Reinforced concrete with biobased fibers appears to be favorable for applying stiff pavement in freeze-thaw situations. • Biofibers reinforced RCC shows higher mechanical properties which is more useful for reducing the thickness of concrete roadways. • The structural performance of the biofiber based road test section was found to be equivalent to that of the plain concrete, despite having a design thickness of 7% less. This highlights the potential for creating cost-effective and sustainable concrete roadways through the utilization of natural fiber reinforcement.
Environmental engineering	Wastewater treatment	• Composites of chitosan and cotton fiber have been successfully developed to eliminate Au(III), Pb(II), Ni(II), Cd(II), Cu(II), and Hg(II) • Banana fibers can effectively remove nutrients and organic materials from kitchen wastewater. Banana trunk biofibers can serve as biosorbents for pollutant removal from kitchen wastewater • Jute fibers have been successfully used to treat effluent from seafood industry before safe disposal

Natural cellulosic fibers like cotton have several beneficial qualities, including comfort, softness, excellent strength and absorbency, and color preservation. Composites of chitosan and cotton fiber have been developed to eliminate Au(III), Pb(II), Ni(II), Cd(II), Cu(II), and Hg(II) [209,210]. This study investigates the efficacy of kitchen wastewater treatment systems in Malaysia and other developing nations, where the discharge of kitchen wastewater into the environment is a major cause of water pollution. It explores the use of inexpensive, natural banana trunk fibers (Musa Sapientum) as biofibers to remove contaminants such as COD, ammonia nitrogen, suspended particles, turbidity, color, and oil and grease from wastewater. The findings suggest that banana fibers can effectively remove nutrients and organic materials from kitchen wastewater. According to the study, banana trunk biofibers can serve as biosorbents for pollutant removal from kitchen wastewater. Among the pollutants, COD exhibited the highest removal rate, reaching 88% [205,211–220]. This optimal removal was achieved under specific conditions: pH 6, a biosorbent dosage of 2 g, a shaking speed of 150 rpm, and a contact time of 2 hours. The effluent from seafood processing comprises high levels of nitrogen and ammonia, which are essential for eutrophication to develop. In order to treat wastewater from seafood processing more efficiently than with traditional SBR, researchers have used jute fiber and activated sludge in a sequencing batch reactor (JF-SBR). The results of this study showed that treating seafood effluent for safe disposal can be accomplished with the JF-SBR [221]. In environmental engineering, biofibers are being used to develop biocomposite materials for water and wastewater treatment. For example, banana fibers have been shown to effectively remove organic pollutants from kitchen wastewater, offering a sustainable solution for water purification [222]. Plant biomass has emerged as a sustainable and cost-effective solution for wastewater treatment, capable of removing harmful organic and inorganic pollutants. Its renewable and biodegradable nature, along with its ability to be processed into nano-scaled cellulose, makes it highly effective in eliminating toxic contaminants from water. As industrial discharges, oil spills, and climate change worsen water pollution, researchers worldwide are exploring simple yet efficient methods to transform various plant-based biomass into high-performance water purifiers. This eco-friendly approach not only addresses pressing environmental challenges but also offers a practical alternative to conventional purification techniques, showcasing the potential of natural resources in tackling global water contamination issues [223]. A recent study evaluated six natural fibers—sisal, jute, hemp, coir, oil palm, and banana—as filter media for nitrate (NO_3^-) removal in rainwater harvesting. Coir fiber showed the highest adsorption capacity (10.3% NO_3^- removal) and total solids reduction (88%), followed by oil palm and sisal. Freundlich isotherm best described the adsorption process, with jute achieving equilibrium fastest (6 h). The results highlight coir as the most effective biodegradable filter medium for stormwater treatment [224].

6 Conclusions and future perspectives

The growing emphasis on sustainability in civil engineering has propelled biofibers into the spotlight as viable alternatives to conventional construction materials. This review article stands out due to its comprehensive and multidisciplinary approach to exploring the use of biofibers in civil engineering. Unlike many existing reviews that focus narrowly on specific applications or properties of biofibers, this article provides a holistic overview, covering structural, geotechnical, transportation, and environmental engineering domains. It not only discusses the mechanical and chemical properties of biofibers but also delves into surface modification techniques, which are crucial for enhancing their performance in composite materials. The inclusion of bibliometric analysis adds a unique dimension, offering insights into the global research trends and the geographical distribution of studies on biofibers. Furthermore, the article bridges the gap between laboratory research and practical applications by discussing real-world case studies, such as the use of flax fibers in bridge construction and hemp fibers in building materials. This integration of theoretical knowledge with practical applications, combined with a forward-looking perspective on sustainability, makes this review a valuable resource for researchers and practitioners aiming to adopt biofibers in civil engineering. Based on the review following recommendations can be made.

In structural engineering domain, future research should focus on improving the fire resistance and moisture absorption properties of biofiber composites to meet stringent building codes. Developing hybrid composites that combine biofibers with synthetic fibers or nanoparticles could enhance mechanical strength and durability. Additionally, more studies are needed to optimize the fiber-matrix interface to prevent delamination and improve load-bearing capacity in structural elements like beams and columns.

In the field of geotechnical engineering, researchers should explore the use of biofibers in soil stabilization and erosion control, particularly in regions prone to landslides or flooding. Investigating the long-term performance of biofiber-reinforced soils under cyclic loading and varying moisture conditions is crucial. Furthermore, the development of biodegradable geotextiles using biofibers could revolutionize temporary reinforcement applications in geotechnical projects.

In the area of flexible pavements, future work should focus on optimizing the proportion of biofibers in bituminous mixes to enhance fatigue life and resistance to rutting. For rigid pavements, research should investigate the use of biofibers in roller-compacted concrete (RCC) to improve crack resistance and reduce thickness, thereby lowering material costs. Additionally, the development of standardized testing protocols for biofiber-reinforced concrete is essential for its widespread adoption in road construction.

Future research in environmental engineering should explore the use of biofibers in wastewater treatment systems, particularly for the removal of heavy metals and organic pollutants. Developing biocomposite membranes with enhanced adsorption capacity and durability could significantly improve the efficiency of water treatment processes. Additionally, the integration of biofibers with advanced technologies like nanotechnology could lead to the development of high-performance filtration systems for industrial and municipal wastewater treatment.

While the article provides a thorough review of biofibers and their applications, it has some limitations. Firstly, the discussion on the long-term durability of biofiber-based composites, especially in harsh environmental conditions, is somewhat limited. For instance, the article does not extensively address the degradation mechanisms of biofibers when exposed to UV radiation, moisture, or microbial attack over extended periods. Secondly, the economic feasibility of using biofibers in large-scale civil engineering projects is not thoroughly explored. The cost comparison between biofiber composites and traditional materials like steel and concrete is only briefly mentioned, leaving a gap in understanding the financial viability of these sustainable alternatives. Lastly, the article could have included more detailed case studies or experimental data to support the claims made about the performance of biofiber composites in real-world applications, particularly in structural retrofitting and offshore engineering.

By addressing these specific areas, future research can overcome the current limitations and unlock the full potential of biofibers in civil engineering, paving the way for more sustainable and eco-friendly infrastructure development.

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The authors declare that they have no conflicts of interest to report regarding the present study.

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