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Review

Recycling Water Hyacinth as Supplementary Cementitious Material, Admixture, and Fiber in Mortar and Concrete: Current Trends and Research Gaps

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Abstract: This review explores the potential of water hyacinth (WH) as a sustainable material in cement-based applications, focusing on its use as an addition, admixture, and fiber reinforcement. WH's unique physical and chemical properties, such as high cellulose content and pozzolanic potential, make it suitable for bio-composites and eco-friendly concrete formulations. The present study highlights several promising findings, including the enhancement of the resulting mechanical properties and the reduction in their environmental impact when the WH is incorporated in controlled quantities. Challenges such as workability and durability issues at higher dosages are discussed. This review aims to bridge knowledge gaps and support WH's adoption in sustainable construction practices.

Keywords: water hyacinth; bio admixture; supplementary cementitious material; natural fibers; natural fiber reinforced concrete; natural fiber reinforced mortar; eco-concrete; vegetable fibers

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1. Introduction

The high production of concrete and cement (14 billion m^3 and 4.2 billion tons, respectively, in 2020) [1], along with the resulting CO_2 emissions released into the atmosphere [2], around 3.4 gigatons [3], has led to the exploration of alternative materials with a lower carbon footprint [4]. This has prompted the search for solutions such as the use of recycled materials [5–8] and the development of more eco-friendly cements and concretes [7,9–11]. A growing trend has been exhibited in the use of biomaterials such as natural fibers [12,13], bio-aggregates [14,15], bio-additives [16–18], and bio-additions [19,20] to achieve such results. One such biomaterial with limited available information regarding concrete technology is water hyacinth (WH). WH, also known as *Eichhornia crassipes*, is one of the 100 most dangerous invasive species globally [21]. It poses significant threats to aquatic ecosystems due to its rapid growth and reproduction [22], enabling it to proliferate uncontrollably and cover large areas of water bodies [23]. This invasive species forms dense mats that obstruct sunlight, impeding photosynthesis in submerged aquatic plants, disrupting ecosystems [24] and economies [25]. Its decomposition depletes oxygen levels, threatening aquatic life and biodiversity [26]. Additionally, WH alters water quality by promoting sediment accumulation and eutrophication, fostering algal blooms and rendering water unsuitable for human use [27]. Its dense mats also displace native species, modify habitats, and provide breeding grounds for disease vectors such as mosquitoes [28,29]. Significant water losses due to evapotranspiration from aquatic weeds have also been reported, such as in

the Rosetta Branch of the Nile River, where annual water loss is approximately 21.3 million m^3 [30]. WH obstructs waterways, affecting navigation, irrigation, and fishing [23]. These challenges have been reported worldwide, including in the United States [31], Mexico [32], Africa [33–35], Malaysia [36], Indonesia [37], China [26], and Spain [21,38]. Despite these challenges, WH has demonstrated potential as a sustainable material. Various commercial products are based on WH [39–42], including applications in biogas [35,43], biofuel [40,44], and bio-energy production [45]. However, there are certain aspects, such as its technical feasibility on a large scale, its efficiency, and the technology needed for manufacturing value-added products with it, that need improvement [46].

This paper proposes the use of WH as a sustainable material in concrete production, addressing its potential applications as a supplementary cementitious material (SCM), admixture, and reinforcement in fiber-reinforced concrete. It will also provide an overview of current trends in WH utilization, focusing on its potential to contribute to more eco-friendly concrete formulations. By doing so, this study aims to bridge the knowledge gap and promote the adoption of WH as a viable and sustainable alternative in the construction industry.

2. Water Hyacinth Composition

Water hyacinth (*Eichhornia crassipes*) exhibits unique physical and chemical properties, making it a versatile component of several applications. Physically, it features a floating rosette structure with thick, waxy leaves supported by spongy, air-filled petioles that provide buoyancy (Figure 1). Its fibrous and feathery roots extend underwater, aiding it with its nutrient absorption process, while the plant's vibrant green leaves and purple flowers add to its distinct appearance.



Figure 1. WH visual aspect.

WH is characterized by a high moisture content (83–95%), medium cellulose content (18–33%), and low lignin content (1–9%), as reported by Romero et al. [47]. This composition makes it suitable for bio-composites and reinforcement materials. Chemically, it is rich in nitrogen, phosphorus, and potassium, this being the reason why it is often used for phytoremediation, owing to its ability to absorb heavy metals like lead, cadmium, and mercury from polluted water. The plant also contains secondary metabolites such as polyphenols and tannins, along with silica in its roots, which can contribute to pozzolanic activity in cementitious systems. Its high ash content (~10%) and carbon-to-nitrogen ratio further enhance its potential for bio-conversion and sustainable applications. The high cellulose content and low lignin in WH biomass indicate potential for biofuel production [44,48,49]. Table 1 shows the composition of WH according to various authors. Differences in composition may arise from diverse WH origins, growth conditions [35,42,49], and selected plant parts (leaf, stems, or roots), as noted by Serrano et al. [48] and Gbiete et al. [35]. Cellulose and hemicellulose contribute to the tensile strength and absorption properties of natural fibers, while lignin provides biodegradation resistance [12,50].

Table 1. Composition of WH according to different authors.

Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Ref.
18.73–27.08	17.61–25.73	4.47–5.77	-	[35]
20	48.00	3.50	29.50	[40]
24	30.00	16.00	20.00	[43]
32.14	-	0.31	19.63	[44]
13–16	24.00–27.50	8.00–14.00	14.00–26.00	[48]
46.00	21.00	11.00	11.00	[50]
12.20	48.70	3.50	31.90	[51]
32	23.00	9.90	26.00	[52]
24.5	34.00	8.60	1.50	[49]
64.50	-	7.69	12.00	[53]

The elemental composition of WH (Table 2) shows significant variability, with carbon (14.4–42.5%) and oxygen (27–70%) indicating a high organic content and potential for bio-conversion applications. As previously stated, its elemental composition varies depending on the environment where WH grows [42]. Nutrient elements such as potassium (up to 8.26%), calcium (4.73%), and magnesium (1.96%) make it suitable for use as a bio-fertilizer. Meanwhile, the presence of silica (5.33%) and iron (4.71%) suggests its potential in the construction industry, particularly as a pozzolanic additive, as reported by Salas et al. [21] who highlight its practical applications in street furniture, paving, or precast products.

Table 2. Element composition of WH according to different authors.

Element	[40]	[43]	[45]	[54]
C	40–42.5	38.4	24	14.4
O	27–29	38.1	70	49.5
N	1.2–4.6	2.9	0.6	-
H	5.2–6.5	5.85	4	-
S	-	0.47	0.70	-
P	-	0.77	-	-
K	-	2.78	-	8.26
Ca	-	1.32	-	4.73
Na	-	1.44	-	0.58
Mg	-	-	-	1.96
Al	-	-	-	2.32
Zr	-	-	-	2.24
Cl	-	-	-	5.58
Si	-	-	-	5.33
Te	-	-	-	0.27
Fe	-	-	-	4.71

Table 3 summarizes the chemical composition of various WH samples processed under different conditions, highlighting the contents of oxides such as SiO_2, calcium oxide (CaO), potassium oxide (K_2O), aluminum oxide (Al_2O_3), magnesium oxide (MgO), and ferric oxide (Fe_2O_3), along with chlorine (Cl), sulfur trioxide (SO_3), and its loss on ignition (LOI). Silicon dioxide (SiO_2) is the dominant constituent of WH (23.38% to 34.80%), indicating a strong pozzolanic potential, while CaO varies significantly (7.84% to 25.73%), potentially influencing its setting and hardening properties. K_2O and Cl exhibit wide concentration ranges (5.31% to 16.92% and 0.07% to 8.94%, respectively), where higher levels could raise concerns regarding alkali-silica reactions and reinforcement corrosion levels. Al_2O_3 (6.77% to 10.14%), SO_3 (up to 7.95%), MgO (5.40% to 9.69%), and Fe_2O_3 (3.06% to 6.15%) contribute to strength development and material performance, while LOI (4.51% to 17.96%) reflects

varying levels of organic matter and combustion efficiency. Processing conditions, such as washing and burning, significantly impact these compositions. Higher washing temperatures and extended burning times reduce K_2O, Cl, and LOI levels. Samples with high SiO_2 and low LOI are promising for supplementary cementitious applications. However, durability concerns related to elevated Cl and K_2O levels must be addressed. Optimizing washing and burning processes is essential to balance the composition, performance, and feasibility of the resulting materials.

Table 3. Chemical composition of WHA according to different authors.

CaO	SiO_2	K_2O	Cl	Al_2O_3	SO_3	MgO	Fe_2O_3	LOI	Ref.
7.84	24.31	16.92	3.84	7.94	6.04	6.34	3.06	11.15	[21] [a]
11.46	33.52	6.83	0.34	9.30	1.78	8.83	3.75	13.81	[21] [b]
12.03	33.56	5.31	0.07	10.14	0.74	9.69	4.13	13.12	[21] [c]
25.73	23.38	10.90	8.94	8.85	7.95	5.85	3.74	4.51	[55]
10.08	33.89	9.83	3.82	6.77	-	5.40	5.77	17.96	[56] [d]
12.15	34.80	11.55	4.12	7.04	-	5.40	6.15	8.88	[56] [e]
22.61	4.40	14.82	-	2.20	3.09	14.01	1.27	-	[57]

[a] WHA from the roots of the plant; [b] washing with water at 80 °C for 4 h; [c] WHA washing with water at 23 °C for 24 h; [d] WHA burned in air; [e] WHA burned at 950 °C.

3. Water Hyacinth as Supplementary Cementitious Materials

SCMs are materials that, when used in conjunction with Portland cement, contribute to the properties of concrete and mortar. These materials, such as fly ash (FA) [58], slag [59,60], silica fume (SF) [61,62], and natural pozzolans [63], are widely recognized for their ability to enhance the durability, workability, and sustainability of concrete. Recently, bio-SCM derived from natural materials, such as rice husk ash (RHA) [64], cellulose fibers [65,66], or biochar [67,68], have gained attention. By partially replacing cement, SCMs help reduce the environmental impact of concrete production, notably by lowering carbon emissions associated with cement manufacturing. Additionally, they can improve long-term strength, reduce permeability, and increase resistance to chemical attacks for the resulting materials, making SCMs an important component in the production of high-performance, durable concrete and mortar. In this section, the findings reported by different researchers on the use of WH as an SCM in the production of concrete and mortar are presented. Using WH as an SCM is both relevant and sustainable as it helps address the environmental issues caused by this invasive species. By harvesting water hyacinth, which grows rapidly in water bodies, it can be converted into a pozzolanic material, reducing the need for Portland cement and lowering carbon emissions. This approach not only provides an effective solution to manage the invasive plant but also contributes to waste reduction and promotes sustainability in the construction industry.

3.1. Concrete

WH ash (WHA) as an SCM for cement replacement has been reported in the literature. WHA has a density of 2.12 to 2.40 g/cm^3, depending on its production process, with a particle size between 0.5 mm and 50–200 μm [69]. It also shows an absorption of 5.82% and a fineness modulus of 10 [55,69,70]. In the consulted literature, the usual process to obtain WHA is by incineration in an oven at 950 °C for 30 min [71,72], 800 °C for 6 h [73,74], 650 °C for 45 min [21], 600 °C for 6 h [75], and 700–900 °C for 6 h [69,76].

Hodhod et al. [71] studied the effect of WHA in concrete manufacturing (0 to 10% cement replacement). WHA concrete was compared with a control concrete (0% WHA) and concrete with 10% SF as a cement replacement. Results indicated that 10% WHA as a cement replacement improved concrete durability. Regarding pore volume, the in-

corporation of 10% WHA resulted in lower values than the control concrete and values comparable to SF concrete. This improvement is attributed to the smaller particle size of WHA, which fills the pores, produces discontinuous pore structures, and exhibits high pozzolanic activity, forming calcium silicate hydrate (C-S-H), thereby enhancing the durability of resulting materials [71]. The porosity of control concrete was 22.16%, while the porosity of concrete with 7.5% WHA was 19.34%, representing a 13% reduction. This reduction can be attributed to the filling effect of WHA, which also decreases the absorption of WHA concrete [75]. Anchondo et al. [70] studied the incorporation of WHA as a cement replacement at levels between 0% and 3%. Compressive strength results indicated that incorporating 3% WHA reduced compressive strength by up to 44% compared to control concrete. However, 1% WHA achieved similar compressive strength (84 kg/cm^2) to the control concrete (85.5 kg/cm^2).

Abana et al. [77] reported that the initial setting time of both concrete mixes, one with 0.5% wt. and the second one with the 1% wt. WHA addition, was reduced by 8% and 61%, respectively, compared to control concrete (187.2 min). The final setting time was reduced by 35% with a 1% wt. WHA compared to control concrete (255 min). However, the final setting time of concrete with 0.5% wt. WHA was increased by 6% compared to the control sample. This indicates that WHA can act as both a retarder or an accelerator, depending on the amount added. Regarding its mechanical properties, compared with control concrete (20.9 MPa), both 0.5% wt. and 1% wt. WHA improved compressive strength by 2.39% and 3.83%, respectively. This improvement can be attributed to finer WHA particles creating a filling effect within the concrete matrix, as reported in the literature [6,78].

Varghese and Vasudev [79] experimented with concrete containing a fixed proportion of 15% FA and up to 20% WHA. They reported that incorporating WHA increased compressive strength by up to 15% with 15% wt. WHA. However, higher WHA content (e.g., 20% wt.) reduced compressive strength by 13%. A similar trend was observed in splitting tensile strength, where up to 15% wt. WHA improved resistance by 27%, while 20% wt. WHA decreased splitting tensile strength by 8%.

Shaban and Abdel [72] introduced up to 5% wt. WHA in concrete. Slump values revealed that the WHA addition decreased workability by up to 50% with 5% WHA. The incorporation of WHA in varying percentages (0%, 0.5%, 1%, 2%, and 5%) had notable effects on compressive and splitting tensile strengths. Compared with control concrete (30 MPa), the highest compressive strength observed was 35.30 MPa (with 2% WHA), indicating an improved capacity to withstand compressive forces, likely due to the pozzolanic properties of WHA which enhance cement hydration. Similarly, compared with control concrete (2.65 MPa), the highest splitting tensile strength, 3.04 MPa, was achieved with 2% WHA. Lower WHA contents (0.5% wt. and 1% wt.) showed varying results, with 0.5% wt. WHA yielding the lowest compressive strength (25.50 MPa) and tensile strength (2.55 MPa), potentially indicating insufficient benefits at these doses. Higher percentages, such as 5% wt. WHA, reduced performance.

Yehualaw et al. [73] reported that burning WHA at 800 °C for 6 h results in a material with strong pozzolanic properties, making it suitable as a SCM. Concrete containing 5% by wt. WHA exhibited a 37% increase in workability compared to the control concrete (35 mm slump), attributed to the smooth surface and spherical shape of WHA particles. This characteristic also explains the observed reduction in water absorption with increasing WHA content. At 28 days, the compressive strength of concrete improved by 4.23% and 7.85% for 5% and 10% WHA, respectively, while a 15% WHA addition resulted in a 3.23% strength reduction. Results at 10% WHA are aligned with findings in the literature [74]. The improvement in compressive strength was primarily due to the pozzolanic reaction between WHA and calcium hydroxide, leading to the formation of additional C–S–H. In

contrast, concrete without WHA relies solely on cement hydration, producing only limited amounts of C–S–H [73].

Table 4 summarizes the findings mentioned above. Compared with control concrete (50 mm), the incorporation of WHA decreased the slump by 20, 40, and 60% when 0.5, 1, 2, and 5% WHA was incorporated, respectively. Although contradictory results are reported, compared to control concrete (35 mm), the slump increased by 37, 85, and 162% when 5, 10, and 15% WHA were incorporated, respectively. The improvement of the slump its attributed to the spherical shape and smooth surface of the WHA, which lowers the specific surface area [73]. This demonstrates that further studies should be conducted to clarify the contrasts observed in the slump of WHA-incorporated concrete. A similar case occurs with the compressive strength of WHA-incorporated concrete. When 0.5% WHA is used as a cement replacement, the compressive strength increases by 3.82% but also decreases by 16% compared to the respective control concrete strengths (20.90 MPa and 30.40 MPa). These contradictory results are also observed with the incorporation of 1% WHA, where compressive strength increases by 3.82% but decreases by 6.67% compared to the respective control concrete strengths (20.90 MPa and 30.40 MPa). When 5% WHA is incorporated, similar patterns are observed. Compressive strength increases by 1.8% and 4.22% compared to the control concrete (37.20 MPa and 33.10 MPa, respectively), but also shows a 16% reduction compared to another control (30.40 MPa). Conversely, incorporating 10% WHA shows consistent improvements in compressive strength by 8%, 7.85%, and 5% compared to control concretes (37.20 MPa, 33.10 MPa, and 30.43 MPa, respectively). However, at 20% WHA incorporation, compressive strength decreases by 13% and 10% in all cases compared to the respective control concretes (37.20 MPa and 30.43 MPa). For tensile strength, a 5% WHA incorporation increases tensile strength by 9%, while incorporating 10% WHA results in an increase of 19% to 20%. However, at 20% WHA incorporation, tensile strength decreases by 8.75% to 17.84%. Finally, water absorption decreases with higher WHA incorporation. Compared to the control concrete (4.50%), water absorption decreases by 16%, 19.5%, and 20.8% with 5%, 10%, and 15% WHA incorporation, respectively. These results suggest that WHA can improve specific concrete properties, particularly at moderate replacement levels (5–10%), but further studies are essential to address the inconsistencies observed, particularly in compressive strength and slump behavior.

Regarding durability, Anchondo et al. [70] reported that the inclusion of up to 3% wt. cement of WHA increased the absorption of concrete up to 38% compared to control concrete. This could be related to the hemicellulose content of WHA, which is the component responsible of the absorption of the natural fibers [12]. Anchondo et al. [70] studied Ultrasonic Pulse Velocity (UPV) in WHA concrete. Results indicated that the incorporation of 1% wt. cement of WHA increases the UPV value by 12%, but further WHA inclusions resulted in minimal changes in UPV values compared to control concrete. This is in line with the compressive strengths results, meaning that 1% of WHA improves the concrete matrix, resulting in a closer and less porous structure. Based on an experimental study conducted by Murugeshet et al. [75], concrete with a 10% replacement of cement by WHA exhibited excellent chloride resistance in a 3.5% chloride solution. Blended concrete with WHA demonstrated lower chloride ion permeability and a lower diffusion coefficient compared to control concrete with the same percentage replacement [71]. Therefore, it is suggested that a 10% replacement of WHA is the optimal ratio to reduce chloride ion permeability, diffusion coefficient, and concrete carbonation depth.

Table 4. Influence of the WHA as SCM incorporation on the mechanical properties of concrete according to different authors.

WHA% wt.	Slump (mm)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Water Absorption (%)	Ref.
0	-	20.90	-	-	[77]
0.5	-	21.40	-	-	
1	-	21.70	-	-	
0	-	37.20	2.97	-	[79]
5	-	37.90	3.25	-	
10	-	40.31	3.56	-	
15	-	42.73	3.78	-	
20	-	32.50	2.71	-	
0	50	30.40	2.75	-	[72]
0.5	40	25.50	2.55	-	
1	30	28.37	2.84	-	
2	30	35.30	3.04	-	
5	20	27.97	2.75	-	
0	35	33.10	-	4.50	[73]
5	48	34.50	-	3.77	
10	65	35.70	-	3.62	
15	92	34.60	-	3.56	
0	-	30.43	2.97	-	[74]
10	-	31.95	3.50	-	
20	-	27.13	2.44	-	

3.2. Mortar

Regarding mortars, Salas et al. [21] studied the incorporation of 25% WHA from its roots. They reported that the addition of 25% WHA decreased the compressive strength by 51% and 48% at 28 and 90 days, respectively. This suggests that a lower WHA content should be used in future studies. According to the authors, the loss of strength was attributed to the lower silica content, magnesium silicate, and amorphous material in the WHA [21]. In terms of absorption, a high WHA content increased water absorption, which in turn increased the mortar's water content. However, this absorption decreased over time due to the pozzolanic reaction of the WHA [21]. In contrast to the previous study [21], He et al. [69] investigated the compressive and flexural strength of mortar incorporating 2% of the cement weight as WHA replacement. Two different sizes of WHA were studied: one with a particle size of 0.5 mm (manually crushed WHA) and another with a size of 50–20 µm (ball-milled WHA). Compared to mortar without WHA (39.43 MPa), incorporation of ball-milled WHA mortar resulted in a more significant increase in mortar strength (19%). This could be due to the much smaller particle size of the ball-milled WHA, which contributes to a filler effect, densifying and strengthening the mortar matrix [69]. Additionally, the incorporation of WHA retarded the setting time, which was attributed to water absorption at the surface of the WHA. As the proportion of WHA increased, water absorption also increased, leading to a delay in setting time, as reported in the literature consulted [76]. Das and Singh [76] used up to 25% wt. replacement of cement with WHA. They reported that absorption decreased as the WHA content increased, likely due to the gradual closing of pores in the mortar, as WHA (150 µm) was finer than OPC [76]. Table 5 summarizes the findings reported in this section.

Table 5. Effect of WHA content as SCM in mortar properties according to different authors.

WHA%	Compressive Strength (MPa)	Flexural Strength (MPa)	Water Absorption (%)	Ref.
0	59.61	-	5.20	[21]
25	29.22	-	6.24	
0	39.43	7.13	-	[69]
2 [a]	38.43	7.00	-	
2 [b]	46.96	8.11	-	
0	43.50	-	7.31	[76]
10	38.00	-	6.76	
15	29.00	-	6.451	
20	25.00	-	6.24	
25	22.50	-	5.93	

[a] manually crushed WHA; [b] ball-mill WHA.

In summary, compressive strength decreases progressively as WHA content increases, indicating that high WHA levels reduce the mortar's structural capacity. Flexural strength shows a positive response to lower WHA additions, peaking at 8.11 MPa for 2% WHA, but this parameter was not evaluated for higher WHA levels. Water absorption increases with WHA content, rising from 5.2% at 0% to 6.24% at 25%, suggesting a decline in durability. However, slight reductions in water absorption are observed beyond 20% WHA, possibly due to filler effects. These results suggest that while small amounts of WHA may enhance certain flexural properties, excessive WHA content compromises both strength and durability.

Regarding durability, the literature is scarce, Das and Singh [76] used 10, 15, 20, and 25% wt. replacement of cement for WHA in mortar and studied the durability in terms of water absorption and sorptivity. It was reported that the water absorption and sorptivity decreased as the WHA increased (Figure 2). In the case of absorption, it was reduced by 7.5%, 12%, 15%, and 19% with the addition of 10, 15, 20, and 25% wt. of WHA compared with control concrete (7.31%). Regarding water sorptivity, compared with the control concrete (0.146 mm/min$^{0.5}$), the incorporation of WHA decreased the sorptivity values by 7.5, 13, 15, and 20% with the incorporation of 10, 15, 20, and 25% of WHA. This may be due to the gradual closing of pores in the mortar as WHA (150 µm) was finer than OPC [76]. It could also be attributed to the smooth surface and spherical shape of WHA which creates a denser mortar structure, as reported by He et al. [69].

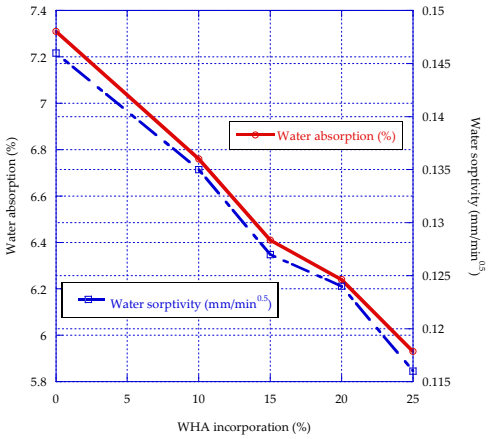


Figure 2. Water absorption and sorptivity of mortars with WHA. Adapted from: [76].

4. Water Hyacinth as an Admixture

An admixture in concrete production refers to any chemical or material added to the concrete mix, other than water, cement, aggregates, or fibers, to modify the properties of the fresh or hardened concrete. Admixtures are used to improve workability, accelerate or lengthen setting time, enhance durability, and achieve other specific performance characteristics. They are typically added in small quantities but can have a significant effect on the overall performance of the resulting concrete. In this section, the studies reported in the literature on the effect of WH as an admixture (WHAD) to produce concrete and mortar will be presented.

4.1. Concrete

Priya et al. [80] experimented with chopped WH pieces, which were then ground into a paste and filtered using a fine screen and added as an admixture. The filtered extract was used as a bio-plasticizer. The percentage increase in WHAD decreases the workability. From this, it can be concluded that the WH, when added as a plasticizer in concrete, has the tendency to reduce the overall water requirement of the concrete. Slump decreases slightly as WH content increases, from 80.50 mm at 0% WH to 67.50 mm at 20% WH. The compressive strength at 28 days increases with WH content, from 39.80 MPa for 0% WH to 43.84 MPa for 20% WH. This higher strength may be due to the presence of the lignocelluloses present in the WH, which increases the binding property when it is added to the concrete as reported in the literature [81]. Okwadha et al. [82] studied the incorporation of WHAD up to 25% as a superplasticizer replacement in self-compacting concrete. Results indicated that the workability increased with the WHAD incorporation. The compressive strength test results increased with an increase in the amount of WHAD, according to the authors [82], the presence of fatty acids, such as palmitic acid and linoleic acid, along with a significant amount of di-unsaturated esters of linoleic acid in the WH, may explain the increased compressive strength with higher amounts of the aforementioned extract. Lamichane et al. [83] reported that the slump increases with WH extract, starting at 47 mm for 0% WH and reaching 170 mm for 1% concentration WH. WH was submerged in water to obtain a liquid extract. The submerged material underwent ultrasonic treatment for 30 min, followed by 24 h of resting. It was then subjected to a second ultrasonic treatment for another 30 min. After ultrasonication, the extract was filtered and subsequently concentrated using a rotary evaporator to remove the solvent. Regarding its compressive strength, it initially showed a slight improvement with 0.25% concentration WH (29.10 MPa at 28 days) compared to the control concrete (28.60 MPa). However, as the WH content increased beyond 0.5% concentration, the compressive strength declined significantly, with the 1% concentration of WH resulting in only 10.20 MPa at 28 days. Table 6 summarizes the findings in the literature reviewed. In general, an increase in WHAD content lead to a reduction in slump values in some cases (e.g., from 80.50 mm at 0% to 67.50 mm at 20% WHAD in one study) while significantly increasing slump in others (e.g., from 520 mm at 0% to 670 mm at 25% WHAD in another study). This suggests that the effect of WHAD on workability is dependent on specific mix proportions. Compressive strength improves consistently with increasing WHAD content, peaking at 57 MPa at 20% WHAD in one study, before slightly decreasing at 25% WHAD to 48 MPa. These findings highlight the potential of WHAD to enhance concrete strength while impacting workability, with optimal performance observed at moderate WHAD levels. It is important to mention that the different methods used to obtain WHAD can impact the results of its fresh and hardened properties, which is why more experiments should be conducted to compare results or propose more efficient methods of obtaining WHAD that yield more favorable outcomes.

Table 6. Effect of WHAD on the fresh and hardened concrete properties at 28 days of age.

WHAD%	Slump and Slump Diameter (mm)	Compressive Strength (MPa)	Ref.
0	80	39.80	[80]
10	70	41.84	
20	67	43.84	
0	520	27.00	[82] *
10	535	40.00	
15	565	51.00	
20	620	57.00	
25	670	48.00	
0	47	28.60	[83]
0.25	120	29.10	
0.50	140	28.50	
0.75	158	14.90	
1	170	10.20	

* These values correspond to slump flow diameter in self-compacting concrete.

4.2. Mortar

The literature on this specific topic is scarce, although, it has been reported that Sathya et al. [84] utilized WHAD at 10, 15, and 20% incorporation in mortars. Results indicate that the workability of mortars increased with the addition of WHAD. Compared with the control mortar (19 mm), the slump of mortars with 10, 15, and 20% WHAD increased by 42, 100, and 142%. At 28 days, the compressive strength of mortar with 20% WHAD increased by 28% compared to control mortar (32.4 MPa). This could be explained because of the presence of photochemicals, such as lingo-cellulose, saturated and unsaturated fatty acids, acting as a strengthening agent of cement in mortar. Nevertheless, due to the novelty of this work and the limited literature available, further studies are needed to compare the presented results, which will confirm whether these amounts of WHAD positively or negatively affect the fresh and hardened properties of mortar.

5. Water Hyacinth Fibers

Natural Fiber Reinforced Concrete (NFRC) combines traditional concrete components with natural fibers NF to enhance the strength of concrete. Unlike conventional mixes, NFRC incorporates fibers from renewable plant-based sources, rather than traditional fibers such as steel [85] or polypropylene [86]. With improved tensile strength, NFRC provides a sustainable alternative for various construction applications, offering resilient, eco-friendly solutions for building structures [12].

WH fibers (WHF) have an average diameter of 229.50 μm [87], a specific gravity of 0.70–0.86 [87,88] and a density of 1.20 g/cm^3 [89]. As observed in Table 1, the cellulose content varies from 12 to 64%. The cellulose content determines the tensile strength of the fiber. Regarding its mechanical properties, it has been reported that WH fibers have a Young's Modulus of 2.95–7.7 GPa [87,89,90] and a moisture content and tensile strength of 12–13% [50,87] and 313–318 MPa [50,89], respectively. These characteristics align with the literature regarding natural fiber mechanical properties [12].

Verdian and Muin [53] incorporated 0.75% cement wt. of WHF into concrete. The reductions in compressive strength of WHF concrete with fiber lengths of 2 cm, 1.5 cm, and 1 cm were 10.76%, 14.16%, and 18.76%, respectively, compared to the control concrete. This reduction can be attributed to the cavities created by the WHF within the concrete matrix, resulting in a more brittle material. However, the 2 cm WHF length exhibited the highest

compressive strength compared to the other fiber lengths. The decrease in the split tensile strength of the concrete occurred due to fiber agglomeration during sample preparation, as the fibers were not evenly distributed, leading to clumping. Additionally, the reduction in the elastic modulus of the concrete was caused by the less homogeneous bonding between the cement and aggregate, making the concrete particles more prone to deformation under applied loads. In general, to mitigate these issues, optimizing fiber length and treating fibers to enhance adhesion could ensure better distribution, reduce clumping, and improve overall mechanical properties. In this case, the reduction in mechanical properties could be due to the fiber length not being optimal, which may have caused fiber agglomerations within the concrete matrix, creating cavities and pores that affected the strength of the NFRC.

Xu et al. [91] developed lightweight aggregate concrete (LWAC) with two different aggregates and expanded polystyrene (EPS) and ceramsite lightweight aggregates (CLA). In both mixes, a 2% wt. cement of WHF was added. At 28 days, WHF exhibited an increase in the compressive strength of EPS-LWCA by 2.5% while CLA-LWCA did not have an effect on the compressive strength because the reduction in the compressive strength was minimal (1%). Regarding split tensile strength, the increase in this mechanical property in EPS-LWCA and CLA-LWCA was 5% and 7%, respectively, at 28 days of age. Kiptum et al. [92] added WHF from 0 to 0.3%vol. concrete to investigate the effect of the fiber orientation. Results indicated that the incorporation of up to 0.3%vol. of WHF decreased the compressive strength by 15% and 38% when the orientation was horizontal and vertical, respectively. A similar trend is presented in splitting tensile strength, where up to 0.3%vol. of WHF reduced the resistance by 12% and 49% when the WHF orientation was horizontal and vertical, respectively. It was concluded that the incorporation of WHF reduced both compressive strength and splitting tensile strength regarding the fiber orientation, although, 0.10%vol of WHF incorporation had the highest results in both mechanical properties. Dewi et al. [88] reported that the more WHF (2 cm length) is added, the more the compressive and tensile strength increases, with values up to 50% due to the incorporation of 0.75% vol. of WHF. The authors recommend not using more than 0.50% because a higher WHF incorporation can decrease the workability of the resulting concrete. Table 7 summarizes the findings of this section.

Table 7. Effect of WHF content in concrete according to different authors.

WHF%	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Ref.
0	45.42	3.74	[53] *
0.75 [a]	36.90	3.65	
0.75 [b]	38.99	3.47	
0.75 [c]	40.53	2.76	
0	12.15	1.51	[91] *
2 [d]	12.45	1.44	
0	17.96	1.59	
2 [e]	17.75	1.70	
0	28.06	1.37	[92] **
0.10 [f]	27.05	1.50	
0.20 [f]	24.80	1.37	
0.30 [f]	23.95	1.21	
0	26.18	1.25	
0.10 [g]	18.94	1.08	
0.20 [g]	18.12	0.79	
0.30 [g]	16.32	0.64	

Table 7. *Cont.*

WHF%	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Ref.
0	30.00	3.00	[88] **
0.25	35.00	3.50	
0.50	40.00	4.00	
0.75	45.00	4.50	

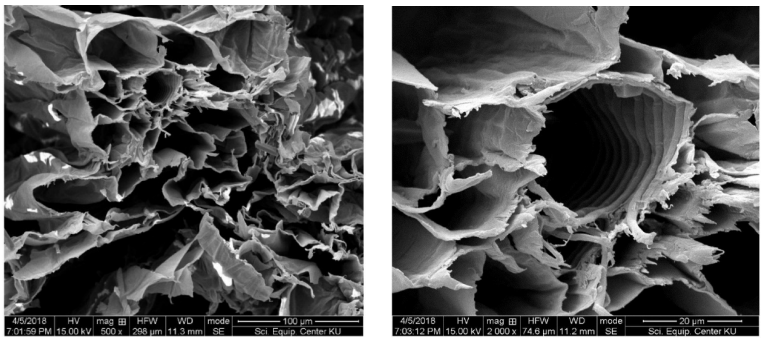
[a] WHF length of 1 cm; [b] WHF length of 1.5 cm; [c] WHF length of 2 cm; [d] LWAC with expanded polystyrene; [e] LWAC with ceramsite lightweight aggregate; [f] horizontal orientation; [g] vertical orientation: * % wt. cement; ** %vol. concrete.

6. Water Hyacinth Microstructure

The study of the microstructure of concrete is essential for understanding its performance, durability, and long-term stability. Microstructural analysis provides insights into the distribution and interaction of the material's components, such as cement hydration products, aggregate bonding, and pore structure. In this context, WH offers potential as a natural fiber reinforcement for concrete and mortar. Its abundant cellulose content and fibrous structure make it a sustainable and eco-friendly alternative.

6.1. Water Hyacinth Fibers

WHF are primarily composed of organic matter, including lignin and hemicellulose, which form cell wall-like structures and elongated rods interconnected by numerous fibers. As illustrated in Figure 3a, the SEM microstructures of WH reveal microfibrils crosslinked by cellulosic nanofibers. The WHF features an irregular porous structure with internal air cavities, often interconnected to form bundles of fibers reinforced by strong connective elements (Figure 3b). This unique composition imparts a high ductility and elastic modulus while providing adequate strength, making WHF an excellent candidate for a bio-filler in concrete and other construction materials. The WHF morphology will depend on the extracting process, as stated by Ajithram et al. [93], and a mechanical extraction method will produce good quality fiber.



(**a**) (**b**)

Figure 3. WH microstructure: WH microfibrils at 500× (**a**) and internal structure of WH at 2000× (**b**). Retrieved from: [90].

In addition, Figure 4a illustrates that the WHF is a monofilament fiber [50]. Monofilaments lack the fuzziness or irregular texture typically observed in multifilament or composite fibers. Additionally, their production process often involves direct extraction, resulting in single filaments rather than a combination of smaller fibers (Figure 4b).

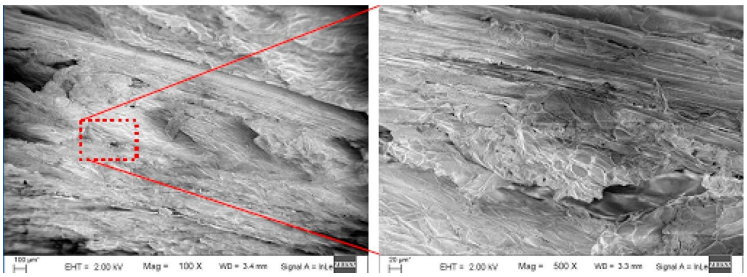


Figure 4. WHF stem structure at 100× (**a**) and at 500× (**b**). Retrieved from: [50].

Mohit et al. [94] reported that the surface of WHF can be improved with an alkaline treatment (Figure 5). The WHF were initially soaked in a saltwater solution composed of sodium chloride and distilled water in a 20:1 ratio. This soaking process lasted for 24 h at room temperature (28 ± 2 °C) and a relative humidity of 60 ± 2%. After soaking, the fibers were thoroughly rinsed with tap water to eliminate any remaining impurities and dust. Subsequently, the fibers underwent an alkaline treatment by immersing them in a 10% by weight sodium hydroxide solution at room temperature for 12 h. The treated fibers were then rinsed with deionized water until their pH was neutral. Finally, the cleaned fibers were dried in a heating furnace for 48 h at 80 ± 2 °C. Dewi et al. [89] demonstrated that heating WHF at 100 °C enhanced the fiber surface by removing impurities such as dirt and wax, which in turn improved the modulus of elasticity by 47%, compared to untreated fibers (6.78 GPa). The process of extracting WHF began with drying the stems, followed by brushing them with a fine wire brush to separate the fibers. The extracted fibers were then subjected to a thermal treatment at 60 °C for 1 h to alleviate residual stress. Finally, the heating process was applied at temperatures ranging from 60 °C to 120 °C.

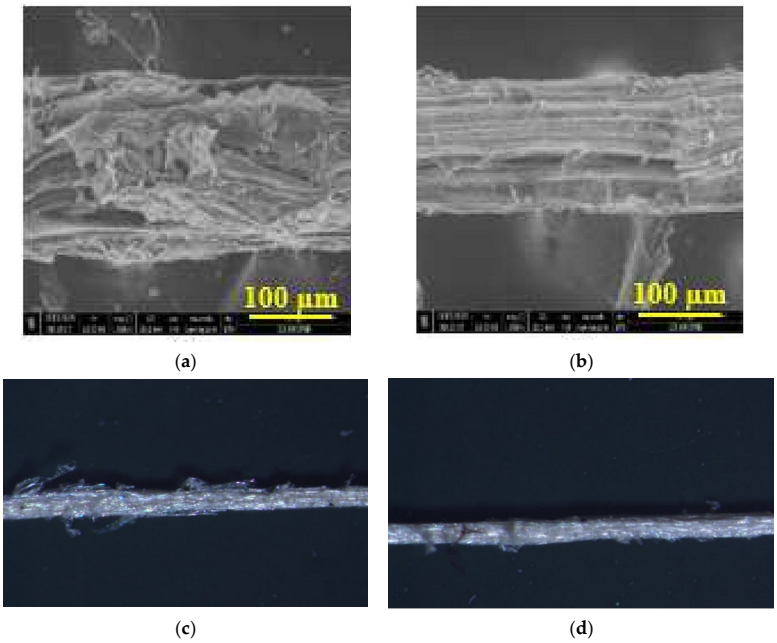


Figure 5. Untreated (**a**) and alkaline treated (**b**) WHF; untreated (**c**) and heated treated (**d**). Retrieved from: [89,94].

6.2. Water Hyacinth Ash

Information regarding the microstructure of WHA is scarce. In this regard, it has been reported that the WHA particles sizes ranges under 500 to 200 µm [69], 420 µm [48], 150 µm [55,73,74,76], and 75 µm [71]. Ajithram et al. [95] study the morphology of WHA and WH powder. WH powder comes from the process of crushing and blending the WH

plant, meanwhile WHA comes from the same process with the addition of burning to obtain the ash. It was reported that compared with WH powder (Figure 6a–c), the WHA particles (Figure 6d–f) have a more closed morphology. The reason why the morphology of a particle, such as WHA, may be more closed and have fewer pores or openings compared to a particle obtained through a crushing process lies in the differences between the production methods and the physical and thermal processes to which the particles are exposed.

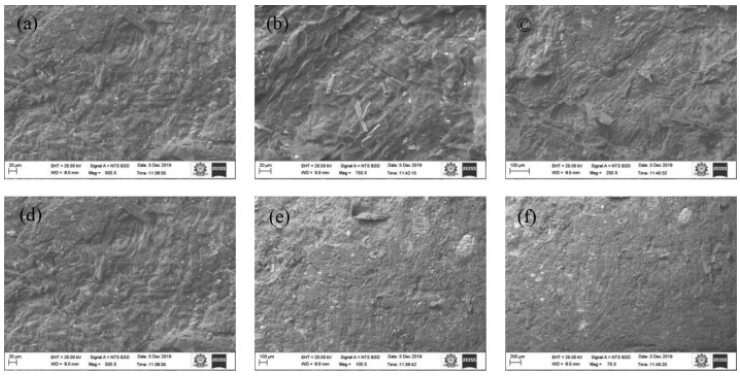


Figure 6. SEM images of WH powder particles at different magnifications (**a**–**c**) and WHA particles at different magnifications (**d**–**f**). Retrieved from: [95].

7. Environmental Assessment

The environmental assessment of WH within the concrete context in the literature is scarce. In this regard, Petroche and Ramirez [96] reported that the global warming potential (GWP) of ordinary Portland cement ranges between 632 and 950 kg CO_2 eq per ton of cement. However, the GWP of cement blended with additives like pozzolan, slag, limestone, or FA decreases to a range of 452 and 850 kg CO_2 eq per ton. This means a reduction range between 28 and 11% of kg CO_2 eq per ton. The production processes for WH biochar and WHA differ significantly, yet they share some similarities. WH biochar is produced through pyrolysis, a process where organic material is heated in a low-oxygen environment at high temperatures, leading to the formation of a stable, carbon-rich material. In contrast, WH ash is created through combustion, where the plant material is burned in the presence of oxygen, resulting in the oxidation of the organic matter and the formation of inorganic mineral residues. Despite these differing processes, both materials can contribute to reducing the environmental impact of concrete production.

He et al. [69] estimated that producing 1 ton of WH biochar generates only 263.50 kg CO_2 eq, which is significantly lower than the emissions associated with traditional Portland cement, which typically range from 459.89 to 798.70 kg CO_2 eq per ton. [97]. By incorporating WH as a SCM, the GWP of concrete could be significantly reduced. Witte and Garg [98] reported that incorporating 55% to 70% SCMs (fly ash and ground granulated blast furnace slag) in concrete mixes resulted in lower GWP compared to conventional concrete, reducing it from around 450 to 240 kg CO_2 eq/m^3. This demonstrates that both WH biochar and WHA, despite their differing production methods, offer potential environmental benefits in concrete applications. Further studies are needed to assess the environmental impact of WHA or WH biochar as cement replacements and to clarify this point.

8. Other Applications

8.1. Masonry

Goel and Kalamdhad [99] fabricated bricks using alluvial soil and laterite soil with WH (finer particles than 600 μm) of added up to 20% by weight. The bricks were fired at 850 °C and 900 °C. The incorporation of WH resulted in lower firing linear shrinkages

compared to control bricks for both soil types at all firing temperatures. Bricks made with laterite soil had bulk densities of 1.52 g/cm^3 and 1.56 g/cm^3 after firing at 850 °C and 900 °C, respectively, while those made with alluvial soil had bulk densities of 1.49 g/cm^3 and 1.51 g/cm^3. The addition of WH decreased bulk density at both firing temperatures, though a rise in firing temperature led to higher densification. Water absorption increased significantly with WH addition, rising by 24.3% and 25.2% in laterite soil bricks and by 40.2% and 41.4% in alluvial soil bricks at 850 °C and 900 °C, respectively. Increased porosity from WH inclusion contributed to this higher water absorption. Compressive strength was notably higher at 900 °C than at 850 °C, indicating greater densification at elevated temperatures. However, a 10% WH blend caused compressive strength reductions of 73% and 72% in laterite soil bricks and 42% and 29% in alluvial soil bricks at 850 °C and 900 °C, respectively.

8.2. Water Replacement in Concrete

Ayyadurai [100,101] investigated the impact of utilized WH treated wastewater (WHTW) on the mechanical properties of concrete, with a particular focus on compressive strength at different curing times (7, 14, and 28 days) and varying percentages of WHTW in the mix. The findings, summarized in Table 8, show that the compressive strength of concrete generally increases with the percentage of WHTW up to 80%. When comparing the concrete mix containing 0% WHTW (control concrete) with mixes containing various percentages of WHTW, the control concrete consistently shows lower compressive strength at 7 and 14 days. At 7 days, the control concrete has a compressive strength of 13.00 MPa, while concrete with 80% WHTW achieves a strength of 14.00 MPa, showing a slight improvement. At 14 days, the control concrete strength is 18.00 MPa, compared to 19.00 MPa for the 80% WHTW mix, indicating a modest enhancement. By 28 days, the control concrete reaches 23.00 MPa, same as the 80% WHTW mix, indicating the optimal performance at this concentration. However, the strength starts to decline at 100% WHTW (19.00 MPa at 28 days), suggesting that while WHTW generally improves concrete strength up to 80%, higher concentrations do not yield better results compared to the control concrete.

Table 8. The effect of WHW in fresh and mechanical properties of concrete according to different authors.

WHTW%	Compressive Strength (MPa)			Ref.
	7 Days	14 Days	28 Days	
0	13.00	18.00	23.00	[100]
20	11.00	16.00	17.50	
40	12.50	17.00	18.00	
60	13.00	17.50	20.00	
80	14.00	19.00	23.00	
100	13.00	18.50	19.00	

9. Conclusions

This article showed a review of the literature focused on WH, information regarding its composition, and its uses as an SCM, admixture, and fiber reinforcement in addition to explaining how it affects fresh and hardened concrete and mortar properties. The following conclusions are presented based on the above:

- WH holds significant potential as a sustainable material in cement-based applications. Its composition and properties make it suitable for use as an addition, admixture, and fiber reinforcement in concrete.
- WH as SCM improves workability and mechanical properties at optimal dosages. It should be noted that the type of WH-based SCM manufacturing can positively or

negatively affect the properties in the hardened state. There are better results when the size of the SCM is under 150 μm.

- There are contradictory results regarding the use of WHAD in concrete. It should be taken into account that, as in the case of WH-based SCM, the manufacturing process of the admixtures can have a great influence on the mechanical and fresh state behavior of the concrete.
- The positive or negative effect of using WHF will depend on whether they are pre-treated, the fiber length, and its quantity. No more than 0.5%vol WFH should be used to have adequate results.
- Microstructure analysis showed the effect of different treatments on the surface of WFH. However, studies showcasing this information are scarce, so it is recommended that future research address this topic.
- Environmental analysis in the literature demonstrates that the use of WH biochar as SCM can reduce the GPW emissions both in cement and concrete manufacturing.
- Further studies should be conducted on the effects of WH-SCM, WHF, and WHAD on the durability of both concrete and mortar. These studies will provide a better understanding of the long-term effects of this material, thus enabling the proposal of practical applications for the construction industry.

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