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Review Article

## Towards sustainable concrete: reviewing the potential and challenges of plant fiber reinforcement with a life cycle case study using date palm fibers

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### Article Info

### Abstract

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This study explores the use of plant fibers as reinforcement in cementitious composites, with a focus on their potential to enhance concrete performance and the complex interactions between fibers and the cement matrix. Particular attention is given to the chemical and physical reactions that influence material durability and performance. The paper further reviews various approaches to improve fiber-cement interactions and the durability of cementitious composites. Including matrix modification through pozzolan additions and carbonation, as well as fiber-specific treatments, such as physical and chemical modifications or optimized production processes, all these approaches aim to enhance the performance of fiber-reinforced concrete. Additionally, a life cycle assessment case study was conducted, comparing the production of polypropylene fibers and date palm fibers, as well as the environmental performance of two types of concrete reinforced with these fibers. The results reveal that date palm fibers offer significant environmental advantages over polypropylene fibers. The production process of date palm fibers can reduce CO<sub>2</sub>-equivalent emissions by up to 57% compared to the same quantity of polypropylene fibers, while concrete reinforced with date palm fibers achieves a 2.36% reduction in global warming potential compared to concrete reinforced with polypropylene fibers.

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## 1. Introduction

In the construction field, cement and concrete stand as the primary materials used on a large scale, valued for their widespread availability, affordability, and adaptability [1,2]. However, their massive production contributes approximately 5% to 8% of global CO<sub>2</sub> emissions [3], making them a significant source of greenhouse gases. According to Ali et al. [4], incorporating industrial steel fibers into concrete raises its carbon footprint by approximately 50% for a volumetric fraction of 0.5% and by 90% for a volumetric fraction of 1%.

On the other hand, the management of agricultural residues remains largely inadequate, and in many countries a significant proportion is still disposed of through open burning, a practice that causes severe air pollution. In Indonesia [5], for example, it is estimated that around 45 million tons of crop residues are burned annually. This process releases mainly carbon dioxide (about 90 % of total emissions) and carbon monoxide (around 8 %), while the remainder consists of methane, sulfur dioxide, nitrogen oxides, ammonia, nitrous oxide, non-methane volatile organic compounds, and fine particulate matter. These emissions are estimated to account for approximately 12–14 % of the global warming potential associated with open burning of crop residues.

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In this regard, research on the integration of plant fibers into cementitious composites is advancing rapidly [6]. Derived from renewable resources, these natural fibers offer a dual promise: improving certain mechanical properties of concrete while reducing its environmental impact. They are generally classified by their chemical, physical, and mechanical properties [7], which vary not only between species but also within the same species depending on harvest time, origin, and processing conditions. Owing to these attributes, plant fibers represent a significant opportunity for developing sustainable and innovative construction materials, offering a viable pathway to reduce the construction sector's ecological footprint while meeting the growing demand for mechanical and environmental performance. A deeper understanding of fiber-matrix interactions and optimization strategies is essential to fully unlock their potential in real-world applications.

Plant fibers, such as sisal [8], bamboo [9], or jute [10], have demonstrated notable mechanical performance, particularly in enhancing crack resistance and improving the flexibility of cementitious composites. Additionally, they reduce the amount of cement required, directly contributing to lower CO<sub>2</sub> emissions. Moreover, their abundance, low cost, and biodegradability provide significant economic and environmental benefits [11]. By utilizing agricultural wastes or local resources, these fibers also promote a circular economy and help reduce unused agricultural waste. However, their incorporation into cementitious composites alters the material's properties in complex ways. The effects vary depending on the type of fibers, their length, volumetric fraction, and distribution within the cement matrix. Despite enhancing flexural strength and limiting cracking, their impact on compressive strength is lower compared to metallic or synthetic fibers. Furthermore, their hygroscopic nature (tendency to absorb water) can reduce cement hydration, thereby affecting the microstructure and overall mechanical properties of the concrete. Plant fibers also face limitations in terms of durability, including their degradation in the alkaline environments typical of cementitious matrices, low thermal resistance, and often insufficient interfacial bonding with cement. These factors restrict their use in demanding structural applications.

To address these challenges, a focused review is required to systematically evaluate the potential of plant fibers and to identify the main obstacles to their use in concrete reinforcement. Such a review should also outline practical strategies to overcome these limitations and enhance the performance and durability of fiber-reinforced concrete. This constitutes the objective of the first part of the present article. Although there is growing interest in incorporating plant fibers into cementitious composites, few studies have rigorously and comparatively assessed their environmental impact relative to commonly used synthetic fibers, such as polypropylene. In particular, the use of fibers derived from dead palm fronds of date palms, a locally available and underutilized natural resource, has not been the subject of any comprehensive environmental assessment within the context of fiber-reinforced concrete.

To address this gap and build on the insights from the preceding review, the second part of this paper presents a life cycle assessment (LCA) case study comparing concrete reinforced with date palm fibers to concrete reinforced with polypropylene fibers. This analysis provides a practical evaluation of the environmental performance of natural fiber-reinforced concrete, and demonstrates how it can be optimized, thereby complementing the technical review with empirical evidence.

## **2. Literature Review on Cementitious Composites Reinforced with Plant Fibers**

### **2.1 Potential of Plant Fibers in Cementitious Composites**

Studies have demonstrated that concrete made from biomass aggregates offers significant advantages, such as a reduction in the density of hardened concretes, which improves their lightness while maintaining optimal performance. This type of concrete can also reach the required strength to be used as structural concrete, as long as the biomass content is appropriately adjusted. Additionally, the use of biomass aggregates enhances flexural strength, ductility, and fracture energy. This material is also notable for its energy efficiency, providing better thermal insulation and effective sound absorption, contributing to energy savings, particularly during the winter season. These properties make it an attractive option for sustainable applications [12].

It is essential to acknowledge the limitations of plant fibers, including inconsistencies in fiber quality, production conditions, and variability in properties due to factors such as harvest location and timing, and sensitivity to environmental factors like humidity or ultraviolet exposure [7].

2.1.1 Mechanical Properties

Various studies have been conducted on different types of plant-based fibers, like banana [13], coconut [14], bamboo [9], sisal [8], jute [10], hemp [15], alfa [16], and date palm fibers [17], demonstrating their potential to improve the mechanical properties of concrete. The experimental conditions and mix designs are summarized in Table 1, while the corresponding results are presented in the graphs presented in Fig. 1, Fig. 2, and Fig. 3.

Table 1. The experimental parameters and mix designs of the reviewed studies

Reference	Fiber type	Length (mm)	Optimal content	Mix design (Kg/m <sup>3</sup> )		Age of cure (day)	
[8]	Sisal	NA*	1% by cement weight	Cement	500	28	
				Coarse aggregate	1015		
				Fine aggregate	723		
				Water	170.5		
				Superplasticizer	4.5		
[9]	Bamboo	20	1% by volume	Cement	440	28	
				Coarse aggregate	1141		
				Fine aggregate	605		
				Water	214		
				Water reducer	2.08		
[10]	Jute	10	0.1% by volume	Cement	372	28	
				Coarse aggregate	793		
				Fine aggregate	703		
				Water	186		
[13]	Banana	25-30	1% by volume	Cement	330	28	
				Coarse aggregate	1069		
				Fine aggregate	789		
				Water	165		
				Superplasticizer	1.65		
[14]	Coconut	75	0.5% by cement weight	Cement	346	28	
				Coarse aggregate	1115		
				Fine aggregate	687		
				Water	217		
[15]	Hemp	20	1% by cement weight	Cement	450	28	
				Coarse aggregate	1350		
				Water	225		
[16]	Alfa	12	1% by volume	Cement	350	28	
				Coarse aggregate	1207		
				Fine aggregate	605		
				Water	180		
[17]	Date palm	15-60	2% by volume	Cement	400	28	
				aggregate	982		
				Sand	750		
				Water	270		

\*NA: not available in the cited study

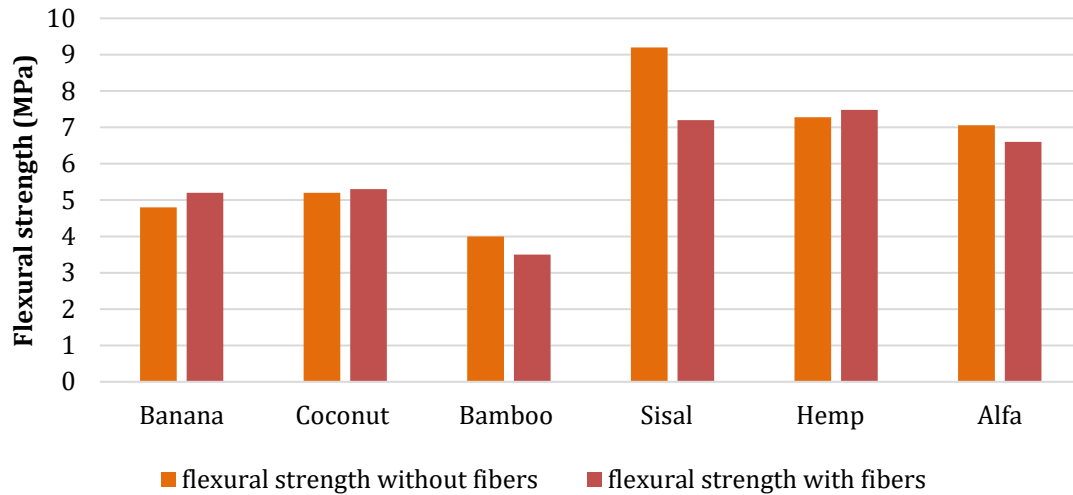


Fig. 1. Flexural strength of concrete at 28 days

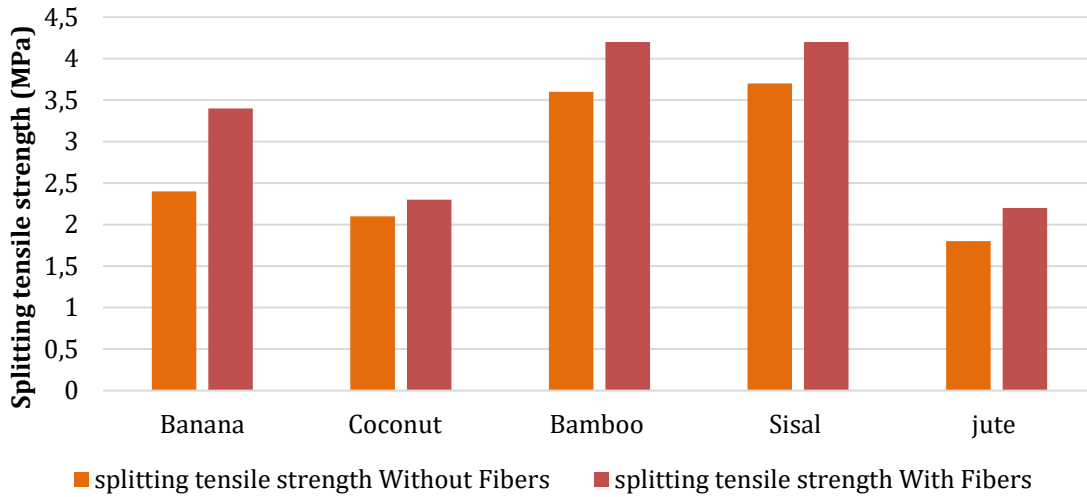


Fig. 2. Splitting tensile strength of concrete at 28 days

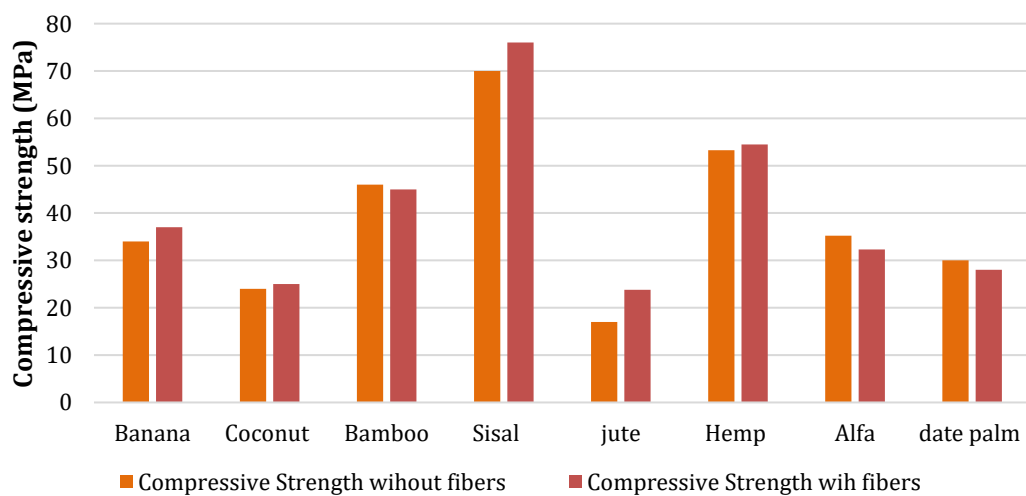


Fig. 3. Compressive strength of concrete at 28 days

The incorporation of plant-based fibers into cementitious composites variably influences their mechanical properties according to fiber type and content. Fibers such as sisal and hemp stand out for their superior performance, significantly enhancing compressive and tensile strength. Other fibers, such as bamboo and banana, yield moderate results, while the overall effectiveness of plant-based fibers largely depends on their intrinsic characteristics and their integration into the cement matrix.

These contrasting results highlight that the benefits of fiber reinforcement are not universal, but strongly depend on the quality and appropriate treatment of the fibers, which improve fiber-matrix bonding and stress transfer. Therefore, the importance of a careful selection based on specific mechanical requirements and usage conditions is essential to fully exploit the potential of plant fibers and achieve consistent and reliable mechanical improvements in sustainable composite materials.

### 2.1.2 Shrinkage

Plastic shrinkage refers to the reduction in the volume of cementitious materials that occurs during the initial hours after placement, while the material remains in a plastic state. This phenomenon results from the interaction between inherent mechanisms and capillary force generated in the pores near the surface. It occurs when the rate of water evaporation exceeds the rate at which bleed water (the excess water within the mixture) can rise to the surface [18].

Shrinkage generates tensile stresses within the material. When these stresses surpass the tensile capacity of the concrete, cracks appear [18]. The addition of short and randomly distributed fibers in concrete has been shown to be a reliable approach for reducing cracking caused by plastic shrinkage [19]. These fibers act in two primary ways: firstly, they decrease the global shrinkage stresses, thereby lowering the risk of tensile stresses surpassing the concrete's tensile strength; secondly, they limit crack propagation once cracks begin to form [20].

Adding plant fibers can also reduce this phenomenon, as the fibers serve as reinforcement points and help control cracking. During mixing, the fibers absorb water and swell. However, as the humidity level within the matrix gradually drops, they release the absorbed water. This mechanism effectively reduces drying shrinkage and promotes the internal self-curing process in the matrix [21]. Kouta et al. [22] report that incorporating flax fibers in the range of 0.3% to 0.6% reduces the plastic shrinkage rate by a factor of 2 to 2.4, while also lowering the amount of plastic shrinkage development by 10.7% to 17.3% compared to the initial values.

Increasing the volumetric fraction of fibers incorporated into cement-based materials plays a crucial role in controlling plastic shrinkage cracking. However, a maximum fiber content must be maintained to avoid undesirable effects. Bertelsen et al. [19] demonstrated that microfibers yield good results when added at volumetric fractions greater than 0.1%, while macro fibers require volumetric fractions above 0.5%. Specifically, coarser macro fibers must be added in higher volume fractions than microfibers to be effective. Hwang et al. [23] showed that increasing the coconut fiber dosage from 0% to 4% significantly reduced cracking. The crack number is reduced from 11 to 0, while the crack index dropped from 2.95 mm to 0 mm, demonstrating the effectiveness of coconut fibers in controlling cracking.

The experimental study by Boghossian and Wegner [24] showed that with a volumetric fraction of 0.3% of flax fibers, the cumulative surface area of cracks on the sample's surface after 24 hours was reduced by over 99.5% compared to ordinary mortar. The maximum width of cracks decreased by 98.5%, ensuring that all crack openings remained below 0.022 mm. Continuous enhancement was observed with the increase in fiber volumetric fraction. However, the difference in fiber length ranges from 10 to 38.

In conclusion, the incorporation of plant fibers can effectively reduce this phenomenon. By acting as reinforcement within the material, these fibers help to distribute stresses more evenly, minimize shrinkage, and limit the formation of cracks. Additionally, plant fibers can improve the material's ability to retain moisture during the curing process, reducing surface drying and associated issues. As a result, plant fibers contribute significantly to improving the performance and durability of cementitious composites, particularly by addressing challenges like shrinkage and cracking.

Table 2. Summary of studies on the effect of different fiber types and contents on shrinkage behavior

Reference	Fiber type	Matrix composition (kg/m <sup>3</sup> )		Fiber content	Effect on shrinkage
[23]	Coconut	Cement	499	4% by mortar volume	Increasing the coconut fiber dosage from 0% to 4% significantly reduced cracking. The crack number is reduced from 11 to 0.
		Fly ash	171		
		Ground blast furnace slag	166		
		Sand	967		
		Superplasticizer	3.91		
		Water	292		
[25]	Coconut	Fibers	51.2	1 % of cement content	The incorporation of fibers helps mitigate drying shrinkage due to the crack-bridging effect.
		Cement	487		
		Water	177		
		Sand	629		
		Coarse aggregates	1114		
		Superplasticizer	4.98		
[24]	Flax	Fibers	5	0.3% by volume	With a volumetric fraction of 0.3% of flax fibers, the cumulative surface area of cracks on the sample's surface after 24 hours was reduced by over 99.5% compared to ordinary mortar.
		Cement	1		
		Water	0.46		
		Sand	0.95		
[26]	Flax	Fibers	Varied	0.3% - 0.5% by weight of cement	Flax fiber incorporation significantly reduced endogenous shrinkage. A decrease in endogenous shrinkage at 7 days, reaching 23 and 26%, respectively, was observed with 0.3% and 0.5% of fibers.
		Cement	500		
		Silica fume	50		
		Water	175		
		Sand	703		
		Gravel	1000		
		Superplasticizer	5		
[27]	Flax	Flax	2.5	0.30 % by weight of cement	A 27% decrease in deformation at 100 days was observed in comparison with the control mix indicating reduced autogenous shrinkage.
		Cement	420		
		Blast furnace slag	47		
		Coarse aggregates	993		
		Sand	836		
		Superplasticizer	5		
[28]	Date palm	Water	140	1.2Kg / m <sup>3</sup>	The incorporation of date palm fibers notably mitigated shrinkage, with the optimal performance achieved at a dosage of 1.2 kg/m <sup>3</sup> .
		Flax	1.51		
		Cement	350		
		Limestone filler	200		
		Water	200		
		Silica sand	384		
		Quarry sand	284		
		Gravel (3/8)	490		
[29]	Date palm	Gravel (8/16)	460	0.1% by volume	The addition of palm fibers to the mix decreased shrinkage in hot-dry conditions. The decrease depended on the length and volume of fibers: the addition of 0.1%-1cm, 0.2%-1cm, 0.1%-2cm, and 0.2%-2cm of DPF reduced the shrinkage of SCC by 8.6%, 26.6%, 50%, and 20.4% respectively
		Plasticizer	6,6		
		Fibers	1.2		
		Cement	350		
		Limestone filler	350		
		Water	170		
[29]	Date palm	Coarse aggregates	790	0.1% by volume	The addition of palm fibers to the mix decreased shrinkage in hot-dry conditions. The decrease depended on the length and volume of fibers: the addition of 0.1%-1cm, 0.2%-1cm, 0.1%-2cm, and 0.2%-2cm of DPF reduced the shrinkage of SCC by 8.6%, 26.6%, 50%, and 20.4% respectively
		Sand	686		
		Superplasticizer	3.5		
		Fibers	1.06		
		Fibers	1.06		

### 2.1.3 Thermal Properties

Thermal insulation represents a key solution for enhancing energy efficiency by reducing energy consumption linked to heating in winter and air conditioning in summer. The thermal performance of an insulating material is mainly determined by two essential parameters: thermal conductivity and specific heat; *Table 3* gives the values of these two key parameters for some plant fibers. Thermal conductivity quantifies how efficiently a material can transfer heat, while specific heat indicates the material's capacity to store heat. Both properties are essential for evaluating the performance of insulation materials, as they determine how a material responds to temperature fluctuations and its resistance to heat transfer. For plant fibers, the values of these two parameters vary based on the type of fiber, as detailed in *Table 3*.

Table 3. Thermal conductivity and specific heat of some plant fibers

Fiber	Thermal Conductivity (W/m.K)	Specific heat (KJ/kg.K)	Reference
Wood	0,038–0,050	1.9–2.1	[30]
Hemp	0,038–0,060	1.6–1.7	
Kenaf	0,034–0,043	1.6–1.7	
Flax	0,038–0,075	1.4–1.6	
Coco	0,040–0,045	1.3–1.6	
Jute	0,038–0,055	2.3	

The natural fibers presented in *Table 3* offer varied thermal performances, suitable for different applications. Kenaf and hemp fibers stand out for their low thermal conductivity, making them excellent choices for insulation. Jute, with its high specific heat capacity, is particularly interesting for applications requiring increased thermal storage. However, it is worth noting that these parameters can vary based on the particular part of the plant from which the fibers are sourced, thereby influencing their thermal properties. Furthermore, a study conducted by Agoudjil et al. [31] examined the influence of palm variety and wood type on thermophysical properties. The results revealed that thermal conductivity and thermal diffusivity values vary depending on the palm variety and the specific part of the palm analyzed. These variations highlight the importance of these parameters in assessing the thermal insulation of materials derived from palms.

Roma et al. [32] examined the thermal performance of roofing tiles made from fiber-reinforced cement. Their results demonstrated that the integration of plant fibers provides the tiles with satisfactory thermal insulation, making them an interesting alternative to asbestos-cement sheets. Similarly, Khedari et al. [33] showed that the thermal conductivity of soil-cement blocks decreases with an increasing amount of incorporated coconut fibers. Additionally, it has been established that hemp concrete offers remarkable thermal insulation, thanks to its low thermal conductivity, which helps to ensure consistent indoor temperatures [34].

## 2.2 Limitations of Natural Fibers in Cementitious Composites

### 2.2.1 Chemical Reaction Between Cement and Plant Fibers

The integration of vegetal fibers into cementitious composites raises questions about the chemical interactions that may occur between these two materials. Although plant fibers are primarily composed of organic compounds, their incorporation into a highly alkaline cement matrix can lead to specific reactions. These interactions, often limited to the surface of the fibers, play a crucial role in determining the durability and mechanical properties of the composites.

#### 2.2.1.1 Influence of Cellulose on Cement Hydration

Plant fibers, which are rich in cellulose, can actively interact with the materials produced as a result of cement hydration. For example, the hydroxyl groups (-OH) present in cellulose fibers may interact with calcium ions ( $\text{Ca}^{2+}$ ) in the cement. However, these interactions are relatively weak compared to the impact of chemical admixtures specifically designed to enhance the cement matrix.

Savastano et al. [35] reported that the setting time of the cement matrix is extended by the acidic compounds released by plant fibers. Similarly, Bilba et al. [36] demonstrated that hemicellulose and lignin, components found in sugary fibers, can disrupt or slow down the cement hydration

process. Sedan et al. [37] reported that incorporating fibers can also reduce the setting time by up to 45 minutes. This reduction is associated with the presence of pectin, a component of fibers, which binds calcium and thereby inhibits the development of C-S-H (calcium silicate hydrate) structures, essential for cement hardening.

#### 2.2.1.2 Risks of Chemical Degradation of Fibers

Plant fibers can degrade over time due to the humid and alkaline conditions of concrete, particularly if they are not properly treated. The high alkalinity of concrete (pH between 12 and 13) can affect the stability of plant fibers, especially when left unprotected. This chemical degradation weakens the fibers and can significantly reduce the long-term mechanical performance of fiber-reinforced composites. Moreover, the overall durability of cementitious materials reinforced with plant fibers depends not only on their resistance to these internal alkaline conditions but also on their ability to withstand external factors such as humidity fluctuations, temperature variations, and chemical attacks from sulfates and chlorides. The complex interaction between the fibers and the cementitious matrix, combined with volumetric changes within the composite, further influences the extent of degradation and the resulting mechanical integrity of the material [38] [39]. Researchers propose two mechanisms to explain the mechanisms behind sisal fiber degradation in cement matrices [40] :

- *Primary Mechanism:* The main deterioration process of plant fibers in a cementitious environment is the accumulation of calcium hydroxide crystals on their surface, leading to progressive mineralization of the fibers and a reduction in their cellulose content. Additionally, the degradation of other constituents, like hemicellulose and lignin, constitutes a complementary mechanism [21].
- *Secondary Mechanism:* The lignin and cellulose in the middle layers of the fibers dissolve under the influence of the alkaline interstitial water in the concrete. This solubilization results from the alkaline attack and fiber mineralization, along with the alkaline hydrolysis of cellulose molecules. The fiber mineralization is mainly driven by the movement of calcium hydroxide towards the cell walls and lumen, which accelerates their structural degradation [21].

The degradation of plant fibers has been studied by subjecting them to alkaline conditions and assessing variations in their tensile properties. This degradation is linked to the highly alkaline conditions present in Portland cement, which dissolve the lignin and hemicellulose phases. This process weakens the fiber structure, adversely affecting its performance in composites [38].

On the other hand, Kriker et al. [41] studied the durability characteristics of male date palm surface fibers (MDPSF) by assessing the reduction of tensile strength and fiber elongation when exposed to alkaline environments, using tensile tests. The findings indicated that the peak load (P max) and the ultimate load ratio (D max) increased with fiber length and volume percentage. However, for every type of concrete, P max and D max decreased with fiber aging due to the progressive reduction of tensile strength in highly alkaline cementitious matrices [42]. These fibers are particularly sensitive to alkaline solutions, especially calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), sodium hydroxide (NaOH) at pH 12.5, and Lawrence's solution at pH 12.95. After immersion for six months in a  $\text{Ca}(\text{OH})_2$  solution, date palm fibers preserved, respectively, about 69%, 40%, and less than 10% of their initial strength for diameters of 0.8 mm, 0.6 mm, and 0.4 mm. In a NaOH solution, the fibers retained approximately 76%, 46%, and 16% of their initial strength for the same diameters. These results highlight the significant degradation of fibers depending on their size and the alkaline environment [41].

Toledo Filho et al. [42] highlighted the effects of alkaline exposure on fibers following multiple wet-dry cycles. They studied the behavior of sisal and coconut fibers when exposed to alkaline environments. The results show that after being immersed for 420 days in a sodium hydroxide (NaOH) solution, sisal and coconut fibers retained 72.7% and 60.9% of their initial strength, respectively. However, when immersed in a calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) solution, their initial strength was entirely lost after 300 days. This degradation caused by calcium hydroxide can be attributed to the crystallization of lime (calcium hydroxide) within the pores of the fibers, which weakens their structure. The severity of the alkaline attack was reduced when they were immersed

in a sodium hydroxide (NaOH) solution for conditioning. The degradation of composites can also be linked to the mineralization of fibers caused by the movement of hydration products, particularly calcium hydroxide, into the lumen, walls, and internal voids of the fibers. This process weakens fibers and compromises their mechanical characteristics within the composite material.

In a sodium hydroxide solution, according to Ramakrishna and Sundararajan [43], Coconut fibers retain about 40% to 60% of their initial strength. In contrast, sisal, jute, and Hibiscus cannabinus fibers retain only 10% to 20% of their tensile strength, regardless of the type of immersion. When immersed in fresh water, coconut and sisal fibers retain approximately 50% to 60% and 60% to 70% of their initial strength, respectively. Conversely, jute and Hibiscus cannabinus fibers only manage to preserve up to 20% of their strength, whatever the type of immersion. These findings reveal significant variability in fiber durability depending on their nature and the exposure environment. However, further research is needed to establish a precise correlation between fiber strength and durability in alkaline environments and the performance of composites under laboratory or field conditions.

In conclusion, the chemical degradation of fibers, particularly in alkaline environments, poses significant risks to their performance in composite materials. Exposure to solutions such as calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) and sodium hydroxide (NaOH) can lead to a loss of strength and structural integrity in fibers, particularly those of smaller diameters. Understanding and mitigating these risks through fiber treatment or matrix modification is essential for enhancing the durability of fiber-reinforced composites.

### 2.2.2 Physical Interaction Between Cement and Plant Fibers

Beyond their chemical compatibility, the physical interaction between the fibers and the cementitious matrix plays a crucial role in determining the overall performance and long-term durability of the composite.

#### 2.2.2.1 Water Absorption by Plant Fibers

Plant fibers, being hygroscopic in nature, have a high capacity to absorb water, which can present challenges during concrete preparation. On one hand, they can sequester a portion of the water intended for cement hydration, thereby reducing the amount available for this crucial process. This absorption can compromise the final strength of the concrete, particularly if the remaining water is insufficient to ensure optimal hydration. On the other hand, water absorption by the fibers influences the mix's consistency, complicating workability control. It thus becomes essential to precisely adjust the moisture content and water quantity to ensure high-quality concrete.

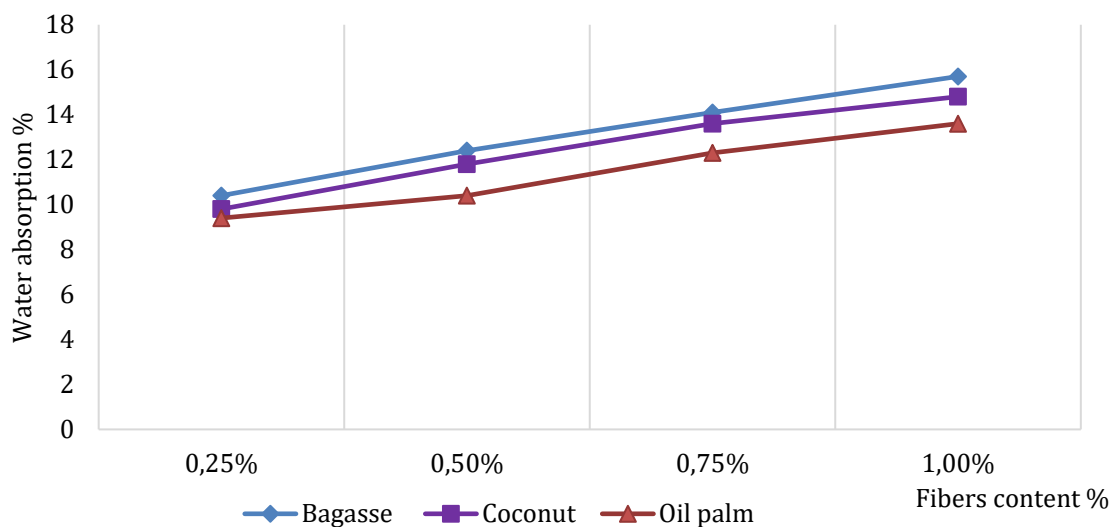


Fig. 4. Water absorption of some fibers studied by Danso et al. [45]

Over time, the shrinkage of plant fibers can create voids at the interface with the cement matrix. These voids increase water absorption, reduce the concrete's impermeability, and facilitate chloride penetration, thereby compromising the material's overall durability [21]. Similarly, Alonge et al. [44] demonstrated that porosity and water absorption are directly correlated.

According to Hwang et al. [23], samples prepared with coconut fiber volume fractions of 0%, 1%, 2.5%, and 4% exhibited water absorption rates of 6.2%, 7.1%, 7.5%, and 8%, respectively. These results indicate that the water absorption of the samples was 14%, 20%, and 29% higher, respectively, than that of the samples without coconut fibers. This increase can be attributed to the significant water absorption capacity of coconut fibers combined with the increased voids in the binder matrix. On the other hand, Danso et al. [45], demonstrated that the water absorption of fiber-reinforced composites rises as the fiber content increases. The results of their tests are shown in Fig. 4. The rise in water absorption can be explained by the ability of the cellulose in plant fibers to absorb water. This process creates channels and increases the porosity of the composites, enabling the concrete to retain more water [21].

#### *2.2.2.2 Adhesion Between Cement and Fibers*

The adhesion between the fibers and the matrix is a critical factor influencing the mechanical properties and durability of fiber-reinforced cementitious composites. It refers to the interface interaction between the fibers and the cement matrix in which they are integrated. Strong adhesion allows for better stress transfer between the fibers and the matrix, thereby enhancing the strength and durability of the composite. However, plant fibers do not have the same ability to bond with cement as other types of reinforcements, such as metallic or synthetic fibers. The adhesion between vegetal fibers and the cement paste may be weaker due to the hydrophobic nature of plant fibers. The fiber-matrix interface constitutes a reaction zone where two phases or components combine physically, mechanically, and/or chemically [46].

For example, Sisal fibers exhibit volume variations in the presence of humidity, leading to a swelling behavior [47]. This causes degradation of the interface due to the stresses generated in this zone, thus favoring the appearance of microcracks surrounding the fibers. The drying process can also lead to a reduction in the volume of the fibers, weakening the bond between them and the matrix. This weakening mechanism can explain the observed variation in behavior after wetting and drying cycles [47].

In general, achieving good adhesion in a bio composite system using plant fibers requires suitable surface treatment. Therefore, many studies have been carried out on the chemical and mechanical surface modifications of different natural fibers, with the objective of enhancing interfacial bonding between natural fibers and the matrix, as well as optimizing the composite's overall performance [48].

#### *2.2.2.3 Thermal Degradation*

Natural fibers typically begin to degrade at temperatures around 240°C. This degradation is influenced by the structural components of the fiber, like cellulose, hemicelluloses, and lignin, each of which is sensitive to a specific temperature range [46]. Around 100 °C, plant fibers begin to lose moisture through evaporation. Afterward, within the 250 to 350°C range, a concurrent deterioration of the primary organic constituents is observed. Thermal decomposition of hemicellulose, especially acetyl 4-O-methylglucuronoxylan, typically initiates at approximately 243 °C. As for cellulose, the primary component of plant fibers, its thermal degradation takes place within a temperature range of 330 to 365°C [21].

In the same context, Martin et al. [49], showed that cellulose and hemicellulose degrade at lower temperatures compared to raw sisal fibers, a phenomenon linked to the removal of lignin. Thermal degradation begins around 222°C and intensifies rapidly with increasing temperature, thereby reducing the total mass by 72% between 222 and 415°C. These results indicate a marked degradation process starting at 222 °C. Furthermore, the deterioration of sisal fibers occurs in two distinct stages: the first stage, associated with hemicellulose degradation, is observed between 220 °C and 328 °C, whereas cellulose decomposes at higher temperatures, exhibiting a markedly faster degradation rate.

The results of Joseph et al. [50] align with this, as they showed that for sisal fiber, dehydration and lignin degradation occur in a temperature range between 60 and 200°C. In contrast, the majority of cellulose decomposes at a temperature around 350°C. However, the thermal performance of the fiber can be improved by partially eliminating hemicelluloses and certain lignin components through various chemical treatments [46].

Finally, according to Martin et al. [49], it was concluded that the polymer matrix intended for the production of composites incorporating sisal fibers and other plant fibers requires a treatment at temperatures below 185°C, because of the degradation of their components, which begins at 186°C.

### **2.3 Approaches to Improve Interaction Between Plant Fibers and Cement**

Two principal approaches have been investigated to enhance the durability of biomass-based materials: treating the biomass content and modifying the matrix to resolve concerns associated with the use of biomass [12].

#### *2.3.1 Matrix Composition Modification*

This approach primarily focuses on modifying the composition of the matrix by reducing free alkalis in cement matrices [51]. This involves the development of low-alkali binders derived from residues of industrial and agricultural processes. The addition of these by-products, such as fly ash, silica fume, and metakaolin to Portland cement, helps decrease the alkalinity of the binders and, consequently, improves the durability of biomass-based materials. Furthermore, the introduction of certain hydration accelerators into the matrix has enhanced the compatibility of wood-cement-water systems, increasing the flexural strength of cementitious composites [12].

The results of Castoldi et al. [47] show that incorporating pozzolanic materials at a 50% substitution rate for cement led to a matrix with a low calcium hydroxide content, thereby creating an environment conducive to reinforcing sisal fibers. Also, Alonge et al. [44] revealed that concrete samples containing 10% metakaolin (MK) and 1% colloidal Nano silica exhibited remarkable durability, with optimal performance for all the properties studied.

According to de Almeida MeloFilho et al. [40], microstructural observation revealed that sisal fibers are mineralized when used to reinforce conventional Portland cement-based materials. Following multiple wetting and drying cycles, the cell walls of the fibers showed signs of damage. However, no degradation was observed for sisal fibers incorporated into composites, where 50% of the cement was replaced with Metakaolin. This increased resistance suggests that the addition of Metakaolin enhances the durability and stability of the fibers within the composite.

Fast carbonation represents another alternative studied to enhance the durability of cellulose-based cement composites. This process allows the rapid reaction of  $\text{Ca(OH)}_2$  with carbon dioxide ( $\text{CO}_2$ ) to form  $\text{CaCO}_3$ . In addition to its effect on durability, carbonation also influences the mechanical properties of the composites by enhancing their strength while decreasing specific energy and water absorption [51]. This process results in the petrification of plant fibers, where reaction products occupy voids and potentially impregnate the cell walls. This process strengthens the bond between plant fibers and cement [21].

In conclusion, modifying the matrix composition can significantly improve the performance and durability of cementitious composites. Adjustments to the composition, such as incorporating pozzolanic materials to reduce alkalinity or accelerate carbonation, can optimize the fiber-matrix interaction, enhancing the composite's mechanical performance, reducing degradation, and better overall stability in various environments.

#### *2.3.2 Modification of Fibers*

This approach aims to protect plant fibers by applying coatings or pre-treatments to minimize the harmful effects of alkalis and water. Chemical or physical treatments have been applied to ensure optimal chemical bonding between biomass fibers and the matrix, leading to enhanced material durability [12], [51]. The influence of plant fibers on the durability of concrete largely depends on these pre-treatments. Indeed, untreated fibers are vulnerable to degradation caused by environmental conditions such as moisture, temperature, or chemical attacks. However, when

properly treated, these fibers can improve the durability of concrete by reducing crack formation and ensuring a uniform distribution of stresses.

Claramunt et al. [39] assessed the mechanical properties of cement composites reinforced with vegetal fibers, following a 28-day curing period and subsequent exposure to four wet–dry aging cycles. The findings indicated that the pre-treatment of the fibers had a positive impact on the strength and long-term performance of the composites, even after several aging cycles. Boix et al. [52] applied three treatment methods to *Miscanthus*: alkali treatment, salinization, and a combination of both. The incorporation of alkali-treated stalks as fillers significantly improved the strength of the blocks, with even greater strength achieved when the alkali-treated fibers were covered with silica. A relationship was shown between the quantity of sugary compounds obtained from the *Miscanthus* stalk fragments and the mechanical characteristics of the blocks. In particular, the less residual sugars from *Miscanthus* remain in the concrete, the better its mechanical strength. Sedan et al. [37] demonstrated that alkali treatment enhances the flexural strength of cement composites containing hemp fibers, with an increase of approximately 94% compared to the cement paste. The alkali treatment not only positively affects the strength of the fibers but also improves the fiber-matrix adhesion.

### *2.3.3 Manufacturing Process*

The production of fiber-reinforced concrete must ensure a uniform fiber distribution within the matrix, reduced porosity, and strong adhesion to achieve optimal fiber reinforcement [21]. The literature categorizes cellulose-based cement composite preparation methods into two groups based on fiber arrangement: randomly dispersed fibers within the matrix and fibers aligned or structured into fibrous formations [51]. However, the different distribution of short fibers within the matrix can lead to negative effects on the material's mechanical properties. To overcome this challenge, several manufacturing methods have been introduced to mitigate these effects and enhance the performance of the composites. Among these methods, the Hatschek process has proven particularly effective in improving fiber distribution and reinforcing the overall mechanical properties of the material [21].

Li et al. [53] found that using a wet mix enhanced the dispersion of the fillers rather than mixing the components in their dry state. This method enables more uniform integration of the materials into the matrix, thereby improving the mechanical characteristics and durability of the composites. Indeed, the wet mixing improves fiber–matrix compatibility [12]. The different approaches described above can be combined to maximize the effectiveness of fibers in concrete. However, it is essential to experimentally verify the effectiveness of these combinations in order to quantify their real impact and identify the optimal solution. Table 4 summarizes the main degradation mechanisms observed in fiber-reinforced concrete and the corresponding mitigation measures.

When optimizing fiber-reinforced concrete, it is important to consider the trade-offs associated with different treatments. For example, chemical or physical treatments can significantly improve adhesion at the fiber-matrix interface, mechanical properties, and crack resistance, but can also increase material costs and embodied energy. Similarly, accelerated carbonation can densify the matrix and reduce permeability, but it can also alter early-age properties, potentially affecting workability or early strength development.

The addition of pozzolanic materials (e.g., metakaolin, silica fume, fly ash) can improve durability and reduce portlandite content, but can also alter setting time, workability, or cost. These trade-offs must be carefully evaluated to reconcile improved performance with economic, environmental, and practical considerations, ensuring a holistic approach to the design of sustainable concrete.

Table 4. Degradation mechanisms and mitigation actions in fiber-reinforced concrete

Processes	Type	Description	Proposed mitigation actions
Influence of Cellulose on Cement Hydration	Chemical	The setting time of the cement matrix is extended by the acidic compounds released by plant fibers.	Chemical fiber treatments (with NaOH) to remove soluble hemicelluloses/pectins and reduce leaching; Introduction of certain hydration accelerators;
Chemical degradation of fibers	Chemical	Plant fibers can degrade over time due to the humid and alkaline conditions of concrete.	Protection of the fiber by surface treatments, such as Silane (1–2%), which allows the formation of a layer that binds the fiber to the matrix and reduces ion penetration; Modification of the matrix by pozzolanic additions in order to consume Ca(OH) <sub>2</sub> and reduce the local effective pH; Some additions like Metakaolin enhances the durability and stability of the fibers within the composite.
Water Absorption by Plant Fibers	Physical	Fibers can sequester a portion of the water intended for cement hydration. This absorption can compromise the final strength of the concrete,	Use chemical treatments to remove surface impurities; Modification of the matrix to reduce its porosity (e.g., pozzolanic additions, nano-silica) and limit water penetration around the fibers; Fast carbonation decreases water absorption; Thermal treatments including drying and moderate pyro-treatment (below 200 °C), to reduce hygroscopicity while preventing thermal degradation of the fibers; Coating fibers to enhance their impermeability.
Adhesion between Cement and Fibers	Physical	The adhesion between vegetal fibers and the cement paste may be weaker due to the hydrophobic nature of plant fibers, which can negatively affect the mechanical properties and durability of fiber-reinforced cement composites.	Chemical treatment through alkalization to remove hemicelluloses and waxes, and to increase surface roughness. Modification of the matrix by adding pozzolanic materials (fly ash, slag, metakaolin) to protect the fibers and maintain their bond with the matrix; Fast carbonation process results in the partial mineralization of the plant fibers, so that the surface of the fibers becomes more rigid and better integrated into the surrounding matrix; Wet mixing.
Thermal degradation of fibers	Thermal	Natural fibers typically begin to degrade at temperatures around 240 °C. This degradation is influenced by the structural components of the fibers (cellulose, hemicellulose, and lignin), which are sensitive to a specific temperature range.	Protection of fibers using mineral coatings to create a thermal and chemical barrier. Modification of the matrix by adding fines to reduce permeability and slow heat penetration.

### 3. Life Cycle Assessment: A Case Study

A life cycle assessment (LCA) generally involves four essential phases: defining the study's objective, gathering the life cycle inventory data, conducting the life cycle impact assessment (LCIA), and interpreting the outcomes. Each of these stages requires careful consideration and strategic decisions that directly influence the reliability and relevance of the results [54].

In this paper, an LCA was carried out to evaluate the environmental implications of substituting polypropylene fibers with natural fibers derived from palm residues in concrete. The analysis was performed in compliance with the ISO 14040 and ISO 14044 international standards [55] [56], utilizing the openLCA 2.4.1 software.

The assessment focused on evaluating the environmental impacts of the production of two concrete variants throughout multiple stages of their life cycle. These stages encompassed the extraction and processing of raw materials, transportation to the construction site, and the concrete manufacturing process itself, all conducted within the framework established by ISO 14040.

#### 3.1 Objective

The main objective of this study is to evaluate the environmental and sustainability impacts of incorporating date palm fibers (DPF) into concrete as a substitute for conventional polypropylene fibers (PP). This research seeks to determine whether the use of a natural, locally available, and biodegradable fiber, such as that derived from dead date palm fronds, as illustrated in Fig. 5, can contribute to a more sustainable construction material, without compromising performance. In this study, two types of fiber-reinforced concrete were compared: concrete reinforced with date palm fibers (CDPF) and concrete reinforced with polypropylene fibers (CPP). Before conducting the comparative analysis, an environmental impact assessment of the manufacturing processes for both types of fibers were performed. This preliminary step made it possible to identify and assess the environmental impacts linked to the production of natural fibers derived from dead date palm fronds, as well as those related to the industrial production of polypropylene fibers. These initial results provide a necessary foundation for evaluating the global environmental performance of incorporating these fibers into concrete.



Fig. 5. Dead date palm leaves, an unused agricultural residue from southeastern of Morocco

#### 3.2 System Boundary and Functional Unit

The system boundaries of this study are defined using a cradle-to-gate approach, as illustrated in Fig. 6. This means that the assessment focuses exclusively on the stages from the extraction of raw materials to the point at which the concrete is ready to leave the production facility. The following life cycle phases are taken into account:

- Extraction and processing of raw materials, including the fabrication of binders, aggregates, water, and reinforcing fibers (polypropylene or date palm fibers);

- Transportation of raw materials from their point of origin to the concrete manufacturing site, considering typical distances and transportation modes;
- Concrete production process, encompassing the mixing, batching, and preparation of the final product.

This boundary choice excludes subsequent stages such as construction, use phase, and end-of-life treatment of concrete, to isolate the environmental impacts related to concrete production for comparison purposes. This cradle-to-gate scope is commonly used in LCA studies aiming to compare material alternatives at the production stage.

As outlined in the ISO 14040 framework, the functional unit must be clearly defined and accurately reflect the study's intended purpose. It serves as a quantitative reference against which the system's inputs and outputs are normalized, ensuring consistency and comparability throughout the life cycle assessment. The functional unit adopted in this study corresponds to the production of 1 cubic meter ( $1 \text{ m}^3$ ) of concrete. This choice is justified by the need to evaluate and compare the environmental impacts of different concrete mixtures: one reinforced with polypropylene fibers and the other with natural date palm fibers, on a common and practical basis. Concrete is typically produced, specified, and used in volumetric units in construction projects; thus, using  $1 \text{ m}^3$  as the reference unit aligns with real-world practices and enhances the relevance of the results.

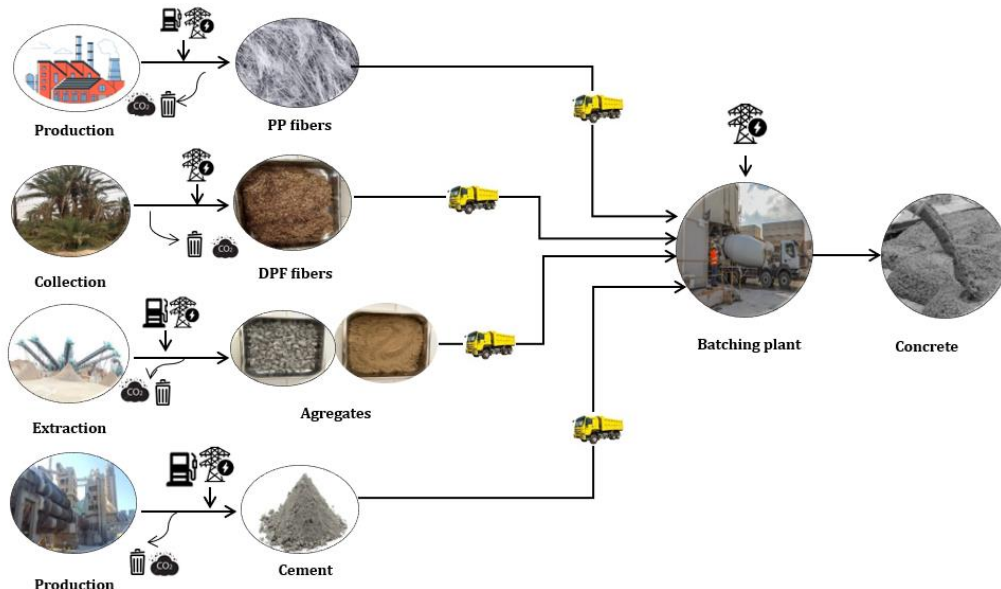


Fig. 6. Process flow from raw material extraction and production to gate for concrete with date palm or polypropylene fibers

### 3.3 Analysis of Inventory

#### 3.3.1 Database and software:

The software openLCA 2.4.1 has been used for the LCA in this study. The Ecoinvent database is recognized as one of the most utilized life cycle inventory databases for construction materials, including fiber-reinforced concrete [57] [58]. In this study, Materials production and transport data were primarily sourced from the Ecoinvent 3.10 database, ensuring recent data, technological and geographical representativeness, and comprehensive coverage of relevant processes, complemented by expert estimates when necessary.

Among the various life cycle impact assessment methods available, CML and ReCiPe are the most frequently applied in environmental assessments [54]. In the present study, the ReCiPe 2016 midpoint (H) was selected as the impact assessment method because it is one of the most recent and widely recognized LCIA methods, ensuring methodological robustness and comparability with a large body of existing studies. The midpoint level provides a higher level of detail and lower uncertainty compared to endpoint indicators, which is particularly relevant for analyzing the environmental performance of construction materials. The hierarchist perspective (H) was chosen

as it reflects the most common scientific consensus and is recommended as the default perspective by the developers of ReCiPe. This choice ensures that the results are transparent, reproducible, and aligned with LCA practices.

### 3.3.2 Energy Consumption and Input Information

The life cycle assessment conducted in this study encompassed the following key stages:

#### 3.3.2.1 Raw Material Production

This stage involves the extraction and processing of the main constituents of concrete, namely sand, aggregates, cement, and reinforcing fibers (either polypropylene or natural date palm fibers). The associated environmental burdens were derived from relevant datasets within the Ecoinvent database, which provided the necessary life cycle inventory data for these key components of the concrete mix. However, some limitations were encountered during the data collection process. Notably, the lack of reliable information on the service life of concrete prevented a full cradle-to-grave analysis and justified the adoption of a cradle-to-gate system boundary in this study. Furthermore, due to the absence of region-specific emission data for certain materials within the Moroccan context, the study relied on the European datasets available in the Ecoinvent database. While this introduces a degree of uncertainty, it was considered a reasonable proxy in the absence of more localized data, in line with practices commonly adopted in similar LCA studies.

As reported by the National Authority for Electricity Regulation [59], and illustrated in Fig. 7, electricity generation in Morocco is largely dominated by coal, which accounts for approximately 64% of the total production. Since the Moroccan electricity mix data were not available in the selected database, the Polish electricity mix was adopted as a suitable proxy. This choice is justified by the strong structural similarity between the two energy systems: both are heavily reliant on coal, around 63% of electricity generation in Poland [60] and 64% in Morocco in 2023, while also incorporating smaller shares of natural gas and a growing contribution from renewable sources. This parallel allows for a consistent and representative modelling of Morocco's electricity generation profile.

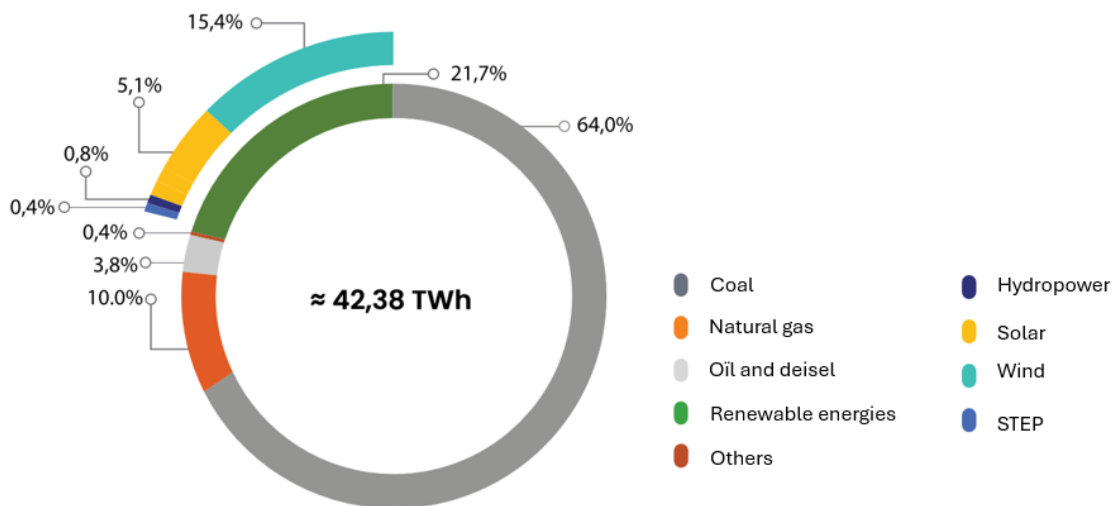


Fig. 7. Distribution of Moroccan electricity production

The polypropylene (PP) fiber production process in this study, as represented in the Eco invent database, includes not only the transformation of propylene into fibers but also all the upstream stages required for their manufacturing. It accounts for both energy and material flows associated with the extraction and refining of fossil resources, up to the production of fibers suitable for concrete reinforcement. While date palm fibers are extracted from the dead leaves of the date palm, an agricultural by-product naturally available in large quantities. These leaves, already dry due to their natural life cycle, require neither active harvesting nor additional energy-intensive drying processes.

The palm leaves used as fibers in this study were modeled as burden-free, since they are considered agricultural waste. These leaves are regularly pruned as part of the routine maintenance of date palms, independently of any potential valorization. Consequently, no upstream environmental burdens related to palm cultivation or maintenance were allocated to these residues. In line with ISO 14044 recommendations, a cut-off approach was applied at the point of waste generation.

These fibers are obtained through a mechanical defibration operation. To produce 1 kg of date palm fibers from dead leaves, approximately 3,5 kg of dry leaves are needed [61] (yield ≈ 28 %). For the grinding and defibration operations, an average energy consumption of 1.5 kWh is assumed based on several literature sources [62] [63] [64]. Transport for the collection and delivery of the leaves is estimated at around 10 km. The fibers were then washed with water to remove impurities and dried under ambient conditions. The process yields 1 kg of usable fibers and approximately 2,5 kg of non-usable lignocellulosic residues, representing the fraction lost due to the process yield.

### 3.3.2.2 Transportation

This phase accounts for the transport of raw materials to the concrete production facility, incorporating parameters such as transport distance, vehicle type, and fuel consumption. In this study, transportation was modeled using diesel-powered trucks compliant with EURO 3 standards, with a payload capacity ranging from 16 to 32 tons. A fixed transport distance of 40 km was uniformly applied for all materials, in line with local construction practices and the absence of more specific logistical data.

### 3.3.2.3 Concrete Production

The final stage includes the mixing and preparation of concrete. In this process, electricity was considered the sole energy input. Based on literature sources [65], the production of 1 m<sup>3</sup> of concrete was assumed to require 17 kWh of electricity. As reported in the experimental research performed by Althoey et al. [66], date palm fibers and polypropylene fibers exhibited comparable performance when incorporated into concrete at a dosage of 1% by binder weight. Specifically, the inclusion of 1% date palm fibers led to a 17% improvement in splitting tensile strength, while 1% polypropylene fibers resulted in a 16% increase for the same property. Moreover, adding 1% of fibers enhanced the flexural strength of concrete, with improvements ranging from 60% to 85% for concrete incorporating date palm fibers, and from 61% to 79% for concrete containing polypropylene fibers.

Table 5. LCA inventory of the Concrete mixes

Input	unit	CDPF	CPP
		quantity	quantity
Cement	kg		400
Gravel	kg		1100
Sand	kg		740
Water	kg		178
Electricity	kWh		17
Distance of transport	km		40
DPF	kg	4	
PP	kg		4

This comparative experimental study, carried out by Althoey et al. [66], on polypropylene fibers and date palm fibers, showed that at a dosage of 1% by binder weight, both types of fibers provide equivalent reinforcement and mechanical performance. Based on these findings, the present environmental assessment focuses on comparing two concrete formulations, both incorporating 1% fibers by binder weight, one reinforced with date palm fibers and the other with polypropylene fibers, to evaluate the environmental trade-offs associated with each fiber type while maintaining equivalent mechanical performance. The concrete mix composition considered in this environmental impact assessment is presented for indicative purposes and detailed in Table 5.

### 3.4 Impact Assessment

The LCA results for the fiber manufacturing processes and the concrete mixes reinforced with fibers are summarized in Table 6 and Table 7, respectively. The impact indicators analyzed were based on the most commonly used environmental categories in life cycle assessment studies of fiber-reinforced concrete. These include:

- Climate change (GWP): refers to the Global Warming Potential, which measures the contribution of greenhouse gas emissions to global warming over a defined period, typically 100 years. It expresses the impact in terms of CO<sub>2</sub> equivalents (kg CO<sub>2</sub> eq);
- Fossil resource scarcity (FRS): Measures the depletion of non-renewable fossil resources such as petroleum, natural gas, and carbon used for energy and materials. The results are expressed in kilograms of oil equivalent (kg oil eq), representing the amount of fossil resources consumed compared to an equivalent quantity of crude oil. This indicator reflects the system's dependence on finite fossil resources.
- Ozone depletion (ODP): measures the destruction of the stratospheric ozone layer, which serves as a shield against biologically damaging ultraviolet radiation. This indicator expresses the potential damage relative to a reference substance, typically CFC-11 (trichlorofluoromethane), and the results are expressed in kilograms of CFC-11 equivalent (kg CFC-11 eq).
- Terrestrial acidification (TAP) quantifies the acidifying emissions, such as nitrogen oxides or sulfur dioxide, that contribute to soil acidification, negatively affecting ecosystems, forests, and agriculture, measured in kg SO<sub>2</sub> eq.
- Terrestrial ecotoxicity (T-ECO): Evaluates the toxic effects of chemical substances on terrestrial organisms (plants, animals, microorganisms). The results are expressed in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB eq), reflecting the potential impacts of heavy metals, pesticides, or other pollutants.

These indicators offer an in-depth assessment of the environmental behavior of the concrete formulations under study, enabling a detailed comparison between the use of synthetic and bio-based fibers.

Table 6. ReCiPe Midpoint H method results for 1 kg of fibers

Impact Indicator	Unit	PP	DPF
Fossil resource scarcity	kg oil eq	1.9564361	0.2499993
Global warming	kg CO <sub>2</sub> eq	4.21866724	1.8055703
Stratospheric ozone depletion	kg CFC-11 eq	8.7683 .10 <sup>-07</sup>	2.89 .10 <sup>-07</sup>
Terrestrial acidification	kg SO <sub>2</sub> eq	0.0274039	0.0200558
Terrestrial ecotoxicity	kg 1,4 -DCB	1.2176134	0.5711840

The comparative evaluation of the environmental impacts linked to the production of fibers, as illustrated in Fig. 8, highlights the clear environmental superiority of date palm fibers (DPF) over polypropylene fibers (PP) across all the impact categories considered. In particular, for the production of 1 kg of fibers, the impacts on terrestrial ecotoxicity, terrestrial acidification, stratospheric ozone depletion, global warming, and fossil resource scarcity are reduced by approximately 53%, 26%, 67%, 57%, and 87%, respectively, when using date palm fibers instead of polypropylene fibers.

The results may be attributed to the renewable and locally available nature of date palm fibers, derived from unusable agricultural waste abundant in the region, particularly dead palm leaves. Their use requires neither specific cultivation nor significant input of fossil energy for the supply of raw materials, which considerably limits their environmental footprint compared to synthetic polypropylene fibers.

Table 7. ReCiPe Midpoint H method results for 1 m<sup>3</sup> of concrete mix

Impact Indicator	Unit	CPP	CDPF
Fossil resource scarcity	kg oil eq	40.8299575	34.0042105
Global warming	kg CO <sub>2</sub> eq	409.2988165	399.6464289
Stratospheric ozone depletion	kg CFC11 eq	3.80934 · 10 <sup>-05</sup>	3.57 · 10 <sup>-05</sup>
Terrestrial acidification	kg SO <sub>2</sub> eq	0.9620841	0.9326918
Terrestrial ecotoxicity	kg 1,4-DCB	60.1270131	57.5412956

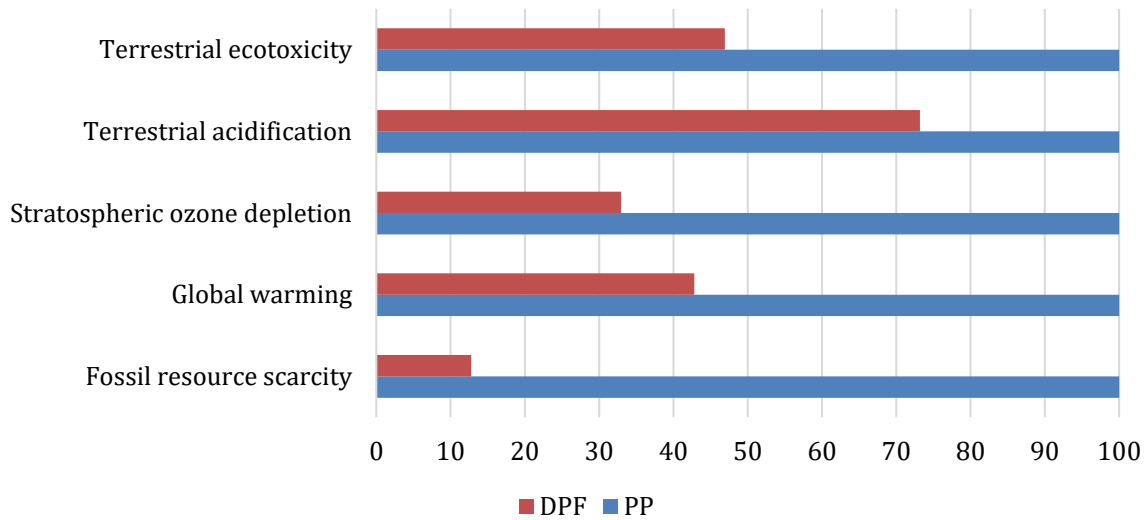


Fig. 8. Midpoint comparison for the production of DPF and PP fibers

The environmental impacts of both concrete types show a slight reduction when date palm fibers (DPF) are used instead of polypropylene fibers (PP), as illustrated in Fig. 9. This modest improvement is primarily attributed to the low fiber content incorporated in the mix (1%), which limits the direct influence of the fibers on the overall life cycle results. Nevertheless, the analysis indicates a marginally better environmental performance for CDPF compared to CPP. Specifically, for the production of 1 m<sup>3</sup> of concrete, the impacts on terrestrial Ecotoxicity, terrestrial acidification, stratospheric ozone depletion, global warming, and fossil resource scarcity decrease by approximately 4.3%, 3.06%, 6.17%, 2.36%, and 16.72%, respectively, when date palm fibers are used as reinforcement. Although these differences are moderate, they suggest that incorporating DPF fibers could represent a more sustainable and environmentally friendly alternative to synthetic fibers in concrete. Following this analysis, it is crucial to assess how each parameter individually affects the environmental performance of concrete. Such an evaluation helps to identify which factors contribute most to the overall environmental burden and which offer the greatest potential for improvement. This step is therefore essential for optimizing concrete formulations toward more sustainable and eco-efficient solutions.

The results are illustrated in Fig. 10 for CPP and in Fig. 11 for CDPF. The contribution analysis reveals that Portland cement is the main contributor to environmental impacts, contributing 88% to global warming and 79% to terrestrial toxicity. Electricity, meanwhile, is the almost exclusive cause of ozone depletion. Polypropylene fibers and transport appear to be significant secondary contributors, particularly to stratospheric ozone depletion and the scarcity of fossil resources. Overall, the results highlight that Portland cement production is the main source of environmental pollution, suggesting that reducing its use or replacing it with alternative materials could significantly reduce the process's environmental footprint [67]. Transitioning to carbon-free electricity can effectively reduce the overall environmental footprint. Nevertheless, the substitution of polypropylene fibers with date palm fibers offers a potential reduction in the environmental burden associated with the fiber fraction of the material.

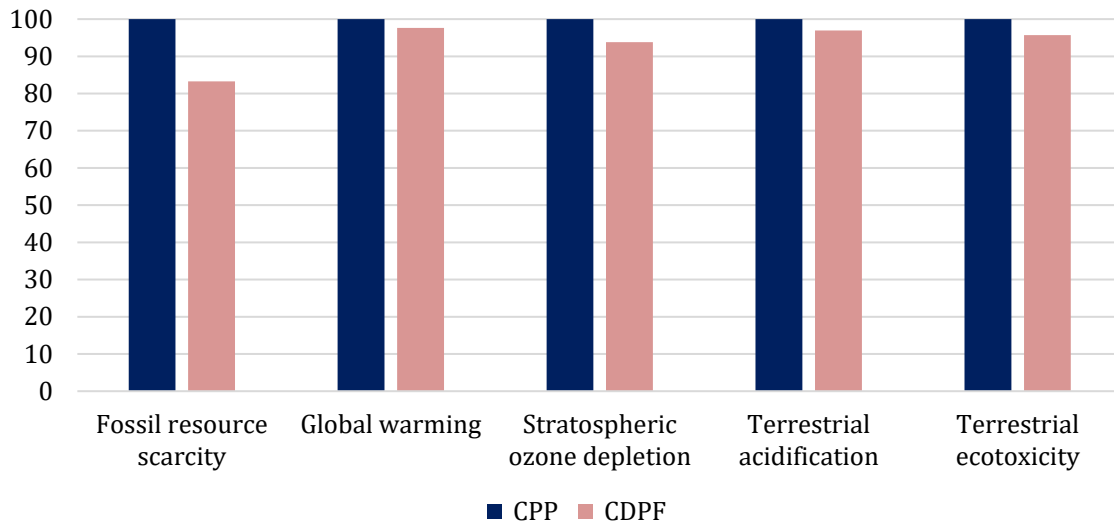


Fig. 9. Midpoint comparison of concrete reinforced by PP and DPF fibers.

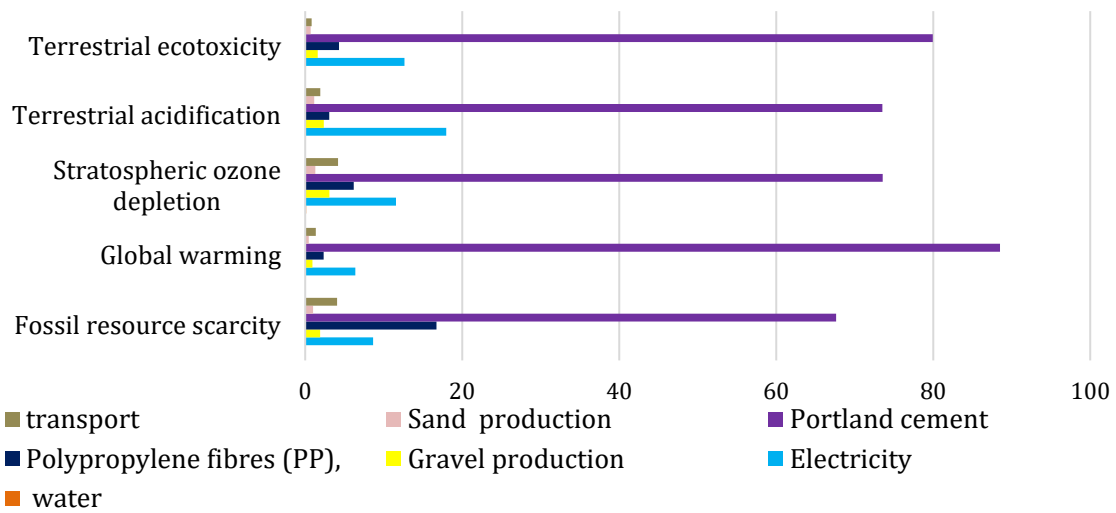


Fig. 10. Contribution of different flows in the impacts of CPP

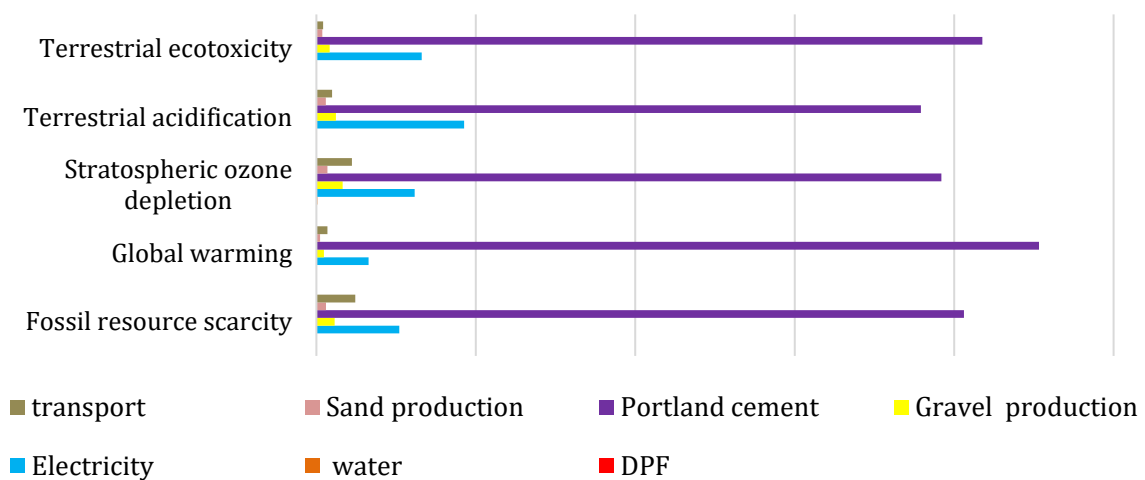


Fig. 11. Contribution of flows in the impacts of CDPF

### 3.5 Uncertainty Analysis

As part of this study, an uncertainty analysis was conducted to assess the impact of different scenarios on the results obtained and to quantify the model's sensitivity to parameter variations. This approach also addresses the unavailability of certain local data in the Moroccan context and provides a rigorous framework for interpreting results despite data gaps and identifying the elements that most influence the conclusions.

Table 8. Uncertainty Analysis

Parameter	Low Scenario (-25%)		Baseline Scenario ( $\pm 0\%$ )		High scenario (+25%)		GWP variation
	Value of parameter	GWP	Value of parameter	GWP	Value of parameter	GWP	
Transport distance (Km)	30	398.271	40	399.646	50	401.021	$\pm 0.34\%$
Electricity mix (kWh)	12.75	394.909	17		21.25	404.383	$\pm 1.18\%$
Fiber fraction (Kg)	3	397.840	4		5	401.452	$\pm 0.45\%$
Binder fraction (Kg)	300	309.084	400		500	490.208	$\pm 22.66\%$

Table 8 highlights that the binder fraction is the predominant parameter in the environmental impact assessment, measured through global warming potential (GWP). A variation of  $\pm 25\%$  in this parameter induces a considerable fluctuation of  $\pm 22.66\%$  in GWP, highlighting its sensitivity and decisive role in the material's carbon footprint.

By comparison, the other variables studied, such as raw material transport distance, electricity mix, and fiber fraction, exert only a marginal influence, with GWP variations of less than  $\pm 1.2\%$ . In this context, since some data, particularly those relating to transport and electricity mix, were not available for the Moroccan context, we used European values as an approximation. Uncertainty analysis showed that the influence of these parameters on the overall results remains low across all the scenarios studied, confirming that their substitution does not significantly affect the study's conclusions.

### 4. Conclusion

In conclusion, plant fibers offer significant advantages for sustainable construction, including low cost, availability, and eco-friendly properties. They offer a viable alternative to synthetic materials in cement-based composites, enhancing both mechanical and thermal performance. Additionally, the incorporation of plant fibers can reduce shrinkage in cementitious materials by acting as reinforcement points and limiting crack formation.

Despite these advantages, the use of plant-based fibers in construction comes with several challenges. Chemically, the fibers are prone to degradation in alkaline environments, which is a characteristic of cementitious matrices. This degradation arises from the interaction between the fibers' organic components and the hydration products of cement, potentially altering setting times and compromising the composite's long-term durability. Physically, these fibers present other challenges, such as low adhesion to the cement matrix, high water absorption, and susceptibility to degradation under high-temperature conditions. Addressing these issues is crucial to completely realizing the potential of plant-based fibers in construction.

To overcome these challenges, several innovative approaches have been proposed. These include modifying the cement matrix by incorporating pozzolanic materials such as fly ash or metakaolin, which reduce its alkalinity and create a more favorable environment for plant fibers. Another

promising solution is accelerated carbonation, which helps stabilize the matrix and improve the fibers' durability. Additionally, physical and chemical treatments, such as surface modifications, coatings, or impregnation with compatible agents, are being explored to enhance fiber-matrix interactions. Improvements in manufacturing processes, including optimizing mixing techniques and fiber dispersion, are also essential for enhancing composite performance. These strategies collectively aim to strengthen fiber-matrix bonds and optimize the overall performance of cementitious composites.

The comparative environmental assessment conducted in this study shows that both types of fiber-reinforced concrete, one with DPF fibers and the other with polypropylene (PP) fibers, exhibit similar overall environmental impacts, primarily due to the low fiber incorporation rate (around 1%), which limits the influence of fibers on the total environmental profile. Nonetheless, the results demonstrate a slight but consistent environmental advantage for the concrete reinforced with DPF fibers. These improvements suggest that DPF fibers could be a more sustainable alternative to conventional industrial fibers, especially in concrete formulations where fiber dosage is limited.

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