Journal of Building Engineering 98 (2024) 111267

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Natural fibers as reinforcement of mortar and concrete: A systematic review from Central and South American regions

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ARTICLE INFO

Keywords:
Natural fiber
Natural fiber-reinforced concrete
Natural fiber-reinforced mortar
Compressive strength
Flexural strength
Agricultural waste

ABSTRACT

This study examines recent research on mortar and concrete reinforced with natural fibers (NF). NF are a sustainable, eco-friendly alternative to conventional fibers, offering a way to reduce waste that would otherwise end up in landfills. The diversity of environments across continents provides a wide range of NF to study, and examining representative regions advances the knowledge obtained by enabling comparisons among varied global conditions. A key challenge with NF is their susceptibility to aggressive environments, thus necessitating pretreatment, with alkaline treatment being the most common method to enhance NF properties. As it has been reported, the workability of concrete and mortar decreases as NF content increases, yet this can be mitigated by adding more water or superplasticizers. Despite their benefits, it is advised not to use more than 0.5 % vol. of NF, as higher amounts typically lead to a reduction in the mechanical properties of the result. The durability and microstructure of NF-reinforced materials varies in accordance with test conditions and fiber types, moreover, testing in saline or accelerated aging environments often yields poor results. Further research on NF durability, particularly regarding dry-wet cycles and chloride penetration, is crucial. Environmental analyses show that concrete with NF offers lower energy requirements and reduces carbon footprints. Given the global complexities of NF, systematic studies in other regions are needed for comparative analysis. Nonetheless, using NF as reinforcement helps reduce agricultural waste by diverting it from landfills, aligning with circular economy principles, and promoting sustainability.

1. Introduction

At present, concrete is the most popular material in the construction sector, with an estimated 14 trillion m^3 produced in 2020 [1]. It is well known that this material works excellently in terms of compression, however, this does not happen when it is subjected to bending and tensile forces. For this reason, the reinforcement of concrete using fibers has been researched for years, with the most common being steel fibers [2] (SF). Other types of fibers studied are polypropylene [3], polyethylene [4], glass [5] etc., which serve as alternatives to conventional SF. The use of natural fibers (NF) has emerged as another alternative to SF and plastic fibers. The nobility of this type of fiber lies in the fact that such raw material is organic waste from various processes, which, if not reused, would be sent to

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https://doi.org/10.1016/j.jobe.2024.111267
Received 20 June 2024; Received in revised form 13 October 2024; Accepted 5 November 2024
Available online 12 November 2024

landfills, closing the production chain.

There are many NF types, the most common reported are wood, grass, fruit, stalk, bast, leaf, seed, silk, and wool. It is relevant to mention that the choice of NF to be used will depend on the geographical conditions of the target country and its availability [6]. According to the DNFI, in 2023, the global production of NF in Europe was 31.4 million tons [7] with an annual value of 60 billion dollars [8]. Recent reports indicate that global NF production in 2024 is estimated at 32.6 million tons, comprising 26.2 million tons of cotton, 2.6 million tons of jute, 1.2 million tons of coir, 1 million tons of wool, and 1.6 million combined tons derived from other fibers [7]. However, the global disposal rate of NF remains unclear. For instance, in Colombia, it has been documented that 88.84 % of banana plants are discarded annually [7]. Moreover, it's reported that only 12 % of banana plant components are utilized, leaving 88 % to waste [9]. In Mexico, agave waste amounted to 337 thousand tons in 2016 [10]. Sisal fiber (SSF) production worldwide reached approximately 200 thousand tons in 2018, with the majority produced in several countries across Africa, Latin America, and Asia [9]. Notably, SSF represents only 3–5 % of the fresh leaf weight of the sisal plant [9]. This means that 95%–97 % of the plant material is left to waste, contributing significantly to agricultural and industrial waste streams. Additionally, the jute industry in Bangladesh generates about 40 thousand tons of processing waste annually [11]. In 2017, 1.84 billion tons of sugarcane were produced worldwide, but 30 % of the pulpy, fibrous residue was left after being processed in sugar mills [12]. Coconut fruit annual worldwide production is reported to be 64 million tons and the processing of coconut water and meat leads to the annual generation of 1,400,980 tons of coconut shell [13]. Fique fiber (FF) represents only 4–5% of the total harvested fique leaf, with the remaining 95–96 % consisting of residue from the fiber extraction process [14]. It has been reported that nearly 93 thousand tons of fique bagasse are produced annually in Colombia [15] then generally discarded in soil and landfills [16]. Flax production worldwide is said to be around 2467 million tons [17]. The main producers of flax are Canada, Kazakhstan, China and Russia [18]. Flax fiber (FxF) accounts for 0.7 % of the world's fiber production [19]. FxF from the stem generates a huge amount of waste which is either dumped as is or used as fuel in industrial furnaces to some extent [20]. Likewise, it has been reported that sunflower production is about 11 million tons, and the volume of waste generated from its cultivation amounts to about one million tons [21].

Therefore, the field of knowledge concerning NF is considerably vast, considering the aforementioned great potential number of plant species from which NF can be extracted, which are determined depending on the use that will be given to them. This results in very heterogeneous conditions and the need to organize the current knowledge according to the environmental characteristics (man-made and ecological) of the different environments where the application of this type of fibers is experimented. In the Central and South American region, which includes a population of more than 624 million inhabitants, 21 countries [22] and 17 vegetation zones [23,24], there is a lack of systematization of knowledge in this area, which hinders the impact of this type of technologies and their application towards materials with a lower carbon footprint, thus interfering with the generation of more sustainable materials. Hence the importance of a study of this nature to organize and prioritize the progress made in the use of NF in mortars and concrete types.

In response to the reported high production of natural fibers (NF), their wide variability depending on the region of the world from which they originate, and the lack of systematization of NF properties in each region in terms of their composition, physical-mechanical properties, and their effect on the fresh and hardened properties of mortar and concrete as reinforcement, this study seeks to systematize this information through a literature review. Given the broad scope of study regions, the authors limited the search for information to the Central and South American regions.

2. Research novelty

The novelty of this work lies in addressing the lack of systematic information regarding NF across different regions of the world. While several papers [25–34] analyze the physico-mechanical properties of NFs and their influence on the mechanical properties of cement-based materials in a general manner, they often do not ascertain the region from which the NFs originate. It is important to consider that each region has its own unique NFs, each with distinct characteristics. Therefore, systematizing and organizing

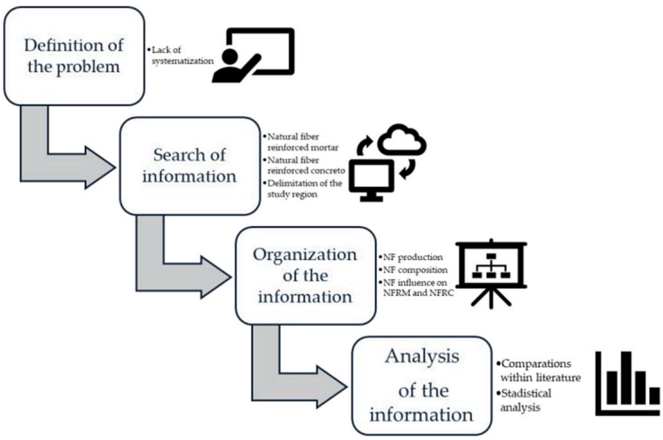

Fig. 1. Methodology diagram.

information about said NFs is crucial for obtaining precise data on their types and distinguishing features. Additionally, analyzing how each type of NF affects both the fresh and hardened properties, durability, and microstructure of cement-based materials provides researchers with a deeper understanding of the effects these fibers can have on the resulting material and how to enhance its performance. The contribution of this work is to build new information stemming from the information consulted related to the NFs of a specific region, which had not been previously systematized and visualized before this work.

3. Methodology

The methodology for this work consisted of four steps, which are presented and developed below. The schematization of the methodological process is presented in Fig. 1.

1) Definition of the problem: As outlined in the previous section, there is a significant lack of systematized information regarding NF and their regional variations (see Fig. 2). The unique characteristics of NF, which vary depending on their geographic origin, are often not distinguished in existing studies. Furthermore, a detailed analysis of how these region-specific fibers influence both the fresh and hardened properties of cement-based materials is needed to better understand their impact and potential for optimizing material performance.
2) Search for information: The information search was conducted in October 2023 using the bibliographic search engine Web of Science and Scopus, employing the keywords 'Natural fiber', 'concrete', and 'mortar'. The selection criteria for said information search was that the articles included studies on the workability, mechanical properties and durability of fiber-reinforced concrete and mortar. The purpose was to generate new knowledge from the published information. The field of knowledge concerning NF is extensive, hence the need to organize the current knowledge according to the environmental characteristics (man-made and ecological) of the different environments wherein the application of this type of fibers is experimented. There is a need to organize and systematize information to generate new knowledge on research trends and areas of opportunity to fill the gap that can be detected within Central and South American countries which is the focus of the present paper. Identified articles were screened to include only those relevant to the region under study. Criteria for inclusion required articles to analyze workability, mechanical properties, and durability of cement-based materials. Conference papers and articles behind paywalls were excluded. The first section of the results in the present document? covers the scientific production of natural fibers NF in the study region.

Fig. 2. Research publications of natural fiber reinforced concrete in Central and South America.

3) Organization of the information: Within the first section, sub-sections address the composition of NF, including α-cellulose, hemicellulose, and lignin, as well as their physical-mechanical properties such as diameter, density, absorption, tensile strength, and elastic modulus. The treatments applied to NF are shown in the second section. The third section focuses on the properties of natural fiber-reinforced mortars (NFRM), covering their fresh state characteristics, mechanical properties, and durability. Finally, the fourth section examines natural fiber-reinforced concretes (NFRC), detailing their fresh state properties, mechanical properties, and durability.
4) Data analysis: The information was processed, analyzed, and compared with findings from the literature reviewed and studied by authors from other regions to ensure a comprehensive analysis. The data analysis is shown by way of figures in the workability, mechanical properties and durability sections of NFRM and NFRC, respectively. Graphical methods were employed using data processing tools such as Kaleidagraph and Scimago Graph to illustrate the findings. Additionally, Pearson's chi-square statistical analysis was used to identify correlations between the compared variables (workability, mechanical properties, and durability). The analysis of the results will generate new knowledge concerning the influence of the NF of the studied region on the fresh properties, mechanical properties, and durability of NFRM and NFRC.

4. Results

4.1. Natural fibers studies in central and South America regions

Due to the extensive use of acronyms in this work, the following list (Table 1) is provided for better understanding.

Understanding the characteristics of these NF in the Central and South American region contributes to the knowledge and understanding of NFRC. Additionally, NF serves as a potential source of raw materials, which can add higher value to the production chains of the construction sector. Using the Web of Science database, a literature search was carried out focusing on NFRC, specifically in Central and South American countries, yielding 236 articles. The countries that stood out, according to the bibliographic search in terms of the number of articles published, were Brazil, Mexico, Chile, and Colombia. The articles found were excluded based on the

Table 1
Abbreviations.

Code	Meaning
AF	Açaí fiber
ALF	Agave lechuguilla fiber
BBF	Babassu fiber
BF	Banana fiber
CCF	Coconut fiber
CF	Curauá fiber
CSF	Cactus fiber
CTF	Cotton fiber
EF	Eucalyptus fiber
FF	Fique fiber
FxF	Flax fiber
FRC	Fiber-reinforced concrete
GF	Guadua fibers (bamboo)
GSF	Glass fiber
GHG	Greenhouse gas
HF	Hemp fiber
HNF	Henequen fiber
JF	Jute fiber
KF	Kenaf fiber
LF	Luffa fiber
LCA	Life cycles assessment
NF	Natural fiber
NFRC	Natural fiber-reinforced concrete
NFRM	Natural fiber-reinforced mortar
NPF	Nopal fiber
PF	Piassava fiber
PHF	Pig hair fiber
PNF	Pineapple fiber
PPF	Polypropylene fiber
PVAF	Polyvinyl alcohol fiber
RHF	Rice husk fiber
SF	Steel fiber
SCF	Sugar cane fiber
SFF	Sunflower fiber
SGF	Sponge gourd fiber
SSF	Sisal fiber
σ	Tensile strength
E	Elastic modulus

criteria detailed in the methodology section; 89 articles were found that met the search criteria (Table 2).

Understanding the prevalence and usage of these NFs is crucial for assessing their impact on various industries and exploring their potential in sustainable development initiatives throughout these regions. Table 2 shows that the most common NFs reported in the literature are sisal, coconut, and curauá. In the case of sisal and carauá, these NF originate from Brazil and appear in the first and third place, respectively, due to the high number of publications stemming from this country. On the other hand, the most common NF in Central and South America are those derived from coconut and sugarcane. It is important to mention that sisal, henequen, and hemp NF come from the agave family; however, in the literature, a differentiation is made between each of these species.

Table 3 shows the summary of the NF works by region. In Brazil, the high production of agro-industrial waste and variety of NF has led to research about new additions in building materials [35]. As previously mentioned, the most studied NFs are sisal and curauá. Sisal fibers (SSF), also known as henequen, originate from the *Agave Sisalana* plant, native to Mexico. It has been reported that Brazil is the largest producer of Sisal, with around 120 thousand tons/year [36]. As for curauá fibers (CF), they come from the leaves of the *Ananas Erectifolius*, a plant in the Amazon region [37]. It has been used as partial replacement of glass fiber in the industrial sector, according to the Brazilian government [38].

The principal NFs generated in Mexico are the agave, sugarcane, flax, nopal, and coconut. Regarding agave production, it was reported to be 303 thousand tons in 2018 [39]. Additionally, coconut production in Mexico was said to be around 220 thousand tons in 2016 [40], which increased to 226.57 thousand tons in 2022 [41]. In this regard, the use of coconut fibers (CCF) has been reported as a feasible way to increase the rheology and mechanical properties of concrete [40]. Sugarcane bagasse (*Saccharum officinarum* L.) is the major source of fiber for the pulp and paper industry in Mexico. In addition, it is used as a soil improver and wastewater treatment, yet a large part of this waste material is incinerated.

In the case of Chile concerning pig hair fibers (PHF), the overall production of pork was reported to be 616 million tons [42]. Particularly in Chile, the swine meat production in 2023 was reported to be 595,000 tons [44]. Whereas In Europe, the production of pig wastes (hair, blood and fat smelting water) was reported to be 890 thousand tons per year, with an annual management cost of 20.7 million euros in 2012 [43].

In the case of Colombia, one of the fibers with the highest production is FF, which comes from a plant native to tropical America. Fique is mainly grown in the zone of Nariño, with 8730 tons of it being produced in 2020 [45], representing 41 % of its overall production, followed by Cauca (39 %), Santander (7 %), Antioquia (6 %), and Guajira (6 %) [46]. Regarding coconut, its production in Colombia was reported to be 155 thousand tons in 2021 [47].

Coconut [48,49] and sisal [3] are the most proposed NFs in Ecuador. Ecuador produced 26,158 tons of coconut in 2020 [50]. According to data from the Food and Agriculture Organization of the United Nations the production of Sisal in Ecuador surpassed 3 thousand tons in 2004 [47].

In short, the usage of NFs is supported due to their high production and the search for alternatives to mitigate solid waste generation. Each country in Central and South America generates different types and quantities of NFs; therefore, harnessing these can be beneficial as concrete reinforcement, creating a stronger, environmentally friendly, and sustainable material for the building engineering field.

4.1.1. Composition

NFs are subject to significant variation in mechanical, physical, and chemical properties due to the plant conditions, the soil

Table 2
Reported NF in the study region.

Type of fiber	Number of works	%
SSF	17	21
CCF	10	12
CF	10	12
SCF	5	9
ALF	6	7
EF	4	5
JF	4	5
PF	3	4
HNF	3	4
FF	3	4
AF	2	2
BBF	1	1
BF	2	1
FxF	3	4
HF	1	1
SFF	1	1
CSF	1	1
PHF	1	1
NPF	1	1
GF	1	2
LF	1	1
Total	81	100

Table 3
Reported NF works by region.

Region	Type of fiber	Number of works	Reference
Brazil	AF	2	[51,52]
	BBF	1	[53]
	BF	1	[54]
	CCF	4	[55–58]
	CF	10	[35,37,59–66]
	EF	3	[67–69]
	JF	2	[70,71]
	PF	3	[72–74]
	SSF	14	[56,71,74–85]
	SCF	4	[54,69,86,87]
Mexico	ALF	6	[88–93]
	CCF	2	[94,95]
	FxF	3	[90,93,96]
	SCF	2	[97,98]
	CSF	1	[99]
	HNF	3	[100–102]
	LF	1	[103]
	NPF	1	[104]
	HF	1	[96]
Chile	PHF	1	[105]
	JF	1	[106]
	EF	1	[107]
Colombia	SFF	1	[108]
	FF	3	[109–111]
	CCF	2	[109,112]
	SCF	1	[113]
	GF	2	[114,115]
	SSF	1	[109]
Ecuador	CCF	2	[48,49]
	SSF	1	[3]
Perú	JF	1	[116]
	SSF	1	[117]
Total	–	82	–

constituents, and the climate variables. In addition, the procedures of extraction used can influence the mechanical performance of the fibers. The shape and morphology of the cross-section of the plant fibers, and thus mechanical properties, are also variable along their length, generally correlated to the distance from the main stem [63].

The composition of a NF can explain its mechanical properties. α-cellulose, hemicellulose, and lignin are the most studied parameters regarding the chemical composition of a NF. Regarding α-cellulose, its content is related to the amount of polymeric chains of cellulose which are the components related with the reinforcement capacity [63]. The hemicelluloses present in a NF are responsible for its water absorption, although other components play an important role as well. The process of water absorption is correlated with the expansion and shrinkage of the fiber. Shrinkage happens when the humidity of the fiber falls below the water level of saturation [111]. Lignin is the amorphous-polymeric element of a fiber and serves as the natural binder responsible for the integrity of said fiber as well as for the consolidation of the micro-fibril chains. NFs are characterized by a huge variability in terms of morphological characterization [70]. CF have a surface roughness with a cross section of an elliptical shape. These characteristics help them to anchor better in a cementitious matrix [64]. JF are characterized by an irregular morphology [118]. Table 4 shows the findings in the literature in accordance with different authors.

Table 4
Composition of the natural fibers according to different authors.

Type	α-cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
EF	41.57–49.91	18.12–32.56	17.60–25.40	[27,107]
CF	68.00–69.00	10.00–14.00	10.00–13.00	[63,64]
PF	31.60–43.23	2.34	48.40–50.05	[63,119,120]
SSF	60.70–61.77	20.72–25.70	12.10–12.42	[63,81]
FF	53.00–70.00	17.00–26.00	4.00–10.10	[111,121]
AF	34.41–46.43	12.26–17.21	7.72–31.12	[52,122,123]
JF	59.00–72.00	14.00–20.00	11.00–15.00	[32,121,124]

4.1.2. Physical-mechanical properties

In this section, the physical-mechanical characteristics of each of the different types of NFs found in Central and South America countries will be presented. The countries with reported NFs works are Brazil, Mexico, Colombia, Argentina, Chile, Ecuador, and Peru.

Table 5 presents the properties of NFs reported in Central and South America. The data collected is the mean of several valorization processes in each NF type. In all of the cases, a high-water absorption level is observed. This is because hemicelluloses in addition to other components play a significant role. The water absorption process is correlated with the expansion and shrinkage of the fiber used. Shrinkage occurs when a fiber's humidity falls below the water saturation level. This reversible process is detrimental to a natural fiber-reinforced Portland cement composite because such a fiber separates from the matrix [51].

As can be seen on the results of Table 5, the diameter of the SSF ranges from 0.13 to 0.22 mm, with a density of 0.90–1.10 g/cm^3. Water absorption values vary from 125 to 152 %. The high level of absorption reported occurs because the SSF was immersed for 96 h [79]. Additionally, it has been reported that the high absorption of the SSF could negatively affect its adherence to cement and its workability [79]. Regarding its mechanical properties, tensile strength and elastic modulus values go from 353 to 639 MPa and from 18 to 25 GPa, respectively.

CF are typical of Brazil, with its diameter values being from 0.08 to 1.42 mm. Regarding density, the reported value is 1.10 g/cm^3.

Table 5
Properties of Natural Fibers according to different authors.

Brazil						
Type	Diameter (mm)	Density (g/cm^3)	Water absorption (%)	σ (MPa)	*E* (GPa)	Reference
SSF	0.15–0.22	0.90–0.95	152.00	353.00–639.01	15.72–21.44	[71,76,78–81,126]
CF	0.08–1.42	1.10	–	550.00–872.00	16.50–64.00	[61–65,71]
CCF	0.10–0.40	0.80–0.93	28.00	150.00–174.00	3.00–300.00	[54,57,78]
JF	–	–	–	249.00–250.00	43.90–44.00	[70,71]
PF	–	–	–	61.00–134.80	1.07–1.82	[63,119]
AF	0.30	–	–		–	[51]
SCF	0.20–0.40	–	–	170.00–290.00	15.00–19.00	[54]
BF	0.15	–	–	384.00	20.00–51.00	[54]
BBF	0.53	1.67	38.24	215.44	–	[53]
SGF	–	–	–	127.00	3.20	[127]
Mexico						
Type	Diameter (mm)	Density (g/cm^3)	Water absorption (%)	σ (MPa)	*E* (GPa)	Reference
ALF	0.02–0.26	1.19–1.48	69.00–97.80	275.00–627.00	–	[90,91,128]
FxF	0.009–0.049	1.42	148.00–111.00	1015.00	–	[90,93,96]
HNF	0.17	1.40	–	500.00	13.20	[100]
Colombia						
Type	Diameter (mm)	Density (g/cm^3)	Water absorption (%)	σ (MPa)	*E* (GPa)	Reference
FF	0.16–0.42	1.47	60.00	43–571	8.20–9.10	[111,129]
CCF	0.10–1.50	–	–	189.24	–	[112]
GF	–	0.80	63.00	–	–	[114]
SFF	–	–	–	470.00	35.00	[108]
Argentina						
Type	Diameter (mm)	Density (g/cm^3)	Water absorption (%)	σ (MPa)	*E* (GPa)	Reference
SCF	–	–	–	82.00	5.60	[130]
HF	–	–	–	250.00	27.00	[130]
Chile						
Type	Diameter (mm)	Density (g/cm^3)	Water absorption (%)	σ (MPa)	*E* (GPa)	Reference
PHF	0.16	–	–	99.20	–	[105]
JF	0.05–0.09	1.12–1.50	–	400.00–800.00	10.00–30.00	[106]
EF	–	–	350	–	–	[107]
Ecuador						
Type	Diameter (mm)	Density (g/cm^3)	Water absorption (%)	σ (MPa)	*E* (GPa)	Reference
SSF	0.10–0.20	1.10	–	328.80	–	[3]
CCF	–	0.58	145.50	–	–	[48]
Peru						
Type	Diameter (mm)	Density (g/cm^3)	Water absorption (%)	σ (MPa)	*E* (GPa)	Reference
SSF	0.13	–	125.00	508.00	25.00	[117]
JF	0.05	–	–	276.00	27.00	[131]

***σ*:** Tensile strength; ***E*:** elastic modulus.

The tensile strength of CF ranges between 550 and 872 MPa and its elastic modulus goes from 28 to 64 GPa. The use of Piassava fibers (PF) is also reported in Brazil, the tensile strength and elastic modules range from 61 to 134 MPa and from 1.07 to 1.82 GPa, respectively. Banana fibers' (BF) use is reported in Brazil. Their diameter, tensile strength, and elastic modulus values are reported to be 0.15 mm, 384 MPa and 20–51 GPa, respectively. Babassu fibers' (BBF) diameter, density and water absorption value is 0.53 mm, 1.67 g/cm^3, and 38.24 % respectively. Regarding their mechanical properties, their tensile strength is reported as 215.44 MPa.

Coconut fibers (CCF) results are reported for Brazil, Colombia, and Ecuador. CCF diameter ranges between 0.10 and 1.50 mm. Density values range from 0.58 to 0.93 g/cm^3. Moisture values vary between 13.50 and 13.70 %. Regarding water absorption, it fluctuates from 28 to 145.50 %. Its tensile strength goes from 150 to 174 MPa and its elastic modulus ranges from 3 to 26 GPa.

Jute fibers (JF) results are stated for Brazil, Chile, and Peru. JF diameter goes from 0.05 to 0.09 mm. Density can range from 1.12 to 1.50 g/cm^3 and their moisture has been reported to be 12 %. It must be noted that no water absorption values for this fiber were reported in any of the works studied in Latin America, this lack of water absorption information is also noted by the ACI [125]. Tensile strength and elastic modules can fluctuate from 249 to 800 MPa and 10–44 GPa, respectively.

Sugarcane fiber (SCF) works are reported for both Brazil and Argentina. Diameter values are ranging from 0.02 to 0.40 mm. Density values are not reported in the collected data, but, according to the literature consulted, these values range from 1.20 to 1.30 g/cm^3 [125].

There is not much information regarding sponge gourd fibers (SGF), although their tensile strength and elastic modulus reported values are 127 MPa and 3.20 GPa, respectively.

Agave Lechuguilla fibers (ALF) are studied mostly in Mexico. The documented diameter of ALF is noted to be from 0.02 to 0.26 mm and its density ranges from 1.19 to 1.48 g/cm^3. Water absorption and tensile strength values vary from 69 to 97.80 % and from 275 to 627 MPa, respectively.

FF studies were reported in Colombia where FF diameter, density, and water absorption were observed to be between 0.16 and 0.42 mm, 1.47 g/cm^3, and 60 %, respectively. Additionally, FF tensile strength values range between 43 and 571 MPa.

Hemp fibers (HF) studies are reported in Argentina where the diameter and water absorption are reported to be 0.03 mm and 151 % respectively. Tensile strength and elastic modulus values are 250 MPa and 27 GPa, respectively.

Henequen fibers (HNF) diameter, density, tensile strength, and elastic modulus values are 0.17 mm, 1.40 g/cm^3, 500 MPa and 13.20 GPa, respectively. Guadua fibers (GF) and sunflower fibers (SFF) studies have been reported in Colombia where density, moisture, and water absorption values of GF were reported as 0.80 g/cm^3, 8 % and 63 %, respectively. Regarding SFF, their tensile strength and elastic modulus values are 470 MPa and 35 GPa, respectively.

PHF and Eucalyptus fibers (EF) studies were reported in Chile. The PHF reported diameter and tensile strength were 0.16 mm and 99.20 MPa, respectively. Additionally, EF's only reported value is water absorption, with a value of 350 %. Which is the highest water absorption value of all the NF reported in this work.

The physical properties of NF, including diameter, density, and water absorption, significantly influence their performance in cement-based materials. Fibers with higher tensile strength and elastic modulus generally provide better reinforcement, therefore improving the material's mechanical properties. However, a high water absorption can negatively impact workability and adhesion, potentially reducing the effectiveness of the fibers. Choosing the right NF for reinforcement requires balancing these properties with the desired performance outcomes. For example, CF and BF show strong mechanical properties, making them effective reinforcements. In contrast, fibers like SSF and EF, which have high water absorption, present challenges that must be managed to ensure their effective use. Fibers with lower water absorption rates are typically preferred for maintaining consistency in cement-based materials. CF, ALF, and SFF are examples of NF that combine strong mechanical properties with manageable water absorption, making them well-suited for high-performance applications.

4.2. Treatments to improve the properties of NF in cement-based materials

The significance of treating NF for integration into concrete is multi-faceted. Firstly, proper treatment enhances the fibers durability by bolstering their resistance to biological and chemical degradation, thereby extending the overall lifespan of the composite material. Secondly, treatments enhance the adhesion between NF and the concrete matrix, ensuring a uniform dispersion and an efficient load transfer, which, in turn, maximizes mechanical properties. Moreover, treatments serve to diminish moisture absorption, safeguarding against premature degradation triggered by moisture-induced expansion and contraction. Lastly, treatments improve the mechanical properties of NF, including strength and toughness, leading to reinforced concrete structures that exhibit greater strength and durability. Ultimately, the pre-treatment of NF before their incorporation into concrete is pivotal for optimizing said material's durability, adhesion, and strength, thus facilitating the creation of sustainable and resilient building structures.

Several methods are used for the treatment of NF, among them, mercerization, acetylation, etherification, peroxide treatments, benzolization, etc. [132]. These treatments improve the fiber's mechanical properties, clean their surface, decrease their moisture absorption and improve their surface, improving their adhesion. Mercerization is another name for the alkaline treatment of NF [133], its advantage over other methods is that it is low cost and environmentally sustainable because it does not require toxic chemicals [134]. This would explain why, in the literature, this method of treatment, together with the use of water to wash the NFs, is the most widely used. In the literature consulted, the environmental impacts of mercerization are related to the water pollution caused by the discharge of untreated effluents, mainly in the textile industry, however, these impacts can also be caused by the treatment of NF for the construction industry. To counteract the aforementioned impacts, various ways of treating contaminated water have been developed, among those are preliminary treatments such as screen treatments, equalization and neutralization and coagulation, to name a few [135]. Considering that the works reported in the literature reviewed are carried out on a laboratory scale, it should be considered that, to counteract the effects on water alkalinization, it must be neutralized for proper disposal into the drainage or rainwater network.

Alkali treatments' objective is to remove hemicellulose and lignin from fiber wall and increase surface roughness by calcium deposition, which has positive infiuence on the fiber-matrix bond [62]. Lima et al. [126] studied the treatment of SSF with biopolymers (cellulose acetate, hydrophobic starch, and cassava starch). The cellulose acetate used (CA) reduced the water absorption of SSF from 200 % (without treatment) to 88 %. This was attributed to a coating layer that formed around the SSF after the biopolymer treatment. The reported tensile strength and elastic modulus of untreated SSF were around 640 MPa and 21 GPa, respectively, however, the biopolymer treatment reduced its mechanical properties.

It was reported that CA treatment and hydrophobic starch (HS) treatment reduced the tensile strength and elastic modulus by 26 and 29 %, respectively. While the cassava starch (CS) reduced the above-mentioned mechanical properties by 35 and 39 %. Velez et al. [48] studied CCF with alkaline treatment and silica fume treatment. The first treatment consisted of immersing CCF in a 4 % by weight NaOH solution for 24 h, followed by the rinse in tap water until neutral pH was achieved. The second treatment consisted of dipped CCF in liquid gum arabic for 1 min, followed by the adhesion of silica fume [48]. The NaOH treatment promoted a slight increase in the maximum elongation of the fibers compared with the natural CF and silica fume treatment. Likewise, a higher linear density was found in relation to the other typologies. However, a lower value of average breaking strength (and consequently, of toughness) was obtained for the CCF fibers in relation to the natural state and silica fume treated ones.

Additionally, the use of washing water in CF has been reported by Teixeira et al. [61], t for the cleaning of impurities retained by the surface of the fiber and to minimize the water absorption. Soltan et al. [63] also reported washing the CF with hot water at 80 °C for at least 18 h and drying it at 90 °C for 12 h at least. De Oliveira et al. [53], treated BBF with a NaOH solution 5 % by weight for 3 h. It was reported that the NaOH treatment produced rough surface regions with more exposed globular marks, from which we may infer that the alkaline treatment promoted the partial removal of hemicellulose and lignin, as well as the dissolution of the other amorphous non-cellulosic components. Chemical treatment cleaned the fiber surfaces, which is a requisite for the adequate adherence of the fibers. Zukowski et al. [136], characterized CF after water washing and alkali treatment. The first treatment consisted of three washing cycles in hot water 80 °C for 3 h. The second treatment was the alkaline treatment of the washing CF, immersion in 1 % calcium hydroxide $Ca(OH)_2$ solution [136].

Marvila et al. [51] studied the alkaline treatment of AF which consisted of immersing the fibers in NaOH solution for 30 min and then washing the material with HCl to neutralize the pH, which should be around 7. Subsequently, the AF were washed with running water, allowing the effluent to be discarded in the sewage system then dried in greenhouses for application in mortar. It was reported that the treatment with NaOH created a rougher surface of the fiber, which is an indication that the treatment with NaOH carried out was effective, since there was an increase in the surface of the material. The treated fiber has an irregular surface with protrusions that helped in adhering to the cementitious matrix [51].

An alkaline and plasma treatment for surface modification applied to GF was reported by Sanchez et al. [114]. The alkaline treatment consisted of the immersion of the crushed material in a 5 % sodium hydroxide solution for a period of 48 h at room temperature. This process was followed by washing with distilled water and drying until a constant mass value was reached. For the plasma treatment, untreated fibers were subjected to the uniform action of a methane cold plasma for 10 min using a working pressure of about 27 Pa and a DC potential of −700 V, with a gas flow of 10 sccm and temperature between 18 °C and 26 °C. The results indicated that the alkaline treatment reduced the absorption capacity of GF by approximately 30 %. For GF treated with plasma, this reduction can reach approximately 60 % [114]. Zukowski et al. [60] immersed CF in a saturated solution of calcium hydroxide $Ca(OH)_2$ with water for 60 min then dried them. This was made to remove hemicellulose and lignin from the fiber wall and to increase surface roughness by calcium deposition, which had a positive influence on the fiber-matrix bond [62].

Castillo et al. [101], alkali treated HF with a NaOH aqueous solution at 2 % for 1 h at 25 °C, after that, the HF were washed until the sodium hydroxide was eliminated. Table 6 presents the results related to the use of biopolymers and fiber treatments, showing their impact on tensile strength and elastic modulus. Compared to untreated SSF, biopolymers like CA, CS, and HS reduced tensile strength by approximately 25 %, 35 %, and 28 %, respectively, while the elastic modulus also decreased by 29 %, 39 %, and 30 % in the same

Table 6
Mechanical properties of natural and treated NF according to different authors.

Material	Tensile strength (MPa)	Elastic Modulus (GPa)	Reference
SSF	639.01	21.44	[126]
SSF-CA	475.42	15.20	
SSF-CS	415.92	13.09	
SSF-HS	467.78	14.93	
CF	735.19	28.71	[136]
CF-W	1096.72	35.92	
CF-ALK	697.19	39.01	
BBF	215.44	–	[53]
BBF-T	250.63	–	
AF	17.80	15.70	[52]
AF-T	–	13.30	

CA: Cellulose acetate treatment; CS: Cassava starch treatment; HS: Hydrophobic starch treatment; W: Water washing treatment; ALK: $Ca(OH)_2$ treatment; T: NaOH treatment.

order. For CF, water treatment (W) increased tensile strength and elastic modulus by about 49 % and 25 %, respectively, as opposed to untreated CF. However, alkaline treatments (ALK) reduced tensile strength by 5 % while increasing elastic modulus by 36 %, likely due to the degradation of hemicellulose and lignin, affecting cellular fiber connections [136]. BBF treated with a calcium hydroxide solution (T) showed a 16.33 % improvement in tensile strength, attributed to increased cellulose content [53]. On the other hand, AF treated with the same solution experienced a 15 % decrease in elastic modulus.

In conclusion, alkali treatment emerges as a method to eliminate hemicellulose and lignin from fiber walls, thereby augmenting surface roughness and enhancing the fiber-matrix bond. Biopolymer treatments, including cellulose acetate and starches, exhibit the ability to reduce water absorption in fibers, albeit potentially diminishing mechanical properties. Washing with hot water serves to cleanse impurities from NFs while minimizing water absorption. Furthermore, treatments like alkaline immersion and silica fume application on NFs yield varied outcomes, eliciting alterations in mechanical properties. Alkali and plasma treatments demonstrate efficacy in decreasing absorption capacity. Additionally, treatments involving calcium hydroxide immersion prove effective in removing hemicellulose and lignin from fiber walls, enhancing surface roughness, and augmenting the fiber-matrix bond. Overall, chemical treatments play a pivotal role in cleansing fiber surfaces and enhancing adhesion with mortar components, consequently enhancing mechanical performance in concrete structures.

4.3. Natural fiber reinforced mortars

NFRM combine traditional mortar components with NF for enhanced strength and durability. Unlike conventional mortar, NFRM utilize fibers from renewable sources like plants instead of conventional fibers like steel fibers or polypropylene fibers. With improved tensile strength, NFRM offer a sustainable alternative for various building applications, promising resilient and eco-friendly structures.

4.3.1. Workability

The problems presented in the rheology of NFRM with NF are loss of workability, increase in yield stress and increase in plastic viscosity, which is due to the increase in the amount and length of NF. This is due to the friction caused between the mortar paste and the interaction with the NF. The surface treatment of a NF increases the roughness of the NF, enhancing interfacial adhesion between NF and the mortar matrix. This stronger bond further reduces the fluidity of the mortar as the NF anchor more effectively in the matrix, consequently impacting workability [137]. Workability directly impacts the ease of mixing, application, and finishing of mortar, which is crucial for efficient construction processes and superior structural integrity. Mortar with good workability ensures uniformity and consistency in application, consequently reducing material waste and boosting durability. Additionally, An adequate mortar workability contributes to stronger bonds between masonry units, improving its resistance to external stresses and optimizing its structural performance. Mansilla et al. [107] studied NFRM with EF inclusion by 0, 2 and 5 % cement wt. with a length of 10–20 mm. Regarding workability, dry EF resulted in a slump decrease from 3.4 to 1.5 cm and a saturated EF resulted in a slump decrease from 4 to 2.5 cm. Regardless of the type of cement or the condition of the fiber used (dry or saturated), the mixes with 5 % EF resulted in the lowest slump values. Saturated EF presented higher slump values, this can be explained by the fact that, in a saturated condition, the EF are unable to

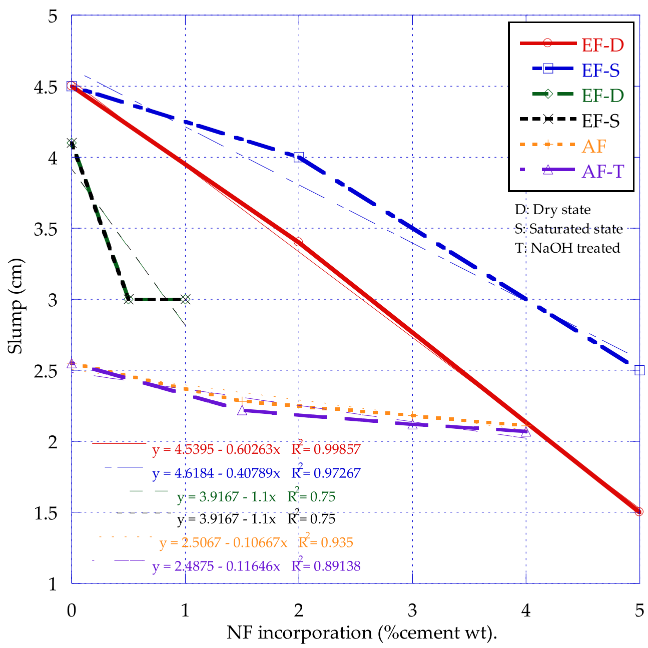

Fig. 3. Effect of the incorporation of NF in mortars workability according to different authors.

absorb water. On the contrary, as dry EF absorb water, there is less water in the mix, which affects its workability [107]. De Azevedo et al. [52] reported that 21 mm AF inclusion (1.5–5 % cement wt.) decreased workability of mortars as their inclusion increased. This reduction is due to the greater mass stability that the addition of AF bestows, providing greater internal cohesion of its constituents and filling any existing gaps. AF treated with a 5 % NaOH solution caused major roughness, generating an interfacial adhesion between the AF reinforcement and the mortar matrix, which corroborates an even greater reduction in mortar fluidity due to AF anchoring in the matrix, thereby affecting workability [52].

Fig. 3 shows the effect of the NF on the workability of mortars. It is observed that as the NF additions increase the workability decreases. This is corroborated by the result of the Pearson chi-square equations, which are very close to 1, meaning that there is a relationship between NF content and loss of workability. EF in a dry state reduced the workability from 24 % to 66 % with 2 and 5 % vol. incorporation. In a saturated state, EF reduced workability 11 % and 55 % with 2 % and 5 % cement wt. incorporation [107]. With a minor EF addition (0.5 and 1%cement wt.) in both dry and saturated states, the workability reduction observed was 27 %. AF in natural state also decreased the workability of mortars from 10 % to 17 % with up to 5 % cement wt. incorporation. AF treated with NaOH reduced the workability from 13 to 19 % with up to 5 % cement wt. incorporation. JF and SSF with a 2%cement wt. and 15 mm length incorporation reduced the workability of mortars up to 25 % and 14 %, respectively as reported by other authors [138]. It has been reported that the addition of JF reduced workability due to their rough surface, porous texture, and irregular stripes [139].

The addition of NF to mortar mixes generally results in reduced workability due to their increased friction and stronger fiber-matrix bonds. This reduction is compounded by factors such as fiber length, amount, and treatment. To counteract these adverse effects and maintain efficient mixing, application, and finishing processes, it is advisable to adjust the water-to-cement (w/c) ratio or use superplasticizers. These adjustments can help offset the negative impacts of NF addition, ensuring that the mortar remains workable and maintains its performance characteristics throughout its application.

Information regarding the rheology of NFRM in the Central and South American region is scarce [30,52,76,83,94]. In this context, De Azevedo et al. [52] reported that air content increases with the rise in untreated AF content due to the larger surface contact area between the matrix and the fibers. Conversely, when AF are added during treatment, the surface becomes rougher as a result of the alkaline treatment, creating a filling effect that reduces voids in the matrix, consequently, lowering air content [52]. The same study also reported that water retention and fresh density are negatively affected by both treated and untreated AF, although the performance of treated AF is better compared to untreated AF [52].

Azevedo et al. [140] reported that the addition of 5 % AF slightly increased the yield stress and viscosity of the cement paste, while a 10 % addition caused a significant increase, with yield stress and viscosity values reaching 40 and 8 times higher than those of plain paste, respectively. Incorporating 5 % untreated AF delayed cement hydration by approximately 2.5 days, and 10 % untreated AF extended the delay to over 160 h. However, alkaline treatment (NaOH and HCl) notably reduced this effect, resulting in only a 3-h delay with 5 % treated fibers.

Silva et al. [76] studied SSF-reinforced cement composites and reported that an optical micrograph of the cross-section, featuring two layers of SSF embedded in the matrix, revealed sufficient matrix penetration and fiber encapsulation. This suggests that the matrix rheology was appropriate for the effective manufacturing of the composite system [76].

Dos Santos et al. [86] reported that untreated SCF negatively affects the rheology and hydration of the cement matrix due to the higher absorption of SCF, which increases the number of pores and results in a less dense material. Additionally, it has been reported that regarding the fiber content, it is crucial to note that there is a critical concentration at which adding fibers to the cementitious matrix prevents the composite from flowing even in highly fluid pastes [141]. Overall, several authors have used superplasticizers and viscosity modifiers [60,62,64,71,84] to avoid segregation in order to improve the workability and rheology of the paste. The amount of each of the previously mentioned additives will depend on the desired results and amount of NF used.

4.3.2. Mechanical properties

The importance of compressive and flexural strength properties in mortars lies in their crucial role in assessing performance and suitability for various construction applications. Compressive strength indicates the mortar's ability to withstand axially applied loads, which is essential for structures subjected to vertical loads such as walls and columns. Conversely, flexural strength reflects the mortar's ability to resist bending forces and it is critical in structural elements subjected to lateral loads, such as beams and slabs. Both properties influence the safety, stability, and durability of structures built with mortar, and their proper evaluation ensures structural integrity and compliance with design and construction requirements.

Reis, J [54]. studied NFRM with 2 % by wt. of CCF, SCF and BF. The flexural strength results from CCF reinforced materials were higher than the other NF and an increase is also observed when compared to the control mortar. A rise of 25.1 % results from CCF reinforcement when flexural strength were analyzed [54].

Marvila et al. [51] studied up to 5 % cement wt. incorporation of AF of 25 mm length in mortar. It was reported that the compressive strength increased up to 34 % with 3 % cement wt. addition of AF. This is because when higher amounts of AF were added, there was a greater adherence in the matrix phase, due to the transfer of efforts provided by the fiber bonding bridges; however, when a quantity of AF is used above the wettability of the matrix, the fibers start to agglomerate, causing greater porosity and impairing the transfer of efforts [51].

De Oliviera et al. [53] reported the use of 30 mm NaOH treated BBF with incorporations ranging from 0.6 to 1.4 % cement wt. It was reported that the increase observed of up to 75 % and 19 % in the mechanical properties (compression strength and flexural strength, respectively) of mortars were due to the NaOH treatment. Treaded BBF is well adhered to the mortar, with no visual differentiation between them. This was attributed to the NaOH treatment caused by the dissolution of surface impurities of the fiber, promoting a less hydrophilic character, a higher aspect ratio, and a roughness that contributes to better mechanical interlocking between the fiber used and the cementitious matrix.

Talavera et al. [98] demonstrated that incorporating SCF enhances the compressive strength of mortars in comparison to control samples. The greatest improvements were observed with SCF additions of 0.5 % (13 % increase), 1 % (34 % increase), and 2 % (60 % increase). This enhancement is attributed to the fibers becoming embedded within the cementitious matrix, thereby reinforcing it and increasing its resistance [98].

Juarez et al. [90] studied the incorporation (0, 0.1 and 0.7 vol%.) of ALF and FxF in mortars. The use of ALF and FxF led to a reduction in compressive strength as opposed to the control mortar. All fiber-reinforced specimens presented a ductile failure. However, they could hold the applied weight and support significant strain without fragmentation contrary to the control mortar, which showed a brittle fracture [90].

Juárez et al. [93] reported the use of 45 mm ALF untreated and treated with a wax-based coating. The treatment of the ALF adversely affected the flexural strength, reducing it by 10 % with up to 1%vol. incorporation. This same reduction was reported for the compressive strength with the same incorporation [59]. The untreated ALF showed better mechanical behavior, increasing the compressive strength up to 14 % and flexural strength by 38 % with 0.4%vol.; this was due to the better adhesion with the cementitious matrix without the presence of a wax-based coating.

Sabathier et al. [96], studied 25–35 mm length FxF and HF with 1 % addition by weight in a hydraulic lime and calcined metakaolin matrix. When compared to the reference mortar (10 MPa), it was reported that the compressive strength increased by 22 and 18 % with FxF and HF additions, respectively. Regarding flexural strength, FxF and HF increased this mechanical property by 33 and 13 % contrary to the control mortar (around 1.5 MPa).

Flores et al. [100] studied 0.5%vol. inclusion of 4 mm length HNF. It has been reported that the fiber-reinforcement enhanced the mechanical properties of the resulting material as opposed to the control material, which is attributed to the enhanced specimen integrity produced by the HNF [100].

Araya et al. [105] studied 30–60 mm length PHF incorporation from 2 to 8 kg/m^3. It has been reported that 8 kg/m^3 of PHF reduced the compressive strength by 13 % compared to the control mortar (around 78 MPa). There is a 14 % increase of the flexural strength of the mortar with 8 kg/m^3 PHF in contrast with the control mortar (around 8.6 MPa) [105]. Fig. 4a shows a summary of the findings reported above. It can be observed that in most of the cases, a higher incorporation of 0.5 % of NF presented an increase of the compressive strength. Fig. 4b shows that the flexural strength is not highly affected by the incorporation of ALF, SCF, and PF. This is corroborated by the result of the Pearson chi-square equations, which are very close to 1, meaning that there is a relationship between fiber content and the mechanical behavior of NFRMs.

Overall, it can be concluded that the use of NF in mortar mixes can be beneficial, but only if their incorporation percentage does not exceed 1 %. This is because a higher amount of NF can reduce the workability of the mix, leading to increased porosity and a loss in mechanical strength. Despite these limitations, the use of NF can be a sustainable approach for managing waste generated by the agricultural industry, contributing to a circular economy, and reducing its environmental impact. To ensure the optimal and effective

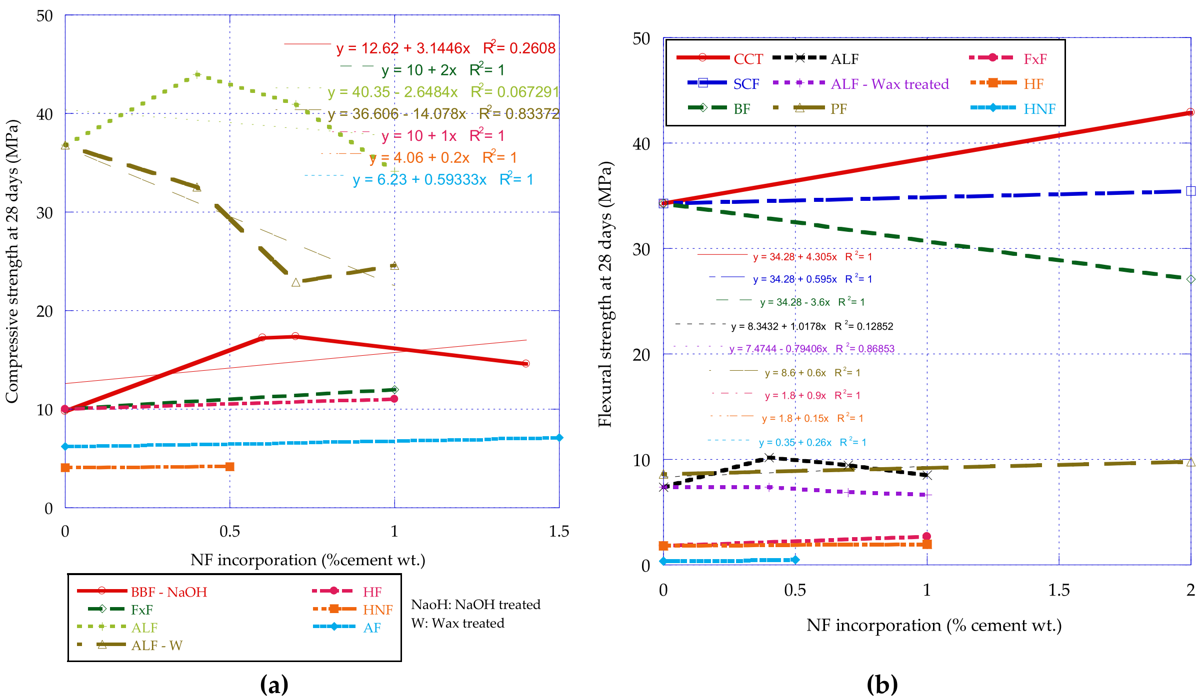

Fig. 4. Compressive strength (**a**) and flexural strength (**b**) of NFRM according to different authors.

use of NF in mortar, it is essential to maintain a balance in the proportions added to gain sustainability benefits without compromising the quality and durability of the material.

4.3.3. Durability

The durability of NFRM is crucial in determining whether these materials can withstand harsh environments. However, their susceptibility to environmental degradation, moisture absorption, and biological attack can limit their longevity. The information available in the studied region is scarce, however, the reported findings may help researchers to find lines of research regarding the durability of NFRM.

Mansilla et al. [107], evaluated concrete durability adding dry and saturated state EF (0 and 0.5%cement wt.). Both types of EF were treated with a paraffin emulsion. The compressive and flexural strength were evaluated after 20 aging cycles consisting of 18 h of heating at 105 °C and 6 h of immersion in water at 20 °C. It was concluded that the aging process does not affect the compressive strength. Regarding flexural strength, dry state EF with 0.5 % addition reported a 34 % compressive strength reduction versus the control concrete (around 45 MPa). According to the authors [107], it was concluded that the addition of EF does not affect the durability of the concrete with the other additional volumes. This is because the paraffin treatment prevents a proper interaction between the EF and the cementitious matrix [107].

Marvila et al. [51] studied the durability of coating mortars with AF at 0, 1.5, 3 and 5%cement wt. in relation to the cement mass. Thirty wet-dry cycles were made, these consisted in 12 h of immersion in distilled water and 12 h of drying at 110 °C. Also, 30 days of saline mist exposure were evaluated, and, finally, 30 days of thermal shock test were performed. The thermal shock consisted in heating the specimens at a temperature of 200 °C for 12 h followed by cooling them at 0 °C for 12 h. The compressive strength after the durability test was evaluated. In the wetting and drying cycle test, mortars with 1.5%cement wt. incorporation of AF (5.35 MPa) and 3.0 % (6.65 MPa) showed a better performance than the reference mortar (4.37 MPa). However, the 5.0%cement wt. AF mortar (4.56 MPa) faced issues due to fiber agglomeration, causing a significant drop in its strength [51]. Saline mist tests revealed problems with chloride salts damaging AF, resulting in 6.02 MPa for the reference mortar and 6.19, 5.98, and 3.42 MPa for compositions containing 1.5 %, 3.0 %, and 5.0%cement wt. AF, respectively [51]. Thermal shock tests showed values of 1.5 % and 3.0 %. AF mortars behaved well, with compressive strengths of 6.45 and 7.02 MPa, respectively, which is higher than the reference's 5.45 MPa. However, the 5.0 % AF mortar experienced considerable strength drop due to poor adhesion between phases, despite surpassing the reference mortar's strength (5.82 MPa) [51].

Araya et al. [105] studied the durability (abrasion resistance by ASTM D968 standard [142]) of mortars containing 2, 4, and 8 kg/m^3 PHF. The inclusion of 2 kg/m^3 s worth of pig hair proved effective in enhancing abrasion resistance, resulting in a reduction of up to 42 % in mass loss compared to plain mortar. During testing, fibers were observed to break due to sand impact, confirming their strong adhesion to the mortar matrix. It is plausible that PHF near the mortar surface exert two opposing effects on abrasion resistance: beyond 4 kg/m^3 of PHF, the surface paste may weaken due to the PHF limited mechanical properties, and at lower fiber dosages (2 kg/m^3), they may effectively reinforce the paste, enhancing its resistance to abrasion [105].

Filho et al. [83] studied 6%vol. SSF content in mortar composites after 25 cycles of aging by wetting-drying cycles. Results showed

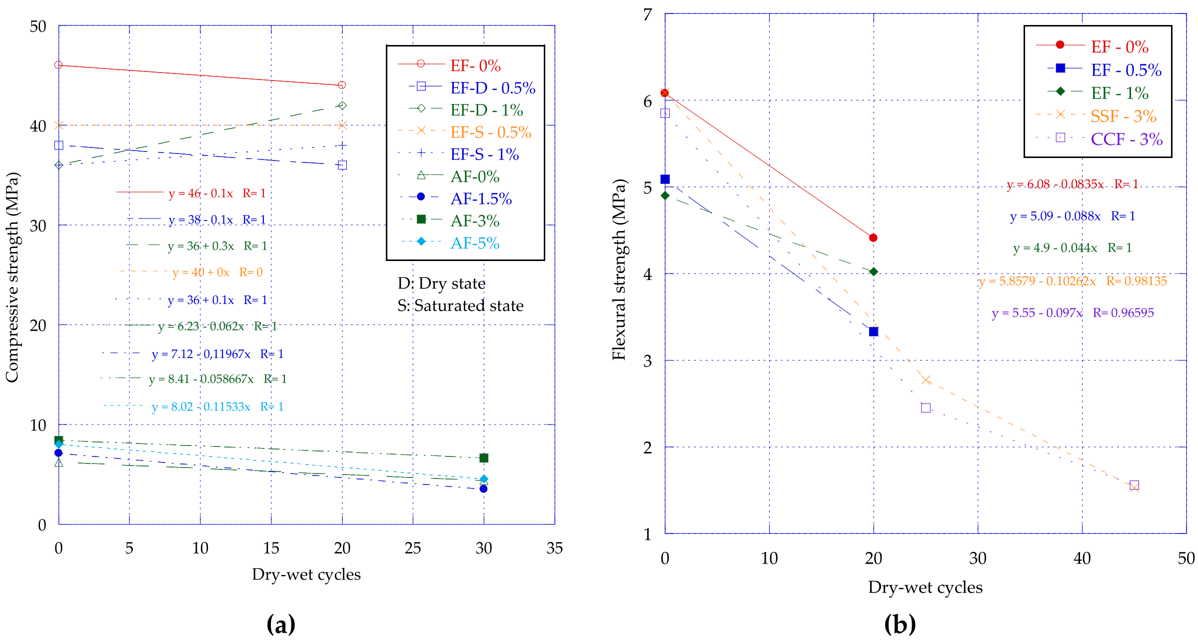

Fig. 5. Influence of NF incorporation in mortars after wet-dry cycles according to different authors: Compressive strength (**a**) and flexural strength (**b**).

that regarding the SSF content, the aging cycles decreased the flexural strength of the mortar composites from 18.73 MPa to 6.93 MPa, resulting in a 63 % flexural strength decrease after 25 aging cycles. This is because the SSF undergoes a mineralization process in the cement matrix, damaging the cell walls of the SSF [83], this also has been reported in other NF such CF [60] and CCF [55,143].

Toledo et al. [58]investigated how adding SSF and CCF affects the drying shrinkage of concrete samples measuring 300 mm in length. They found that the drying shrinkage issue becomes more pronounced with higher amounts of NF. The addition of SSF and CCF raises both the porosity and the connectivity between pores, leading to an increase in drying shrinkage. Fig. 5 shows a summary of the findings on the effect of NF on mechanical resistance to dry-wet cycling.

In summary, the studies discussed provide important insights into the durability of mortars with different types of additive fibers, including EF, AF, PHF, and SSF. They highlight the need to carefully select the type of fiber, its dosage, and the treatment methods used to enhance the durability of the resulting mortar. Notably, the significant decrease in flexural strength observed with SSF due to mineralization underscores its susceptibility to environmental damage. Similar issues have been reported with other fibers like CF and CCF, suggesting a need for exploring alternative fibers or improved treatment techniques to achieve better long-term performance.

4.3.4. Microstructure

The microstructural behavior of NFRM plays a crucial role in understanding their long-term durability, especially when exposed to environmental stressors such as wetting and drying cycles. Various studies have examined how these fibers interact with the cementitious matrix over time, providing an insight into the performance and failure mechanisms of these materials. However, the literature on this topic is relatively scarce, particularly in South and Central America, creating a significant research gap regarding the microstructural analysis of NFRM in these regions. Addressing this gap is essential to optimize the use of locally available NF and enhance the durability of NFRM in sustainable construction practices.

Tonoli et al. [110] conducted a study on the effects of 14 years of weathering on tiles made with cement, river sand, and 4 % added AF, examining both laboratory and outdoor conditions. The microstructural analysis revealed that the AF detached from the cement matrix, primarily due to shrinkage when the tiles dried. The tiles exposed to natural weathering (Fig. 6a) showed much more damage at the fiber-matrix interface compared to those aged under controlled laboratory conditions (Fig. 6b). This damage resulted from the stresses caused by continuous cycles of wetting, drying, and carbonation, which led to changes in fiber volume. Additionally, it was noted that microcracking in the matrix near the fibers created larger spaces or pores in the transition zone of the tiles exposed to weathering [110].

Toledo et al. [55] studied the microstructure of SSF and CCF mortars exposed to 25 cycles of wetting and drying. Observing the microstructural characteristics of the CCF-matrix interface of the composites, it can be seen that the matrix around the CCF of the unaged specimen (Fig. 7a) is relatively more porous and presents more cracks than that of the aged specimen (Fig. 7b). It can also be seen that the mortar zone highlighted by the CCF surface and the crack around the fiber perimeter is larger in an unaged specimen than the one in the specimen submitted to the cycles of wetting and drying. Regarding SSF mortar, when observing the microstructural characteristics of the interface of the aged and unaged composites (Fig. 7c and d), no significant differences can be noted in matrix porosity and volume of matrix cracks around the SSF.

The comparison between these studies emphasizes the contrasting behavior of different NF when incorporated into mortar. AF showed a significant microstructural damage when exposed to natural weathering conditions, with notable detachment from the cement matrix and an increased porosity in its transition zone. This suggests that AF's response to environmental stresses, such as wetting, drying, and carbonation, is more pronounced, leading to a compromised fiber-matrix bond. In contrast, CCF demonstrated an improvement in the microstructure of the aged samples, with reduced porosity and cracks compared to the unaged samples, indicating a strengthening effect due to the wetting and drying cycles. SSF showed no significant changes in the microstructure, suggesting that they maintain a stable bond with the cement matrix regardless of aging or exposure to environmental conditions. These findings indicate that the choice of fiber type significantly affects the durability and performance of NFRM. NF like AF are more susceptible to microstructural damage under weathering conditions, whereas CCF and SSF demonstrate better resistance to environmental effects,

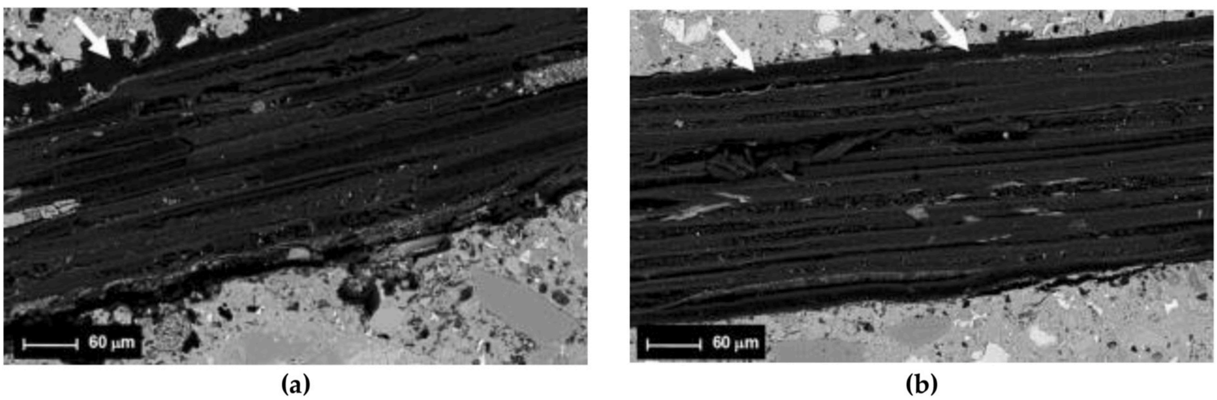

Fig. 6. Detach of FF from the cement paste: (a) outdoor conditions and (b) laboratory conditions. Source [110].

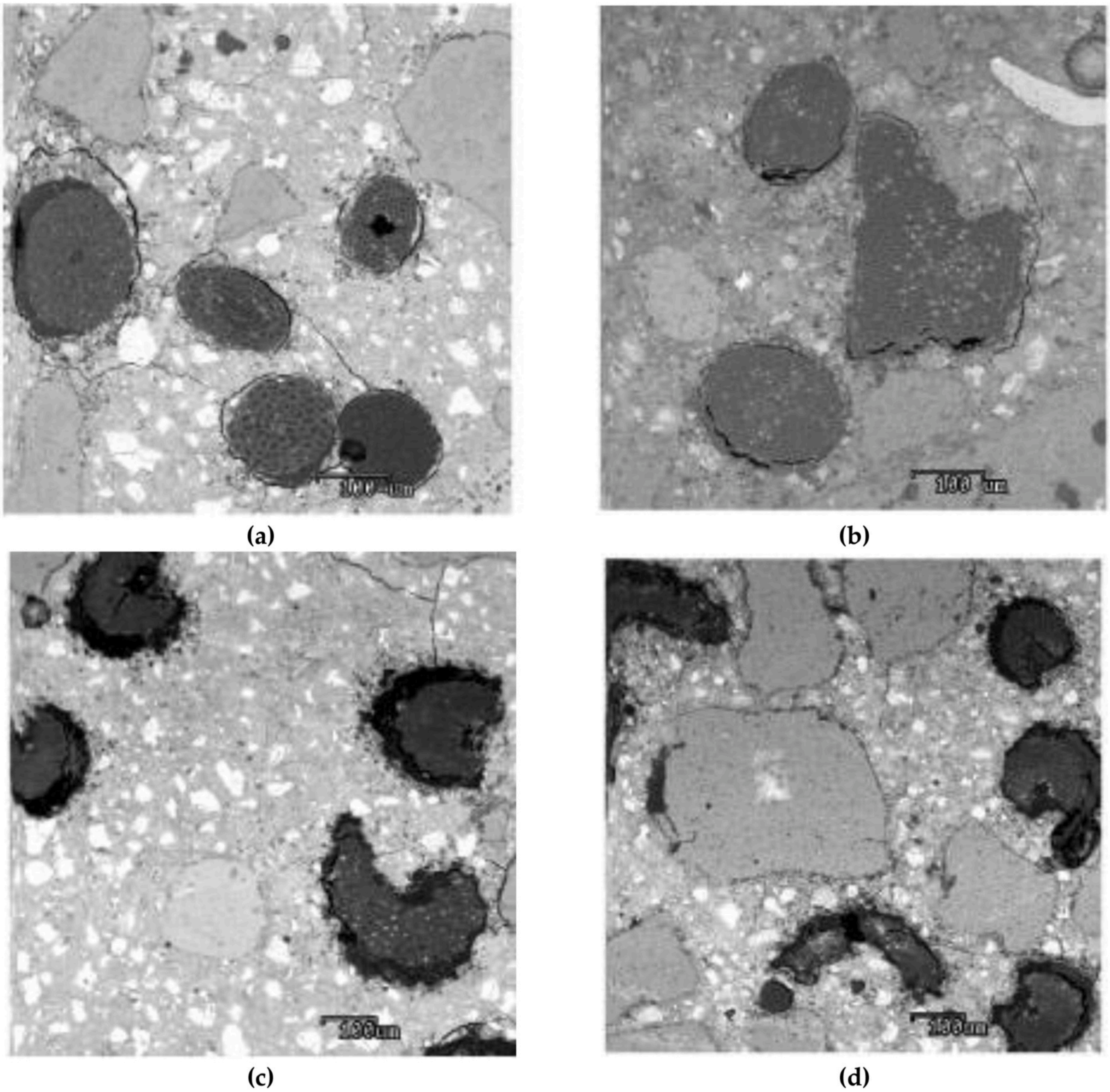

Fig. 7. Microstructure of CCF mortars at 28 days (a) and after 25 cyles of wetting and drying (b); Microstructure of SSF mortars at 28 days (c) and after 25 cycles of wetting and drying (d). Source: [55].

with SSF showing the most stable microstructure. This insight is crucial for designing durable NFRM that can withstand long-term exposure to various environmental conditions.

4.4. Natural fiber reinforced concrete

NFRC is a composite material that combines the traditional properties of concrete with the additional strength provided by NF. Unlike conventional concrete, which primarily relies on steel reinforcement for enhanced performance, NFRC incorporates fibers derived from renewable resources such as plants [125], or even hair of animals [107]. NFRC offers numerous advantages over conventional concrete, including improved crack resistance [76], reduced energy consumption during production, and enhanced sustainability due to the use of renewable resources [48]. Additionally, NFRC exhibits excellent thermal [144,145] and acoustic insulation properties [146], making it an attractive option for building construction projects aiming for energy efficiency and environmental sustainability. At present, the development and application of NFRC has gained significant attention in the construction industry as researchers and engineers seek more sustainable and eco-friendly alternatives to traditional building materials. Through ongoing research and innovation, NFRC continues to evolve, offering new possibilities for creating durable, resilient, and environmentally responsible structures.

4.4.1. Workability

Concrete workability is a fundamental aspect of construction, determining how easily concrete can be mixed, placed, and shaped. It plays a crucial role in the efficiency, quality, and durability of structures, making it a cornerstone of successful construction projects. Acosta et al. [3] reported that the slump of concrete containing 1%vol. of SSF decreased by 21 % compared to the control concrete (102 mm slump); this was attributed to the vegetable cells which absorbed water from the concrete mix, thus, reducing its workability [3].

Mansilla et al. [107] reported that EF addition (0.5%cement wt.) does not show variation with respect to the control concrete regarding its state (dry or saturated). This is because EF addition is not sufficiently large to affect the concrete workability. Amaguaña et al. [49] studied CCF addition up to 1%vol. in concrete. The inclusion of 0.5 %, 0.75 %, and 1 % of CCF decreased the workability of the concrete by approximately 55 %, 76 %, and 100 %, respectively. The same effect was reported in another study reported by Ref. [147], where the reduction of workability was attributed to the large surface area and high-water absorption of CCF. Consequently, increasing the superplasticizer content could be a feasible alternative to mitigate this negative effect.

Fig. 8 shows a summary of the findings above mentioned. It is observed that EF in a saturated state increased the slump of NFRC by 14 %, although EF in a dry state do not affect concrete workability. As previously mentioned, CCF decreased the slump up to 100 % because of the high absorption and high surface area of the CCF. SSF decreased the workability by 21 % with 1%vol. Moreover, lower additions of SSF or higher superplasticizer content could mitigate the workability loss. The results of Pearson's chi-square equations are 1, which means that there is a relationship between fiber content and mechanical behavior of NFRCs. In the case of the equation that gives 0 as the result, it is possible that in a dry state EF have no influence on the fresh state behavior of the concrete. In brief, while the addition of NF can enhance the mechanical properties of concrete, careful attention must be given to their effects on workability. Proper adjustments in the mix design, such as the use of superplasticizers, are essential for ensuring that the benefits of NFRC can be realized without interfering with the construction process.

4.4.2. Mechanical properties

The comprehension of compressive strength and flexural strength of concrete holds pivotal importance. Compressive strength denotes concrete's capacity to withstand axial loads, while flexural strength characterizes its resistance against bending forces. Both properties serve as crucial benchmarks for assessing a concrete's structural performance and longevity. In this section the above-mentioned mechanical properties regarding NFRC will be discussed.

Lima et al. [80] analyzed the incorporation of 6 % by wt. of SSF in concrete (CC) and recycled aggregate concrete (RAC) [43]. The reduction of the compressive strength was about 22 % and 33 % for CC and RAC, this was attributed to the increased matrix porosity according to the authors. As for its splitting tensile strength, the addition of SSF in both CC and RAC resulted in an increase of 2.5 % and 10 % respectively [80].

Vélez et al. [48] studied CCF incorporation by 0.5 and 1%vol. in concrete. 40 mm length CCF was treated with NaOH solution and

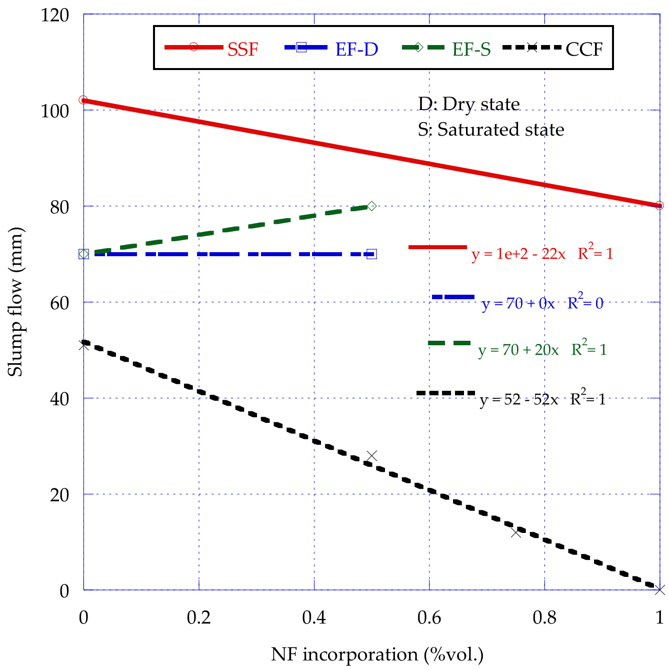

Fig. 8. Workability of NFRC according to different authors.

silica fume. At 28 days, CCF treated with NaOH presented a 14 % higher compressive strength than untreated CCF (23.26 MPa). CCF treated with silica fume presented a 6 % increase compared to untreated CCF. Regarding the elastic modulus, control concrete presented 15.10 GPa, CCF with NaOH treatment with 0.5 and 1 % incorporation presented 13.55 and 14.39 GPa, respectively. The lower modulus was related to a slight reduction in stiffness and inferior toughness. It was concluded that NaOH treatment increased the compressive strength as opposed to untreated and silica fume treated CCF [48]. The effectiveness of CCF in improving the compressive strength of concrete depends on several factors, such as the type and amount of CCF used, the mix design of the concrete, the curing conditions, and the testing method used [49]. It has been reported that at 28 days, the compressive strength of concrete reinforced with CCF increased by 11 and 2.4 % with 0.5 and 0.75%vol. inclusion, respectively [49]. However, with 1 % fiber, compressive strength was lowered by 8.93 %. This could be because adding CCF up to a certain level would not allow a suitable homogenization of materials, and a mixture with low resistance would form [49].

Acosta et al. [3] reported that 1%vol. addition of SSF improved by 16 and 6 % the compressive strength at 7, and 28 days contrary to control concrete (19.2 and 27.6 MPa, respectively). The SSF could have stored water that was released gradually during hydration, helping with the strength development. The presence of SSF does not affect the flexural strength (4.5 MPa) compared to the control concrete (4.4 MPa). It was found that the results were very similar, because the presence of fibers normally does not decrease the flexural strength of concrete, as expected [3]. Mansilla et al. [107] studied the incorporation of 0 and 0.5%cement wt. of EF (dry and saturated state) in concrete. It was reported that the 0.5 % cement wt. does not affect the compressive and flexural strength of concrete because the little amount of EF reduces the fiber concentration, which causes weakening of the concrete matrix [107].

Fig. 9a shows the findings of the above-mentioned literature regarding the compressive strength of NFRC. It is observed that the compressive strength increases with time as expected, regarding its NF addition. However, the inclusion of NF can positively or negatively affect the gain of compressive strength depending on the type of NF and the treatment it undergoes (Fig. 9b). The results of the Pearson's chi-square equations are in most cases 1, which means that there is a relationship between fiber content and the mechanical behavior of NFRC. In conclusion, the incorporation of 0.5%vol. of untreated SSF, silica fume treated CCF, and fly ash coated ALF addition improves the compressive strength of NFRC. The reduction of compressive strength is observed with silica fume treated ALF, untreated ALF, and untreated EF.

Fig. 10 shows the effect of NF addition on the flexural strength of NFRC at 28 days. It is observed that regarding dry or saturated state of EF, the flexural strength is reduced in both cases, although the saturated state EF presented better results, this could have happened because the saturated state reduced the absorption of EF, in consequence improving the flexural strength compared to dry state EF. The addition of SSF and CCF up to 1 and 0.75%vol., respectively increased the flexural strength by 2 and 28 % respectively. Although, 1%vol. addition of CCF reduced the flexural strength by 18 % compared with 0.75%vol. addition. In practical terms, the incorporation of NF into concrete should be carefully managed to balance the enhancement of flexural strength and the potential negative effects at higher fiber contents. Selecting the appropriate fiber type and concentration is crucial to achieving the desired structural performance while maintaining the integrity of the concrete mix.

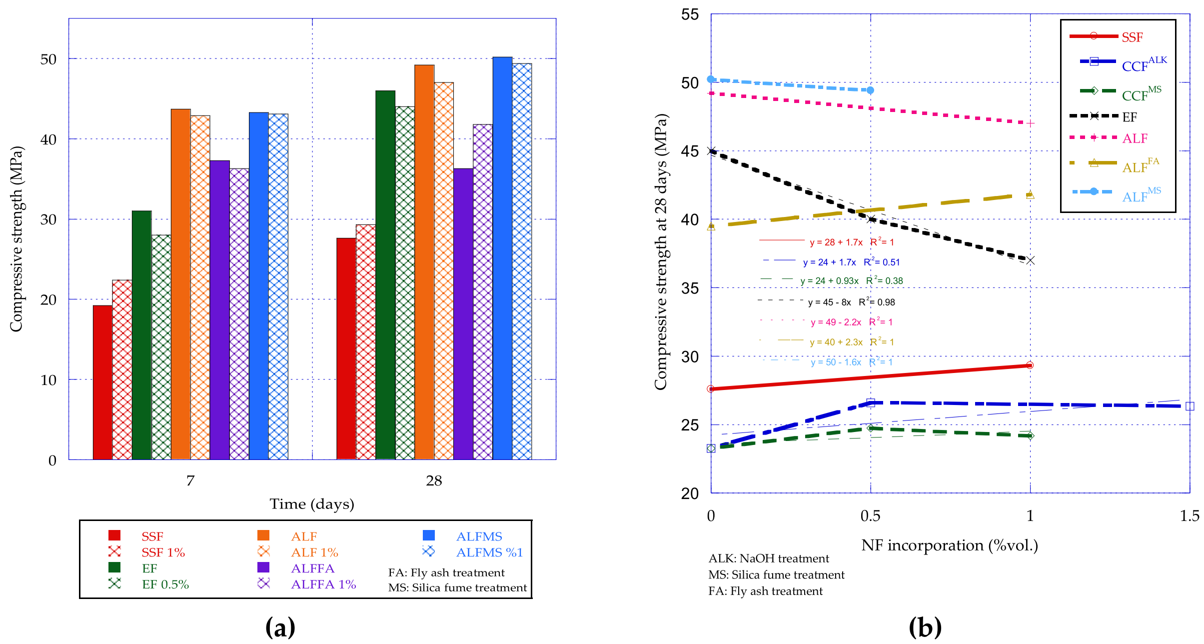

Fig. 9. Compressive strength of concrete. Behavior over time (**a**) and effect of different incorporation volumes (**b**).

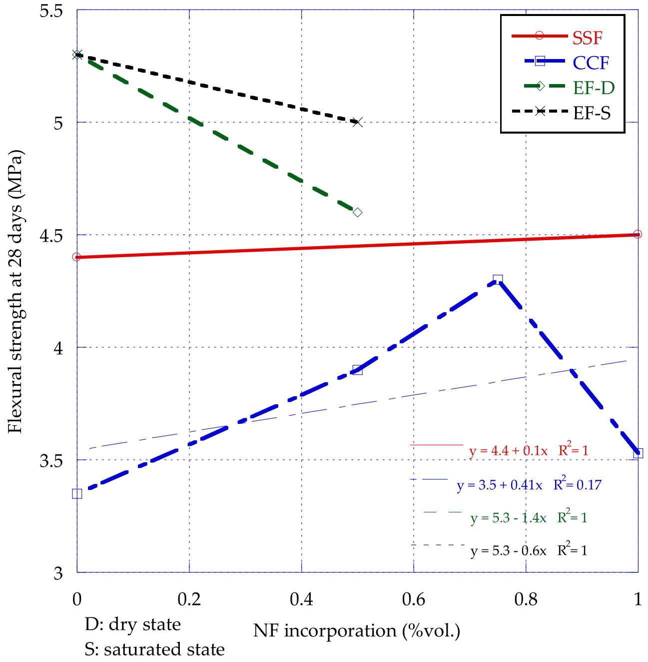

Fig. 10. Effect of NF in flexural strength of NFRC according to different authors.

4.4.3. Durability

The study of NFRC has garnered attention due to its potential to enhance the mechanical properties and sustainability of concrete. However, understanding the durability of NFRC remains a critical challenge, especially in regions like Central and South America where limited research has been conducted on the subject. Among the various techniques used to assess the durability of NFRC, both accelerated deterioration tests and ultrasonic pulse velocity (UPV) testing stand out for their ability to provide valuable insights into the long-term performance of these materials.

Accelerated deterioration tests, such as wetting and drying cycles, simulate harsh environmental conditions to evaluate the resistance of NFRC to degradation over time. This method is particularly useful for assessing how factors like fiber type, treatment, and volume impact concrete's durability when exposed to fluctuating moisture levels. Juarez et al. [93] investigated the accelerated deterioration of NFRC using wax-treated and untreated ALF and FxF at fiber volumes of 0.4 %, 0.7 %, and 1 %. This involved subjecting the concrete to eight cycles of wetting and drying. The results showed that the wax treatment negatively affected the flexural strength of both ALF and FxF concrete. For ALF concrete, the untreated fibers led to a significant increase in flexural strength compared to the control sample (0 % vol. fiber), with improvements of 38 %, 28 %, and 16 % for fiber volumes of 0.4 %, 0.7 %, and 1 %, respectively. In contrast, the wax-treated ALF concrete displayed lower flexural strength values than those of the control sample, indicating a detrimental effect of its coating on its mechanical properties. FxF concrete, both with and without the wax treatment, experienced greater deterioration in flexural strength across all fiber volumes when compared against the control sample. This reduction in strength is likely due to the higher susceptibility of FxF to degradation in the alkaline environment of concrete [93]. In all cases, a tendency to decrease strength was observed as the fiber volume increased.

In the case of SCF used in NFRC [148], their porosity and hygroscopic nature make them vulnerable to the alkaline environment which negatively impacts their performance [149], compromising their durability. This observation aligns with the findings in the literature [150], which indicates that in the absence of chemical treatment, the alkalinity of the pore water in concrete dissolves lignin and hemicellulose, breaking the bonds between the microcells in the fibers. This leads to fiber fragmentation, reducing their ability to reinforce the concrete. Additionally, the microcells in the fibers become full with calcium hydroxide ($Ca(OH)_2$), causing the fibers to lose their flexibility [150]. Moreover, these fibers often undergo a mechanical process to extract sugars, further compromising their durability without the use of a protective agent. Nevertheless, even in this compromised state, the fibers help prevent the collapse of the material, in contrast to unreinforced concrete, which tends to fail in a brittle manner when subjected to its breaking load [148]. Overall, the findings suggest that while NF can significantly enhance concrete properties, the treatment and type of fiber play a crucial role in their performance and durability.

UPV testing is a non-destructive technique that measures the speed of ultrasonic waves traveling through the concrete, offering a reliable indicator of its internal structure and quality. UPV plays a crucial role in evaluating the integrity and durability of NFRC without compromising the structural components, making it a valuable tool for monitoring the performance of these materials over time. Generally, the accepted range for UPV in good-quality concrete is 4500–5500 m/s, while values below 3500 m/s indicate poor quality or potential structural issues. Acosta et al. [3] studied the UPV value (by ASTM C957 standard [151]) of concrete with 1%vol.

SSF addition at 28 days of age. Results indicated that SSF concrete achieved the highest UPV (4400 m/s) compared with the control concrete (4000 m/s). This is because the SSF addition could create a more compact internal structure. Which could, in turn, explain the higher compressive strength of SSF concrete (33.60 MPa) when contrasted to the control concrete (28.50 MPa) [3]. Compared against other such results in the literature reported by Amjad et al. [152], the results of Acosta et al. [3] presented higher UPV values. This is because the NFRC used by Amjad et al. [152] added plastic aggregates, which decreased the density of the concrete, resulting in lower UPV values although the SSF content was the same. When comparing the results of other NFs reported by Alomayri and Ali [153], it can be observed that the incorporation of NFs improves the UPV values, creating a denser concrete with a more uniform structure. It should be taken into account that, depending on the type of fiber, the incorporated amount should not exceed a certain volume of incorporation for the NFRC to have favorable results. Fig. 11 shows a summary of the findings presented above. The enhancement in mechanical properties and structural density demonstrates the potential of SSF in improving the durability of NFRC.

4.4.4. Microstructure

The microstructure of NFRC plays a pivotal role in determining the mechanical performance, durability, and overall integrity of these composites. Understanding the interaction between NF and the cementitious matrix at the microstructural level is essential for enhancing the resulting material's properties. Despite its importance, research on NFRC microstructure is relatively scarce in South and Central America, regions, which are rich in NF resources that could significantly benefit from these sustainable materials. Expanding knowledge in this area is crucial to optimize the use of locally available fibers in concrete applications, particularly under conditions that accelerate material deterioration.

In this regard, Juarez et al. [93] researched the accelerated deterioration of NFRC by incorporating wax-treated and untreated ALF and FxF. The study involved subjecting the composites to eight wetting and drying cycles, with each cycle consisting of one day of wetting followed by three days of drying. Microstructural analysis revealed that untreated ALF experienced rupture due to strong adhesion to the cementitious matrix (Fig. 12a). In contrast, the treated ALF exhibited a pull-out failure (Fig. 12b), indicating a weaker bond with the matrix. These observations suggest that the adhesion between ALF and the cement matrix plays a crucial role in determining the mechanical strength of ALF concrete. SEM analysis of the ALF concrete showed that volumetric changes in the fibers, caused by water absorption during mixing, did not effectively transfer to the surrounding matrix. As the fibers dried, they experienced a volume reduction, which could create adhesion defects at the fiber-matrix interface, leading to a decrease in mechanical strength. In the case of FxF, minimal volumetric changes were observed for the untreated fibers (Fig. 12c). However, an agglomeration of the fibers was noted (Fig. 12d), indicating poor fiber distribution within the matrix. This lack of dispersion likely contributed to the lower mechanical properties and higher porosity of the FxF concrete. These insights highlight the need for further research, especially in regions like South and Central America, to fully understand the microstructural behavior of NF in concrete and develop strategies to optimize their performance in sustainable construction.

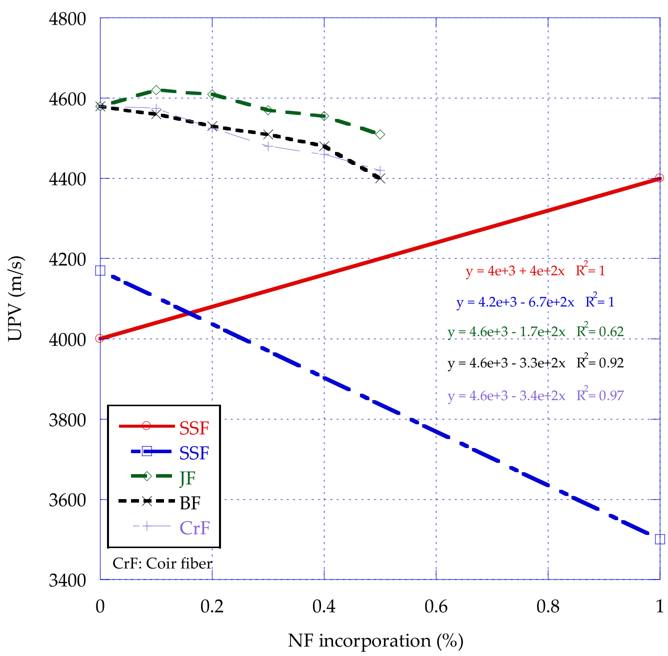

Fig. 11. Influence of NF on concrete in UPV tests according to different authors.

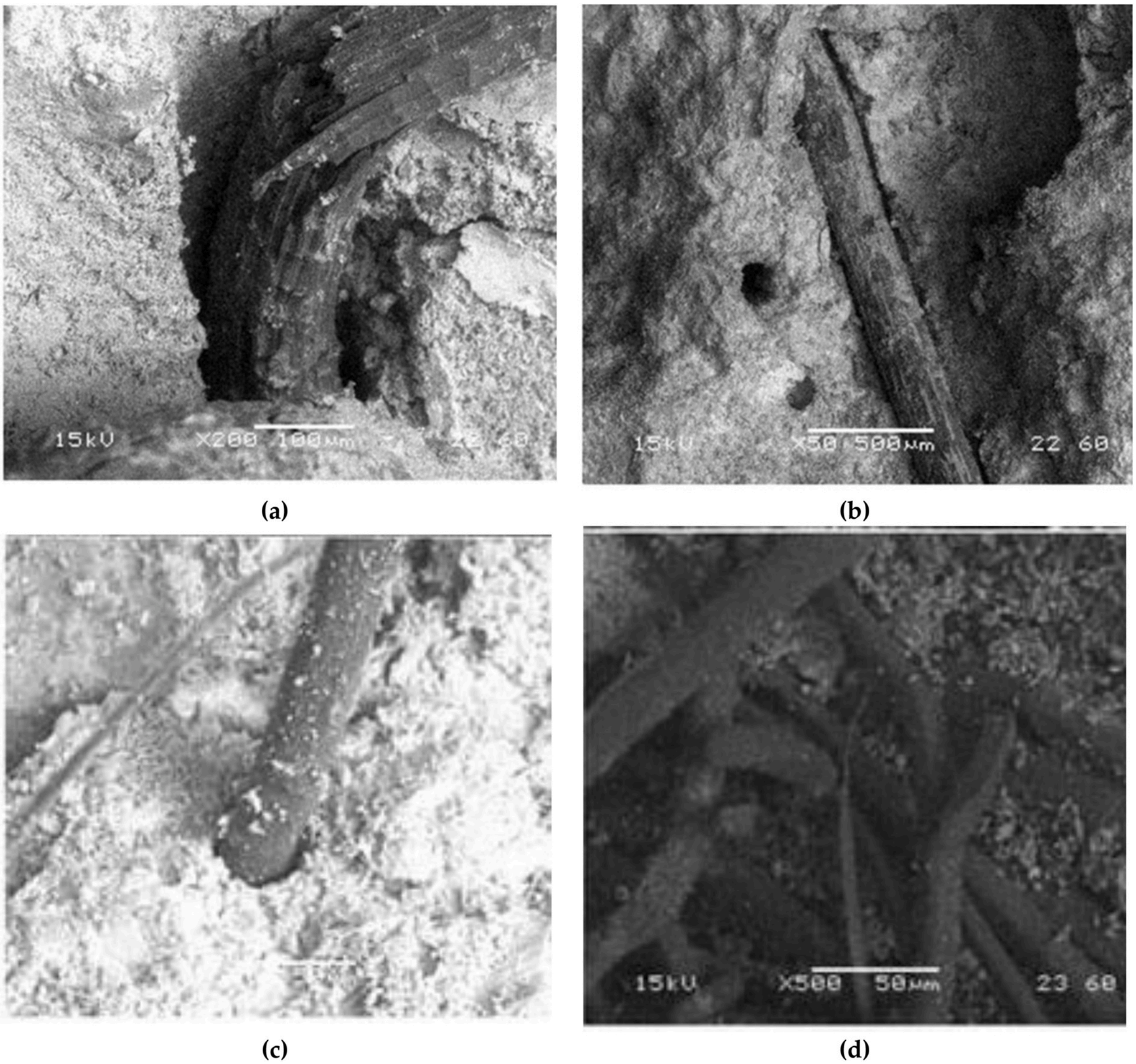

Fig. 12. Microstructure of (**a**) untreated ALF concrete; (**b**) wax-treated ALF concrete; (**c**) untreated FxF concrete; (**d**) wax-treated FxF concrete after accelerated deterioration. Source: [93].

5. Environmental analysis

Due to the reliability of the life cycle analysis (LCA), it has become a tool for assessing the environmental impacts of the construction industry [154,155]. NF offer several benefits in terms of environmental impact such as recyclability, renewability, as well as lower raw material costs and light weight [156]. Therefore, LCA allows the assessment to determine whether NFRM or NFRC are indeed more beneficial to the environment than using metallic or plastic fibers. While the benefit of NFs is intrinsic because many are by-products of the agricultural or livestock industry, the findings reported in this section provide a clearer understanding of the benefits of NFs as a replacement for conventional fibers.

In this regard, the energy consumption of NF is 45 % less energy than ABS copolymers (132 MJ) [157]. It has been reported that the energy requirement for Polyvinyl alcohol fiber (PVAF), Polypropylene fiber (PPF) and SF reinforced cementitious composites is 3.042, 2.985 and 4.029 GJ/m^3, meanwhile the energy required for producing one cubic meter of FxF, HF, kenaf fiber (KF), and pineapple fiber (PNF) reinforced cementitious composites were 2.97, 2.97, 2.98 and 2.97 GJ/m^3 respectively [158]. In addition, it has been reported that for the manufacturing of 1 kg worth of glass fibers (GSF) 54.7 MJ are consumed [159]. The data suggests that NF offer a clear advantage in terms of energy efficiency. Their production requires less energy per m^3 than many synthetic counterparts, especially SF. The information stated above punctuates the importance of considering energy consumption when selecting fibers for cementitious composites. NF emerge as strong candidates for reducing energy demands, supporting both environmental sustainability and efficient material production.

Miller S. [160], reported that in contrast with GSF reinforced polyamide (GRFP), composites with HF (linen) have 10 % lower embodied energy and 41 % lower greenhouse gas (GHG) emissions. Additionally, HF (burlap) and JF (burlap) offer a 140 % reduction in GHG emissions and over a 75 % reduction in embodied energy relative to GRFP. The production of JF (burlap) and HF (burlap) composites has notably lower embodied energy than HF (linen) composites, as the textiles used require less refinement, resulting in reduced energy consumption during production. This makes NF an attractive alternative in applications where reducing embodied energy and GHG emissions is critical.

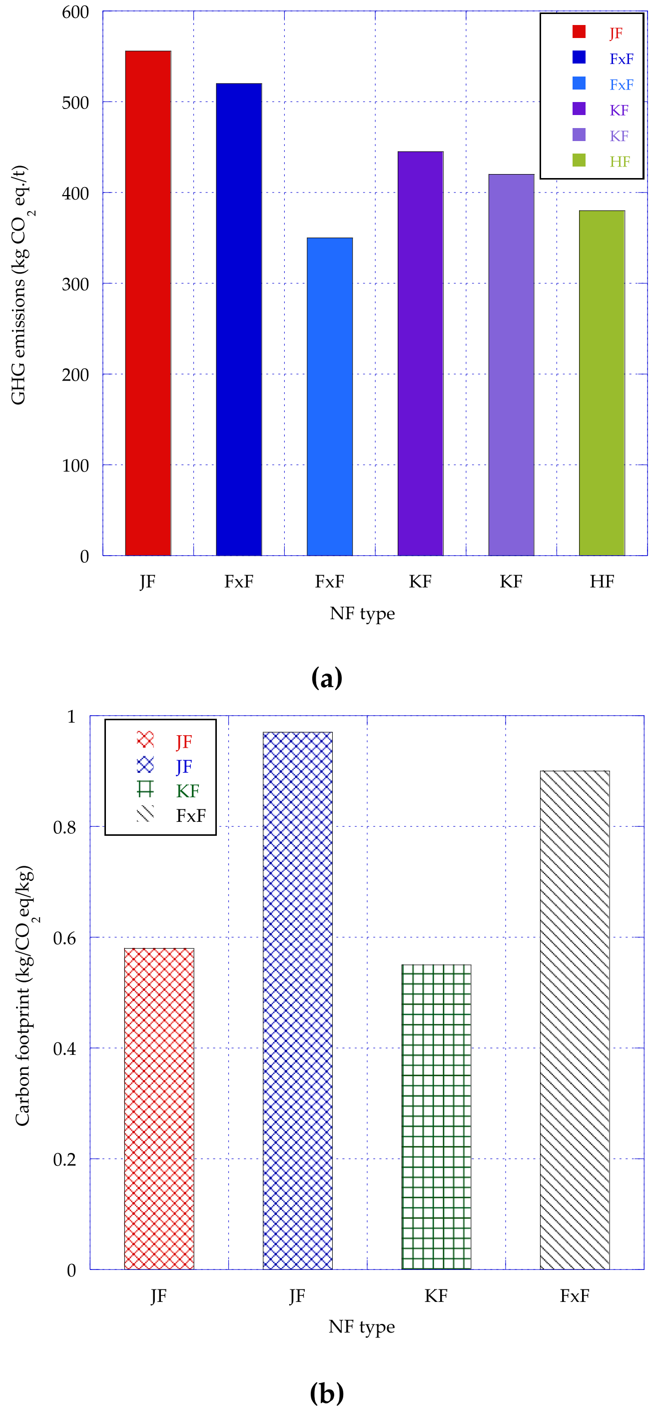

Fig. 13. GHG (**a**) and carbon footprint (**b**) of different NF compared to conventional fibers.

SSF is a highly sustainable alternative to GSF, emitting far fewer GHGs during production [161], this strengthens the case for using SSF to reduce environmental impacts in fiber-reinforced composites. As opposed to GSF production in Europe (2630 kg CO_2 eq./t), SSF produced between 93.53 and 74.90 % less GHG emissions [161]. In this regard, Singh et al. [162] reported that JF, FxF and KF GHG emissions are 556, 520 and 445 kg CO_2 eq./t, which in contrast to GSF production is 78.85 %, 80.22 % and 83.07 % lower, respectively. It has been reported that the carbon content emitted during production of NF flax, hemp, kenaf, and pineapple is 350, 380, 420, and 450 kg-CO_2-eq/t respectively. This is 77–90 % lower than the carbon emissions of conventional fibers such PVAF, PPF, and SF [158]. This highlights the environmental advantages of NF in reducing carbon footprints. Fig. 13a shows the data found in the aforementioned literature.

JF and KF consistently outperform other NF types in terms of their low carbon footprint, reinforcing their role as the most eco-friendly fiber options [157,163,164]. Korol et al. [157] reported that NF have a lower carbon footprint than a polypropylene matrix (3.43 kg CO_2eq/kg). Whereas cotton fibers (CTF) had the highest carbon footprint among NF at 2.95 kg CO_2eq/kg, JF and KF had the lowest values, at 0.58 and 0.55 kg CO_2eq/kg, respectively. However, other studies suggest that the carbon footprint derived from JF and FxF are 0.97 and 0.90 kg CO_2eq/kg, respectively [163] (Fig. 13b). Regarding other types of NF such Alpaca fiber, it has been reported that the impacts per kg ranges from 45 to 109 kg CO_2eq/kg [165]. Additionally, it has been reported that the environmental impacts of EF based panels per kg ranges from 1.4 to 5.29 kg CO_2eq/kg [166]. There is not much information regarding the environmental analysis of NFRC. Although, it has been reported that the incorporation of NF instead of artificial fibers in concrete (M40 grade) showed a change in overall carbon emissions. Specifically, the carbon emission from the production of 1 m^3 of flax, hemp, kenaf, and pineapple reinforced concrete were 567.5, 569.6, 569.2, and 567.1 kg-CO_2-eq/m^3 respectively. The carbon footprint associated with the production of 1 m^3 of M40 grade conventional concrete ranges between 320 and 345.19 kg-CO_2.eq/m^3 [158,164]. This indicates that conventional concrete produces substantially lower emissions compared to NFRC, with the NF types resulting in around 1.6 to 1.8 times more emissions. On the other hand, PVAF, PPF and SF FRC carbon footprint values are 759.43, 614.5 and 1792.81 kg-CO_2.eq/m^3, about 2.0–5.2 times higher than conventional concrete [158].

6. Natural fiber reinforced cement-based materials applications

In recent years, Central and South America have exhibited a growing interest in the application of natural fiber reinforcement in concrete and mortar elements. This trend stems from the region's rich biodiversity, which offers a diverse range of NF suitable for upgrading the mechanical properties of construction materials. Through various case studies [112,167–172] researchers in Central and South America have explored the effectiveness of incorporating NF sourced locally into concrete and mortar structures. These studies not only highlight the technical feasibility of using natural fibers but also underscore the potential economic and environmental benefits of employing sustainable reinforcement alternatives.

In Colombia, there is considerable potential for utilizing CCF to enhance the thermal insulating properties of mortars [112]. Incorporating 15 % w/w of CCF into mortars can potentially double the specific heat value compared to conventional mortar and increase compressive strength by 2.47 %. Furthermore, the thermal conductivity of the resulting mortar decreases significantly, from 1.4 to 0.27 W/m.K, with a 15 % w/w CCF addition. This approach is particularly relevant for heightening thermal comfort in low-income housing structures in tropical regions like Cartagena, Colombia. The study demonstrates that incorporating CCF into the facade coating can improve indoor thermal comfort by 0.5–1.5 °C while maintaining mechanical strength, addressing coconut waste disposal issues, and reducing annual energy consumption and cooling costs by 16 % which is comparable to the estimated 11 % energy savings as reported in India and Nepal [173]. These findings make CCF mortars an affordable and sustainable option for low-income families in the Colombian Caribbean [112].

Another study has been reported in Colombia [168], specifically in the residential complex Yerbamora Reservado, located in the locality of Suba, Bogotá where a mix conformed by 80 % CCF, 10 % white glue, 5 % gypsum and 5 % lime was used as panel for thermic insulation. The CCF panels effectively function as an interior thermal insulation system, meeting insulation standards with a U-value of 1.1 W/m^2 K. Simulations show that implementing these panels on masonry facades raises indoor temperatures from an average of 17 °C to over 21 °C, ensuring compliance with regulations. Despite being thinner and lighter compared to other market systems, the CCF panel system offers an economical and efficient alternative for providing thermal insulation in masonry facade homes [168]. In the case of the study reported by Gaona, M. [170], a series of houses in the rural areas of Timasita, San Luis, and Puente de Tierra, in the municipality of Une, Cundinamarca, were analyzed. This is because they have been affected by mining activities, leading to progressive and exponential deterioration that has jeopardized the structural integrity of the houses. After conducting a visual inspection and analyzing the technical feasibility of various NF, it was decided to use SGF. This decision was based on their suitable mechanical properties and their widespread availability in Colombia [170]. In Colombia, roofing tiles from FF have been manufactured and their durability has been assessed after 14 years of weathering [110]. Tiles exposed to weathering exhibited higher water absorption and apparent void volume compared to those subjected to laboratory conditions. While continuous cement hydration and natural carbonation filled smaller pores, larger pores persisted at the fiber-matrix interface in weathered samples, contributing to increased porosity [110]. Delvasto et al. [111] used vacuum technology to produce corrugated roof sheets reinforced with FF, aiming to develop a cost-effective method that supports masonry housing construction in rural areas.

In Peru, the low temperatures in the high Andean regions demand that thermal comfort be a priority for the habitability of single-family homes, an aspect that residents need to implement in the architectural design of their homes. The objective of the study reported by Sánchez and García [167] was to define general design strategies that produce thermal comfort to improve the habitability of high Andean homes in Shorey Grande, Quiruvilca district, La Libertad – 2021. The results reveal that, to achieve such conditions in high Andean housing through thermal comfort, consideration must be given to the distribution of spaces, materials, orientation, arrangement of solid and void elements, construction systems, and architectural features. It is concluded that high Andean housing should have a distribution of spaces that allow for air circulation and thermal efficiency, built with materials that generate thermal gain such as wood, stone, straw, and rammed earth. What is more, it should have three thermal comfort systems: a traditional constructive-structural, a greenhouse, and an alternative heating and heat preservation system.

In Nicaragua, specifically in "Barrio El Pantanal" (Granada) Moreno and García [169] added SCF in adobe blocks to improve its compressive strength. This case of study also aimed to give workshops to the population of "Barrio El Pantanal "regarding the elaboration of the adobe mix design. Although the case study does not specify the quantity of SCF used, it was reported that adobes reinforced with this fiber achieved a compression strength of 1.53 MPa, representing a 27.5 % increase in contrast to the control adobe (1.20 MPa). This result demonstrates the technical feasibility of using SCF fiber as a sustainable reinforced material.

In Mexico, Ruiz and Perez [172] carried out a case study aimed at promoting sustainable local development in Santa María La Asunción, Municipality of Zumpahuacán, State of Mexico, through the production of clay adobes reinforced with *Agave Angustifolia haw*. The most significant results of the research were that the resources for making adobe blocks with *Agave Angustifolia haw* are readily available in the community environment due to the geographical conditions, including clay soils and the prevalent *Agave Angustifolia haw*, which is commonly used for mezcal production in the region. The incorporation of *Agave Angustifolia Haw* bagasse fiber into adobe significantly enhances its compression strength, resulting in a 35 % increase in resistance to vertical loads compared to conventional adobe (0.32 MPa). With an 18 % bagasse concentration relative to the adobe's weight, an average fiber length of 50 mm, and random orientation, the reinforced adobe remains lighter than traditional adobe. Despite its higher moisture absorption rate (13 %), this characteristic is deemed insignificant for the semi humid sub warm climate of the study area [171,172]. Juarez et al. [89] developed sustainable masonry blocks with embedded PET bottles and 25 mm length ALF at 0.25 %–1 % volume. Results indicated that the compressive strength of masonry with 0.75 % ALF increased by 10 % compared to blocks without ALF (1.93 MPa). Additionally, it was reported that the post-cracking behavior of masonry blocks with ALF was improved compared to those without ALF [89].

The diverse applications of NF in cement-based materials across Central and South America demonstrate their technical viability, sustainability, and cost-effectiveness. Whether improving thermal insulation, enhancing structural integrity, or promoting local resource use, NF offer a renewable alternative to conventional reinforcement methods in construction. Their role in addressing environmental, economic, and social challenges in the region highlights the importance of continued research and adoption of NF in global construction practices.

7. Conclusions

This work consisted of the systematization of the most recent research on NFs, the conclusions of which are as follows.

- The main conclusion is that it was possible to systematize the literature consulted, classifying the type of NF by its origin, its physical and mechanical properties and how it affects the fresh properties, mechanical properties and durability of cement-based materials. This shows that the region studied is showing more sustainable practices for the manufacture of cement-based materials.
- It was found that in the region studied there are 19 types of NF, of which the main ones studied are SSF, CCF and CF. In addition, it was found that the country with the most studies on NF is Brazil, followed by Mexico and Colombia
- NF are characterized by a high content of α-cellulose (30 %–70 %) as well as high absorption (from 28 % to 350 %), which depends on each type of fiber.
- Alkaline solutions are the most used method for treating NF. This method increases fiber roughness, enhancing the bond between the fiber and the cement paste.
- The workability of NFRM and NFRC decreases as the percentage of NF increases. However, this can be mitigated by increasing the dosage of superplasticizer.
- The flexural and compressive strength of NFRM and NFRC can increase with up to 0.5%vol. of NF. Higher NF content could have a negative effect on these mechanical properties.
- The durability of NFRM and NFRC depends on the test type and NF content. With low addition percentages, fibers offer adequate results for wetting-dry cycles, abrasion resistance, UPV, and thermal shock.
- The microstructure analysis of NFRM showed that AF are more susceptible to microstructural damage under weathering conditions, while in NFRC untreated NF, such as ALF and FxF, generally exhibit stronger adhesion to the cementitious matrix.
- The approach of studying the region proposed in this paper is limited by the number of suitable papers published? available, which may decrease the comparability between results from the same region, however, a comparison with results from other regions may validate the reported results.
- As a research suggestion, the authors propose the use of effluents derived from metallization as water for NFRM and NFRC mixtures, since no data were reported in this bibliographic review. This could be a use of the waste generated in the alkaline treatment tests.
- The data shows that NF consistently offer lower energy requirements, lower carbon footprints, and fewer GHG emissions than synthetic fibers. However, the carbon footprint of NFRC, while lower than other FRC, remains higher than conventional concrete. This underscores the importance of continued research into optimizing natural fiber-reinforced composites for improved environmental performance.
- From a sustainability perspective, the adoption of NF could substantially reduce the environmental impacts of construction materials, making them a critical component of greener building practices.

- Future research should focus on optimizing fiber treatments to enhance workability and adhesion to the cement paste, improving the overall performance of NFRM and NFRC. Also, Further research on the durability of NFRM and NFRC should be conducted. For example, moisture-dryness cycles, water penetration, chloride penetration, etc.
- Because it is complex to address the issue of NF from a global perspective, future systematic studies of other regions should be conducted to compare the findings stated in this paper.
- There is a lack of thoroughness in the results presented in published works, as there is a lack of a set of minimum criteria for assessing the methodological strength of an article which should be established.

CRediT authorship contribution statement

Gilberto García: Writing – original draft, Methodology, Formal analysis, Data curation. **René Cabrera:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Julio Rolón:** Writing – review & editing, Visualization, Resources. **Roberto Pichardo:** Writing – review & editing, Visualization, Resources. **Carlos Thomas:** Writing – review & editing, Validation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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