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Fiber-Reinforced concrete and its life cycle assessment: A systematic review

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ABSTRACT

Concrete is the most environmentally demanding construction material in use worldwide, so evaluating the sustainability performance of concrete is therefore essential. Fiber-Reinforced Concrete (FRC) can diminish the carbon footprint of concrete, being verified by Life Cycle Assessment (LCA). In this systematic review, using the preferred reporting items for systematic reviews and meta-analyses, 69 documents were studied to survey the existing literature on FRC, its LCA methodology and results, and the mechanical performance of the mixes. The results were then presented, and the fibers were characterized, to analyze both the environmental and mechanical performance of the selected research papers using representative indexes, mostly regarding Global Warming Potential (GWP). These indexes showed that the environmental impacts of the FRC mixes could be reduced, even reaching reductions in the GWP of FRC of up to 94 %, without hindering their mechanical performance. FRC sustainability was highly dependent upon the nature and treatment of the used fibers. Thus, steel or synthetic fibers were the most common, yet the most polluting to produce, while some recycled fibers reached high environmental impacts due to the necessary treatments to obtain adequate characteristics, as their non-optimized production procedures can result in up to 7 % increase of GWP of FRC despite of the incorporation of these sustainable raw materials. Nevertheless, those FRC mixes achieved promising LCA results, even diving by half their GWP, when these treatments and procedures were carefully designed. Further development of concrete manufacturing processes and sustainable fiber recovery and characterization are also needed for successful implementation of greener solutions.

ACRONYM GLOSSARY:

FRC	Fiber-Reinforced Concrete
LCA	Life Cycle Assessment
EoL	End of Life
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
RC	Reinforced Concrete
FU	Functional Unit

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HPFRC	High-Performance Fiber-Reinforced Concrete
UHPFRC	Ultra-High-Performance Fiber-Reinforced Concrete
GHG	GreenHouse Gas
GWP	Global Warming Potential
WI	Workability Index
SI	Sustainability Index
FSI	Flexural Sustainability Index
CSI	Compressive Sustainability Index

1. Introduction

1.1. Sustainability need in the concrete industry

The concrete-manufacturing industry has no other choice than to address the issue of sustainability today. As concrete infrastructure and building construction continue to expand, the production of concrete is increasing current environmental problems such as climate change, depletion of non-renewable resources, uncontrolled extraction of raw materials and emissions of polluting gases such as CO_2 within the atmosphere [1]. This problem is widely known, and it has even been addressed in the 17 Sustainable Development Goals for the 2030 Agenda [2] of the United Nations, especially the following two: (i) "*Goal 11: Sustainable cities and communities. Make cities and human settlements inclusive, safe, resilient, and sustainable.*" (ii) "*Goal 12: Responsible consumption and production. Ensure sustainable consumption and production patterns*".

The construction industry emitted 11.7 gigatons of CO_2 in 2020, equivalent to 37 % of global total [3], and 14 billion m^3 of concrete were produced worldwide in that same year [4] when the global turnover of the concrete market amounted to $440 billion [4]. Such huge amounts of concrete made notable contributions to high CO_2 emissions in several ways. First, cement is the main, yet the most pollutant concrete component. Among other points, it explains 85–90 % of the actual carbon footprint, depending on the type of cement in use [5]. Second, the concrete industry is also one of the highest consumers of energy, which indirectly contributes to promote CO_2 emissions [3]. It is partly so, due to the energy expended on raw material extraction, such as aggregates, an operation that also damages habitats and natural landscapes [6]. Finally, the admixtures and oils used, apart from emitting greenhouse gases in their manufacturing process [7], also create a threat to the pollution of bodies of water [4].

Many companies are therefore moving towards a circular economy of concrete manufacturing where all the different stages of its production are being considered while trying to envision a net zero industry [4]. The Global Cement and Concrete Association (GCCA) has set the objective of a 40 % reduction in the carbon footprint by 2030 and to achieve net zero production by 2050 [5]. The sustainability issue is so relevant that it is even addressed in the current concrete regulations. The European structural regulations (Eurocode 2 and Spanish Structural Codes) refer to the importance of that problem [8–10], considering how the design of a concrete element and its manufacturing process influences its sustainability through the determination of various indexes. The methods of assessing the sustainability of concrete buildings from their project phase to the End-of-Life (EoL) stages are also explained in the building codes. Likewise, the American Concrete Institute (ACI) refers to the topic of sustainability in its Reinforced Concrete Design Handbook as well, where sustainability is referred to while buildings must remain practical [11].

1.2. Fiber reinforcement as a sustainability improvement

Various solutions are being considered, in order to tackle this issue [2,4,5]. One possibility is to reduce the environmental impact during concrete manufacturing by using green fuels from sustainable materials [12,13], applying the degradation of organic pollutants to treat wastes [14], and using gas treatments such as biogas upgrading, hydrogen storage, and NOx reduction [15,16]. The conventional raw materials of concrete can also be replaced with more sustainable components, mainly binders, which represent the highest environmental impact [17].

On the one hand, methods for waste recycling and reuse within a wide variety of industrial contexts are currently under study, to reduce the proportions of cement and aggregate in concrete. Different industries can be helped to increase their sustainability levels by recovering by-products for use as raw materials in concrete [1], and even the construction industry by producing eco-friendly recycled materials from construction and demolition waste [18]. Another option is the addition of fibers to the concrete mix creating Fiber-Reinforced Concrete (FRC) [19]. These fibers with their various origins improve the mechanical behavior of concrete, especially in flexural and tensile terms. Besides, the cement content can often be reduced through additions of different fiber types with no loss of strength, resulting in a less concrete-related pollution with an equivalent mechanical performance [20].

Both sustainability strategies, fibers and wastes, can be simultaneously applied, as both components can be added to concrete at the same time [21,22]. Furthermore, the fibers can be conventional materials, specifically manufactured for use in the concrete dosage, but they can also be recycled [1]. Among the different concrete fibers, there are steel fibers [23], polymeric fibers [24], glass fibers [25], microfibers [26], carbon fibers [27], natural fibers [20,28] – highlighting especially coconut fibers [29], and bamboo fibers [30,31] – basalt fibers [32–34], and recycled fibers [24,35,36], such as metallic tire fibers [1,37,38], and fibers from the crushing of wind-turbine blades [39,40]. Mixtures of all those fiber types can also be found [41,42].

Nevertheless, the sustainability improvements (or otherwise) of the aforementioned solutions are difficult to evaluate. For example, if recycled fibers are used and the cement content remains equal, cement reduction will not contribute to increased sustainability, but the aggregate amounts could be reduced [43]. Another method is to reduce the proportion of cement when adding the fibers while maintaining the same mechanical performance with an adequate mix design [43]. Life Cycle Assessment (LCA) can therefore give an important answer to all these questions [1,3]. Analyzing all stages of the FRC manufacturing process and life span, from the extraction of raw materials to the EoL stage [44,45], the procedure objectively determines which of the existing options is better to minimize the overall environmental damages caused by the production and use of FRC [3,46].

1.3. *Review approach*

In the present article, the existing scientific bibliography and documents on FRC and its LCA were systematically reviewed, in order to determine the current state of the art of FRC and how its sustainability was evaluated, as information on this topic is yet to be developed in the field. The research scope of this bibliographic review was mainly focused on the past fifteen years, so the most recent findings and innovations could be analyzed. Firstly, a description of the systematic review approach [47] is set out, to understand its advantages and the pieces of information to be considered. Then, a description of the LCA methodology is offered, explaining the most common LCA procedures and raw materials used in various kinds of FRC, as well as the different aspects that are taken into consideration for the determination of their contribution in numerous environmental indicators. Afterwards, an analysis of the data extracted from these studies is implemented, to better understand the aim in each of the LCAs performed by different authors in the form of quantitative indexes. Performing this overview on FRC and its LCA is intended to gain deeper knowledge of the matter, establishing the guidelines for any new line of research on this topic. The idea is also to review all recent proposals to manufacture more environmentally friendly fiber-reinforced concretes, according to LCA [48].

2. Systematic review methodology: PRISMA criteria

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [47,49] was followed, to ensure the required levels of transparency and quality when performing the systematic review.

As described in Fig. 1, recent documents were retrieved from two different databases: Scopus and Web of Science (WoS). Preliminary searches were performed in Scopus and WoS, including the keywords “fiber/fibre”, “reinforced”, “concrete” and “life cycle assessment”. A total 101 and 93 documents were, respectively, extracted from both databases. As there were 65 duplicated documents, a total of 126 documents were finally available for screening and analysis. Among them, 43 documents on Glass Fiber Reinforced Polymers (GFRP) and Carbon Fiber Reinforced Polymers (CFRP) were excluded, as they were used as textile-reinforced concrete or even regular reinforced concrete and not as discrete reinforcement fibers added into the concrete mix [50,51]. After reading these

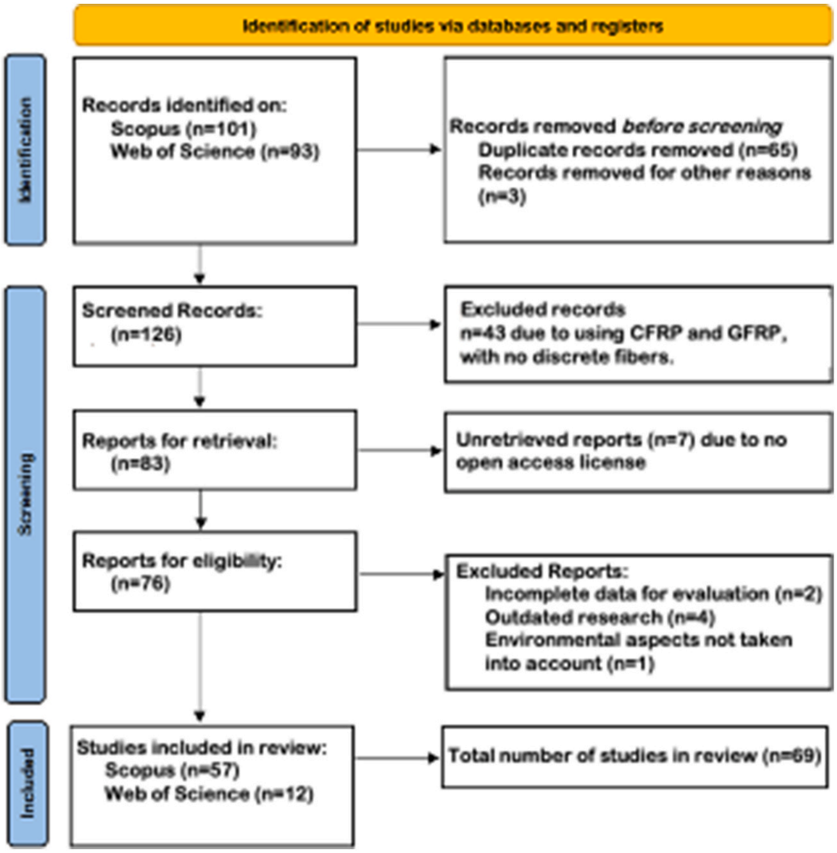

Fig. 1. Prisma flow chart for systematic reviews [47,49].

screened documents, seven of them were excluded due to incomplete or outdated data, or data with no relevance to the topic as no environmental aspects were discussed in the document. Thus, following the PRISMA flowchart [47,49] in Fig. 1, a total of 69 documents were retrieved and analyzed in this systematic review.

Regarding the temporal distribution of the documents screened for this review, the number of documents grew the nearer they were to present times (Fig. 2), but literature on LCA regarding FRC is still rather scarce [52–54], as the growing global issues with sustainability are still being taken into account in recent years [55]. A peak can be seen around 2006 in Fig. 2, as it was when the main regulatory documents where published, containing guidelines and recommendations on performing an LCA [56–58].

Besides, a word cloud was formed with an online tool to verify the selected scientific bibliography following the PRISMA statement [47,49]. This word cloud, visible in Fig. 3, consisted of representing the most repeated keywords to properly construct and visualize the main focus of the selected scientific articles [59]. The most common keywords, such as *"fiber"*, *"concrete"*, and *"life cycle assessment"*, shortened by its acronym *"LCA"*, were colored in red, showing their importance in the topic of this systematic review.

3. LIFE-CYCLE analysis application towards fiber-reinforced concrete

3.1. General overview of life-cycle analysis

LCA is a procedure through which all service-life stages of a product system, service, or building can be evaluated and compiled, by referring to its inputs, outputs and potential environmental impacts during its life cycle [45]. Its procedure is regulated by UNE-EN ISO 14040:2006 and UNE EN ISO 14044:2006 [56], and specially for the construction and building sector by UNE-EN 15804:2012+A2:2020/AC:2021 and UNE-EN 15978:2012 [56,60].

LCA was first used in the 1970s as an energy analysis method applied to beverage containers [61,62]. In the early 2000s, LCA became an important tool for an extensive and holistic view of the environmental impact technique. Afterwards, regulations for LCA were implemented [56] and it became the most widely used tool with which to analyze the environmental burdens of the engineering and construction sectors [45]. From then on, LCA became an assessment and decision tool for numerous aspects of everyday life [63], such as basic consumer products [64,65], solar panels [66], and the evaluation of renewable energy production [67]. Besides, the implementation of LCA avoided carbon tunnel vision [68], which is the illusion that only climate change has an important impact on our lives, due to the importance of carbon emissions. Thus, the use of LCA also implies considering the environmental impacts of products in terms of ozone creation potential [69], eutrophication of bodies of water [70], depletion of non-living natural resources [71], and use of renewable or non-renewable sources of energy [71], among others.

3.2. Procedure on fiber reinforced concrete

LCA can be of assistance when addressing the environmental issues of FRC in a more complete manner [56]. All production stages were assessed, from the extraction and acquisition of raw materials to their recycling and final disposal [56,72]. Whether the environmental advantages of some kinds of FRC compensate the negative impacts of their mechanical properties was discussed and evaluated, as was whether an improvement in mechanical performance that hinders some ecological aspects could be justifiable from an environmental point of view [73,74].

Its structured approach demands that at least four steps should be considered in all LCA analysis [45,56]: goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation. These steps need to be carefully followed and each one of them implies making decisions that will determine the outcome of the LCA, also in the case of FRC [60]. During the preliminary phase of setting the goals and the scope, the main elements, such as functional unit (**Section 3.2.1**) and system boundaries (**Section 3.2.2**), must be determined and explained carefully [56,58,75], in order to move on to the next phases with transparency, a key aspect for a representative and distinctive LCA [76]. LCI and LCIA also need a correct definition of the database and software (**Section 3.2.3)** and of the methodology and environmental indicators (**Section 3.2.4)**. The most frequent choices for LCA of FRC are represented in the form of radar charts in Fig. 4, which will be studied in the following sections.

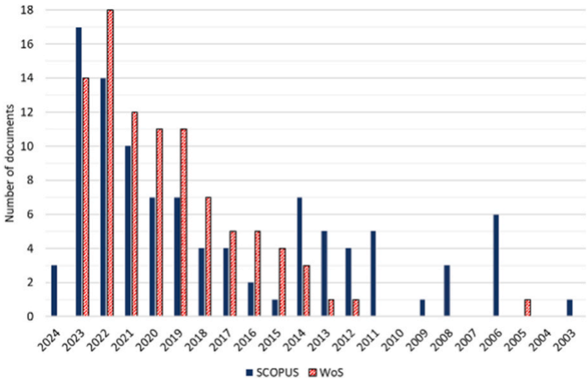

Fig. 2. Yearly distribution of screened documents from Scopus and WoS.

Fig. 3. Word cloud formed by keywords from the reviewed articles.

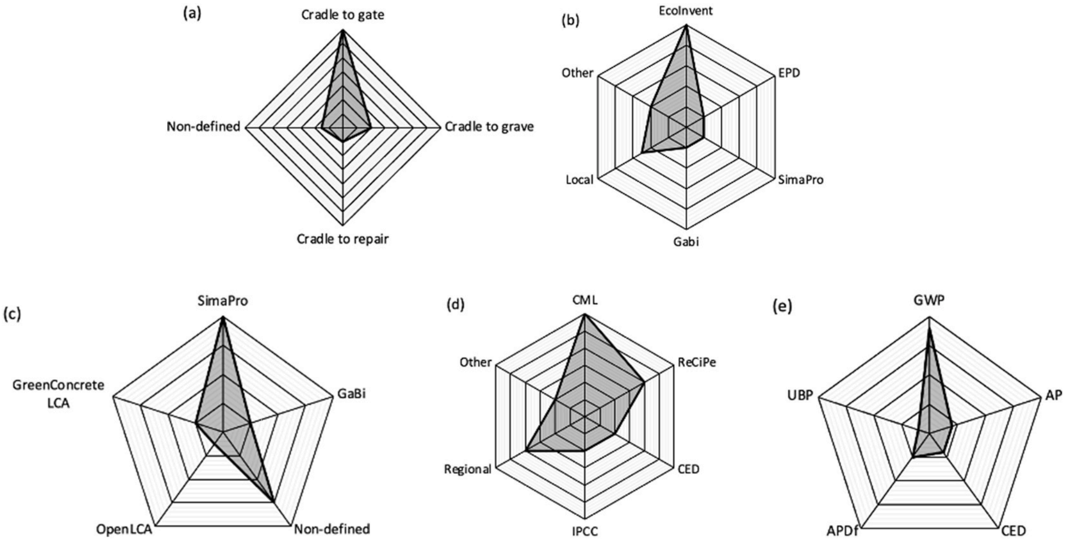

Fig. 4. Radar chart of the most frequent choices for LCA: (a) system boundaries; (b) database; (c) software; (d) methodology; (e) environmental indicators [1,44,45,54,55,63,71,77–87].

3.2.1. Functional unit

The Functional Unit (FU), key to the LCA, is used as a reference for comparison with other LCAs, in line with ISO 14040/44 [56]. The FU must be an accurate representation of what is expected to be studied in the analysis [88]. There are different FUs that can be chosen to achieve a successful LCA regarding FRC, as can be seen in Table 1.

- A cubic meter (1 m^3) of concrete was the typical FU in many of the studies related to FRC composition [1,54,83]. However, some other authors chose the fiber amount as an FU, to measure the environmental impact of a certain quantity (1 kg or 1 ton) [45,77,80].
- Another way to approach the FU was to choose a performance indicator [88]. This approach enables the practitioner to evaluate the structural scale where FRC could have an advantage over Reinforced Concrete (RC) [88], due to its mechanical characteristics and durability [71]. Thus, some authors elected the FU to measure the environmental impact *per* unit of mechanical property [87].
- Finally, the FU has also commonly been represented a *"unit"* of the specific element that is studied, in order to compare different solutions at the same location. For example, the FU could be a complete bridge [89] or a single beam [78] in bridge-performance analysis; or a specific intervention on the whole process of a bridge rehabilitation [79,84]. Another example is a portion of the area needed for concrete coverage (1–100 m^2 of FRC pavement) [44,55], a module of a wall [45], or a bedroom in a building developing a new façade system [63].

3.2.2. System boundary

System boundaries define what is and what is not included in the environmental analysis [60]. It is recognized that their adequate definition is crucial to achieve a representative LCA [90]. Nevertheless, current regulations contain no proper definition of which

Table 1
Results of LCA and mechanical testing.

AUTHOR	AIM	FUNCTIONAL UNIT	GWP	OTHER STUDIED IMPACTS/TESTS	IMPROVEMENT/ WORSENING	CONCLUSION
[45]	1	(i) 1 module of double wall (5 m × 2.5 m x 0.03 m) (ii) 1 m3 of concrete (iii) 1 kg of fibers	453-1369 kgCO$_2$e, due to origin of the fibers and cement used	AP, ADPf, CED	Not clear, depends on the SF or CF origin and cement used	No clear environmental advantage of CRC usage over SRC.
[44]	1	1 m^2 of surface area of RCP	Higher GWP with SFC (up to 55 % higher), lower GWP with GFC and PFC (18–27 % lower)	Mechanical Properties of the FRC towards pavement use and pavement thickness	Improvement in CS (up to 8.5 %), MOE (up to 6 %), FS (up to 48 %), MOR (up to 47 %); FT (2–4 times more). Appearance of RS after 2 mm deflection. Minimum DT (32–35 % lesser thickness)	This study recommends using fibers with more strength *per* unit weight-like glass fiber.
[80]	1	1 metric ton of basalt fibers	1 ton of BF produced 398 kgCO2eq	CA, NC, RI, IR, ODP, RO, AE, TE, TAN, LO, AC, AEU, GWP, NRE, ME, HH, EQ. Environmental efficiency & CO$_2$ efficiency index.	The lowest environmental load associated with BFRC 0.5, followed by BFRC 1.5 and SFRC 0.5. The "environmental costs" *per* MPa for FS and CS were lowest for BFRC 0.5, followed by BFRC 1.5. TSS much lower in the basalt mixtures.	Better environmental performance noted with the application of basalt fibers rather than steel reinforcement. The observed benefit lies in the lower density of the basalt, which reduces the demands on material transport and handling.
[85]	1	(i) Volume (ii) cracking capacity (iii) chloride diffusion coefficient (iv) combination of (ii) and (iii).	–	28-day CS, cracking capacity. Chloride penetration. Energy consumption.	7 % improvement in CS with 0.10 % wt. of BF. 183 % improvement in cracking capacity. Higher chloride diffusion coefficient in the BFRC than in RC.	Adding BF to concrete is a suitable solution to improve the sustainability of RC beams.
[77]	2	1 kg of recycled fibers	GWP reduced up to 94 % compared to virgin fibers	Flexural behavior	−8% and −24 % for 3 and 5 % vol. of fibers in first-cracking strength. Improved dissipated energy by 4–6 times (3–5% vol. fibers respectively)	Synthetic fiber from mechanical processing of end-of-life artificial turf carpets is a promising approach for reducing the large environmental impact of the construction sector.
[54]	2	1 m^3 of concrete	Alfa plant fibers have a positive impact on GWP	CS and TS	14 % lower compressive strength and 18.40 % higher tensile strength	It could be worth replacing PPF by Alfa, in Algeria, but also in other Mediterranean countries for works needing large amounts of concrete.
[55]	2	100 m^2 of concrete footpath - 10 m × 10 m (100 mm thick).	Industrial recycled PP fiber: −50 % of virgin PP CO$_2$e, and −93 % CO$_2$e when compared to the SRM.	EP, WC, fossil fuels	Industrial recycled PP fiber vs virgin PP fiber: −65 % of PO$_4$e, −29 % of water and −78 % of oil-e. Industrial recycled PP fiber vs SRM: −97 % of PO$_4$e, −99 % of water and −91 % of oil-e. The domestic recycled PP fiber generates higher consumption of water associated with the washing processes.	The industrial recycled PP fiber offers substantial environmental benefits over all other reinforcing options.
[1]	2	1 m^3 of FRSCC	Replacing 50 %, 67 %, and 100 % of the ISFs with the recycled fiber reduced GWP impacts up to 10 %.	CS, MOE, FS, and TSS at 28 days. AP; EP; ADPf; ODP; POCP.	Up to −9% in CS; - 23 % in residual FS and −26.4 % in energy dissipation with only RSF. When combined with ISF, flexural behavior is always enhanced. ADP reduced up to 47 %. EnScore reduced up to 46 %. Ap reduced up to 39 %. EP reduced up to 44 %.	A RSF-reinforced concrete with a suitable mechanical performance can be classed as an environmentally less-damaging concrete.
[81]	2	10 m^3 of ready-mixed concrete with 40 kg of domestic PP	Up to 7 % higher GWP due to milling process of the recycled cardboard.	7 and 28-day MoE, CS, TSS, FS. Fresh density, air content, slump test.	As the cardboard content increased: Higher occluded air content, lower slump test results and slightly	The cardboard blended hybrid concrete mixes showed low GWP emissions and favorably compared to

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Table 1 (*continued*)

AUTHOR	AIM	FUNCTIONAL UNIT	GWP	OTHER STUDIED IMPACTS/TESTS	IMPROVEMENT/ WORSENING	CONCLUSION
		fibers (4 kg/m3 dosage)			lower hardened and fresh density. Up to −71 % in CS, up to −45 % in MoE, up to −47 % in FS with high fluctuation among values, slight increase of TSS with low dosages of residue.	structural grade concretes in Australia.
[82]	2	1 m^3 of concrete	15 % lower GWP when adding Ecat to the UHPC mix.	MoE, CS, TSS, FS. Flow Table Test and UPV.	Addition of Ecat resulted in a −24 % in workability, no influence under UPV testing, −9% in CS, −3% MoE, −4% in FS, and −6.5 % in TSS.	The findings of this project could allow the development of eco-friendly UHPFRC mixes in Poland including Ecat and RSF.
[71]	2	1 m^3 of concrete and 1 MPa of indirect tensile strength	17 % lower GWP when using RSFRC	ODP, POCP, AP, EP, ADPe, ADPf; PE-NRe, PE-Re using CED.	Lower impacts using RSF by 20 % for PE-Re, 28 % for PE-NRe, 34 % for POCP and 34 % for ADPf. +13 % ODP for RSFRC, −5% AP, similar EP, +10 % ADPe.	The RSFRC showed lower environmental impact than ISFRC with the same concrete matrix and equal volume of fibers.
[86]	2	1 m^3 of concrete	Equal GWP than plain concrete.	Workability, CS, TSS and FS, UPV and rebound number test. ODP, AP, FE, WC.	−20 % workability for sisal fibers; CS by +6 %; by +2 % in FS; and in TSS by +4 % vs. plain concrete. +10 % UPV and +10 % rebound number. Fiber inclusion in the concrete matrix has no significant impact on the environmental categories.	Sisal fiber showed more promising results, indicating that natural fibers can be a more sustainable alternative to plastic fibers, providing a good balance between workability and strengths.
[87]	2	Mass *per* unit of yield load of a 1 m^2 wall panel. Mass *per* unit of thermal resistance of a 1 m^2 wall panel	Around 30 % lower GWP when using KFRC for the insulation FU and 10 % lower GWP when using KFRC for the structural FU.	FS, thermal insulation. AP, CA, NC, HH criteria air pollutants, EP, TE, Smog, Natural Resource Depletion, Indoor air quality, habitat alteration, WC, OD.	14 % lower flexural strength for KFRC and 21 % lower thermal conductivity. All environmental categories were remarkably higher in GFRC wall panels than in KFRC wall panels in both FUs.	Using KFRC can significantly reduce the environmental impact regarding both structural and insulation functions.
[78]	3	1 unit of edge bridge beam	Annual total GWP can be reduced by 33–60 %.	Flexural capacity. Service Life	Maximum corrosion crack can be reduced from 0.51 mm to 0.13 mm. Service Life can be increased up to 94 % (0.5 % vol.) and 254 % (1.0 % vol.)	37–54 % lower life-cycle costs in hybrid concrete edge bridge beams
[63]	3	1 bedroom 4 m × 4 m x 2.8 m with 30 % window area) with one exposed façade face in Singapore	9.2 % reduction *per* year	FS and CS. Embodied energy.	Higher CS as more binder is used. Higher achievable peak loads in FS. 38 % greater embodied energy.	DSF systems were found to be more energy intensive and more costly to construct. It has a great potential to improve both operational energy and reduce CO2eq emission over the lifetime of buildings.
[79]	3	Rehabilitation of 1 bridge in Slovenia	+107 % GWP with no maintenance involved. −42 % GWP when service life is considered.	–	–	The Eco-UHPFRC solution clearly has a lower GWP than the traditional solution even if only one rehabilitation is considered.
[89]	3	1 bridge	Construction phase: concrete has higher GWP than the UHPFRC bridges. Full-service life: up to 34 % reduction in GWP.	UBP	Construction: plain concrete has higher UBP than the UHPFRC bridges. Full-service life: up to 84 % reduction in UBP.	Using UHPFRC in road bridge design can lead to less environmentally detrimental bridge construction.
[83]	3	1 m^3 of concrete	Up to 31 % reduction in GWP when incorporating 100 % RCA and 1 % vol. steel fibers.	28-day CS, TSS, MoE, 4PFS. Performance efficiency factor.	Lower general costs. Up to 15 % reduction in environmental-mechanical performance efficiency factor.	The application of SFRRC to SBTS can better balance environmental and mechanical performances

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Table 1 (*continued*)

AUTHOR	AIM	FUNCTIONAL UNIT	GWP	OTHER STUDIED IMPACTS/TESTS	IMPROVEMENT/ WORSENING	CONCLUSION
[84]	3	1 intervention on a bridge from 1921 in Switzerland	Up to −70 % GWP vs. PSC and −30 % compared to steel fiber UHPFRC	Cumulative energy demand (CED), and ecological scarcity (UBP)	Up to −60 % in CED vs. PSC and −30 % vs. UHPFRC. Up to −65 % in UBP vs. PSC and −25 % vs. UHPFRC. −55 % and −29 % environmental impact of the PE-UHPFRC vs. RC and conventional UHPFRC methods.	This material is effective for the rehabilitation/ strengthening of structures from the viewpoint of environmental impact.

Acidification Potential (AP); Abiotic Depletion Potential for fossil resources (APDf); Umweltbelastungspunkten/Eco-points (UBP); Steel Fiber (SF); Carbon Fiber (CF); Carbon Reinforced Concrete (CRC); Steel Reinforced Concrete (SRC); Rigid Concrete Pavement (RCP); Glass Fiber Concrete (GFC); Polypropylene Fiber Concrete (PFC); Compressive Strength (CS); Modulus of Elasticity (MoE); Modulus of Rupture (MoR); Flexural Toughness (FT); Residual Strength (RS); Design Thickness (DT); Polypropylene Fiber (PPF); Polypropylene (PP); Steel Reinforcing Mesh (SRM); Industrial Steel Fiber (ISF); Recycled Steel Fiber (RSF); Eutrophication Potential (EP); Depletion Potential of the stratospheric ozone layer (ODP); Formation potential of tropospheric ozone (POCP); Double-skin Façade (DSF); Basalt Fibers (BF); Carcinogens (CA); Non-Carcinogens (NC); Respiratory Inorganics (RI); Ionizing Radiation (IR); Respiratory Organics (RO); Aquatic Ecotoxicity (AE); Terrestrial Ecotoxicity (TE); Terrestrial Acid/Nutri (TAN); Land Occupation (LO); Aquatic acidification (AC); Aquatic eutrophication (AEU); Non-Renewable Energy (NRE); Mineral Extraction (ME); Human Health (HH); Ecosystem Quality (EQ); Basalt Fiber Reinforced Concrete (BFRC); Tensile Splitting Strength (TSS); Spent Equilibrium Catalyst (Ecat); Ultrasonic Pulse Velocity (UPV); Recycled Concrete Aggregate (RCA); 4-Point Flexural Strength (4PFS); Steel Fiber Reinforced Recycled Concrete (SFRRC); Steel-Bar Truss Slab (SBTS); Pre-Stressed Concrete (PSC); Non-renewable primary energy consumption (PE-NRe); Renewable primary energy consumption (PE-Re); Recycled Steel Fiber Reinforced Concrete (RSFRC); Industrial Steel Fiber Reinforced Concrete (ISFRC); Freshwater Eutrophication (FE); Water Consumption (WC); Kenaf Fiber Reinforced Concrete (KFRC); Glass Fiber Reinforced Concrete (GFRC).

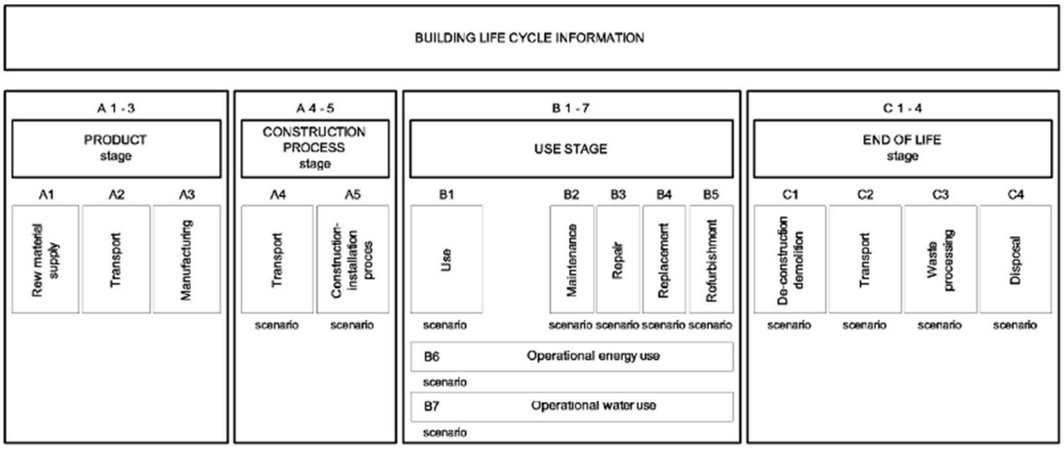

Fig. 5. Different optional stages for system boundaries in building assessment for LCA, UNE-EN 15978:2011 [56].

system boundaries are to be studied and practitioners therefore tend to choose their own system boundaries, sometimes resulting in non-comparable results for similar LCAs [60]. There are many established modules that can be considered in the LCA regarding building construction and materials [56], as depicted in Fig. 5. Current choices for FRC are shown in Fig. 4a.

The optimal solution seems to be the cradle-to-grave approach (A1 – C4 stages according to Fig. 5), in which all phases are evaluated: product development, use, and disposal [56]. Nevertheless, it was not a common method for use with FRC, as it typically involves making assumptions about future events within decades and how a concrete component will be treated at the end of its life cycle [89]. The cradle-to-grave approach was only common in studies regarding the impact of the service life of a concrete element where high/ultra-high-performance fiber-reinforced concrete (HPFRC/UHPFRC) had an important advantage [79,84,89]. According to Fig. 4a, the most common approach [91,92] to system boundaries was cradle-to-gate, which involved phases A1 (raw material supply) to A3 (manufacturing), or even through to A5 (construction or installation phase) [44], as explained in Fig. 5. That system covered the environmental impacts of the early stages of FRC development and helped to identify its stages with the highest energy consumption and pollution levels, such as fiber manufacturing, processing, recycling and/or treatment, and the characteristics of other raw materials that are essential for concrete [93]. The validity of the cradle-to-gate system boundary is only accepted when the practitioner can assure with evidence that the results will be representative and unaffected by the choice of that system [92,94].

3.2.3. Database and software

The next phase to perform an LCA is LCI [56,76]. The LCI is location-specific [55,76], and the information must be reliable, frequently updated, and transparent [76]. A database integrated with software management [76] gives the practitioner a user-friendly interface to manage all data and stages that must be considered in the LCI. The most frequent choices for LCA on FRC regarding database and software are reported in Fig. 4b and c, respectively.

The Ecoinvent database is among the most important and the most widely used LCI databases for FRC, and even worldwide for construction materials [76] and different concrete types [91,95]. It was developed by the Swiss Centre for Life Cycle Inventory and is known for its transparency and consistency [76]. Leading software industries, such as SimaPro [96] and GaBi [97], have developed other important and frequently used databases. SimaPro is a software tool developed by PRé Sustainability Consultants [98]. It is the most common software for FRC analysis, as shown in Fig. 4c. On the other hand, GaBi is developed by Sphera [97], a company that specifically develops LCI databases, that exhibit high quality, consistency, and high-location coverage [76,97]. Other open access software tools that were used for the LCA are OpenLCA [99] and GreenConcrete LCA [100], although their own databases were not included. The Environmental Product Declaration (EPD) is another dataset commonly used for LCA regarding FRC [45,71]. Regulated by UNE-EN ISO 14025:2010 [56], there are standardized documents that the companies have voluntarily developed, to ensure environmental performance and to provide quantifiable product data [56].

Regional databases were also frequently used, such as SimaPro Australian-specific databases [55,101] and the Australian Building Products Industry Council (BPIC) LCI database [55,102]. In Switzerland, the construction and property services of publicly owned buildings make their database available; and the European reference Life-Cycle Database (ELCD) has been used over the past few years [71,103], although without an update since 2012 [76], so it is now somewhat obsolete. There was also a database focused on LCI in the United States of America, known as U.S.LCI [104] and last updated in 2022 [105], that has also been used for FRC analysis [82]. The last dataset option used for LCA on FRC, known as foreground data [71,106], consisted of data received straight from the manufacturers of FRC raw materials without an EPD, which were used to study the environmental aspects of their products to give a precise LCI to a practitioner [63].

3.2.4. Methodology and environmental indicators

The next phase in the LCA process is the Life Cycle Impact Assessment (LCIA). The most frequent choices for methodology on FRC analysis can be seen in Fig. 4d.

- CML or CML01 was the most frequently used methodology in FRC environmental analysis, which was developed in 2001 by the Centre of Environmental Science, Leiden University (Netherlands) [58]. It was used in many studies, mostly in Europe [107], as it had a balanced approach.
- ReCiPe methodology [108] was also applied for FRC analysis, offering the possibility of using 18 midpoint and 3 endpoint categories [109].
- The Intergovernmental Panel on Climate Change (IPCC) methodology [110] was also commonly used [55,84], as it mainly focused on GHG emissions, one of the main concerns of the cement industry [111].
- Cumulative Energy Demand (CED) was an important methodology [79,81], although it was also often embedded in other methodologies as an overall impact (Fig. 4e) [112]. It quantifies the energy that is used, both directly and indirectly, but any waste of energy is not considered during the processes [113].
- The last option for methodologies consisted of the regionally developed ones within either a country or continent, such as the Australian Indicator Set V3.00 [55,101] or the BEES 4.0 [87,114] methodology by the National Institute of Standards and Technology of the United States of America.

The most widely used environmental impact indicators are depicted in Fig. 4e and Table 1. Global Warming Potential (GWP) [56] measured in mass of CO_2 equivalent ($kgCO_2e$) was the most widely used indicator in all studies focused on LCA involving FRC. GWP measures the amount of GHG emitted that contribute to climate change and an increase in global medium temperature [69,115]. Other

Table 2
Processes included in LCA during the LCIA phase in different articles.

AUTHOR	RAW MATERIAL	TRANSPORT	SERVICE LIFE	ENERGY			
				RAW MATERIAL EXTRACTION	FIBER PRODUCTION	FIBER TREATMENT	MIXING
[45]	X	X			X		X
[44]	X	X					X
[77]	X				X	X	
[54]	X	X		X	X	X	
[55]	X	X		X	X	X	
[1]	X	X			X	X	X
[63]	X	X		X			
[79]	X	X	X	X			X
[89]	X	X	X				
[80]	X	X		X	X	X	
[81]	X	X		X	X	X	X
[82]	X	X		X			
[83]	X	X	X				X
[74]	X	X	X				X
[85]	X			X	X		
[71]	X	X			X	X	X
[86]	X	X	X		X		X
[87]	X	X	X		X	X	X

Table 3
Fiber characterization.

AUTHOR	MATERIAL	TYPE	SUB-TYPE	QUANTITY	LENGTH (mm)	DIAMETER (µm)	SHAPE	MOE (GPa)	TENSILE STRENGTH (MPa)	DENSITY (kg/m^3)	OTHER CHARACTERISTICS
[44]	Pavement FRC CEM I/III (400–700 kg/m^3)	Steel	–	39–78 kg/m^3	35	900	Hook-end	200	1200	7750	Glued with chemical against corrosion
[1]	1 m^3 of FRSCC CEM I (500–511 kg/m^3)	Steel	–	90 kg/m^3	35	–	Hook-end	–	1395	7200	Aspect ratio of 64
[63]	1-bedroom HPFRC (285 kg/m^3)	Steel	Macro-fibers	117 kg/m^3	30	–	Hook-end	–	–	–	Aspect ratio of 55/80
[80]	UHPFRC. CEM I (1000 kg/m^3)	Steel	–	0–1.5 % vol.	12	200	Straight, rounded	–	2850	7800	Low carbon steel wire, copper coated. Aspect ratio of 60
[83]	1 m^3 of FRC. CEM I (262–372 kg/m^3)	Steel	–	0–78 kg/m^3	–	–	Shear-cut type	–	1000	–	Aspect ratio of 63.3
[71]	1 m^3 of FRC CEM I (400 kg/m^3)	Steel	Industrial	75.8 kg/m^3	33	550	Hook-end	–	1230	–	Aspect ratio of 60
[44]	Pavement FRC CEM I/III (400–700 kg/m^3)	Synthetic	Polypropylene	4.5–9.0 kg/m^3	12	30	–	5	500	900	–
[55]	FRC footpath	Synthetic	Polypropylene	–	47	–	Flat	–	>550	–	0.7 mm thick and 1.5 mm wide
[63]	1-bedroom HPFRC (285 kg/m^3)	Synthetic	PVA	2 kg/m^3	8	–	–	–	–	–	Aspect ratio of 210
[84]	1 bridge. UHPFRC. CEM I (508 kg/m^3)	Synthetic	UHMW-PE	19.6 kg/m^3	6	–	–	155	4100	Very Low	dtex = 880. Floats and moisture resistant
[86]	1 m^3 of FRC CEM I (300 kg/m^3)	Synthetic	Polypropylene	0.6 kg/m^3	19	–	–	1.47	32.36	910	No water absorption
[77]	Beams FRC OPC mortar	Synthetic	Recycled polyolefin	3–5% vol.	10–40	–	Flat	–	–	–	Fibers present wrinkles that help with adhesion
[55]	FRC footpath	Synthetic	Recycled Industrial Polypropylene	–	30–70	–	–	–	300–450	–	–
[55]	FRC footpath	Synthetic	Recycled Domestic Polypropylene	–	–	–	–	–	300–450	–	–
[1]	1 m^3 of FRSCC CEM I (500–511 kg/m^3)	Steel	Recycled tire	0–90 kg/m^3	33	380	Varying	–	–	3014	Mean aspect ratio of 91
[81]	10 m^3 of FRC CEM I (200 kg/m^3)	Synthetic	Recycled PP	5 kg/m^3	32	100	–	–	–	–	The fiber lengths 2.3:1 ratio to maximum aggregate size
[82]	1 m^3 of UHPFRC CEM I (697–820 kg/m^3)	Steel	Recycled tire	79 kg/m^3	5–35	60–160	Twisted & surface damaged	–	–	–	Small amounts of rubber attached to their surface
[71]	1 m^3 of FRC CEM I (400 kg/m^3)	Steel	Recycled tire	75.8 kg/m^3	20 ± 8	250 ± 80	Irregular	–	2648 ± 423	–	Rubber attached to their surface. Aspect ratio of 110 ± 44.
[54]	1 m^3 of FRC CEM I (350 kg/m^3)	Natural	Alfa plant	10 kg/m^3	20	–	–	–	–	–	High water absorption
[86]	1 m^3 of FRC CEM I (300 kg/m^3)	Natural	Sisal	0.6 kg/m^3	19	100–200	Straight	–	328.8	1100	Elongation at fracture is 2%–2.5 %. High water absorption
[87]	UHPFRC CEM I (840 kg/m^3)	Natural	Kenaf	42.2 kg/m^3	5–20	–	–	–	–	–	Outstanding acoustical absorption coefficients and thermal R-values
[80]	UHPFRC. CEM I (1000 kg/m^3)	Basalt	–	0–1.5 % vol.	45	700	–	42	10000	2150	–
[85]	FRC. CEM I (316.7 kg/m^3)	Basalt	–	–	12–24	12–15	Filament	100–110	4100–4500	2800	Thermal conductivity = 0.03–0.04 W/mk
[44]	Pavement FRC CEM I/III (400–700 kg/m^3)	Glass	–	13–26 kg/m^3	6–18	15	–	72	1500–1700	2600	–

impacts under study were Acidification Potential (AP) of soil and water [56,116]; Abiotic Depletion Potential [54,113] for fossil resources (APDf); CED as mentioned before, but as an overall impact indicator estimating the embodied energy that is used [112]; and the measurement of environmental damage in eco-points or environmental impact points (*Umweltbelastungspunkten* in German, UBP) *per* unit of quantity of FU [84,89], which measure ecological scarcity using an overall score that represents the total impact of a manufactured product [117].

The measurement of ozone-depleting gases is not among the most common indicators when evaluating environmental performance of FRC, as can be seen in Table 1 and Fig. 4e, yet damage of the ozone layer is highly harmful to human life, as it prevents ultraviolet light from reaching the atmosphere [112]. Ozone Depletion Potential (ODP) is highly related to GWP, as both refer to GHG that can be emitted into the atmosphere [80]. The ODP impact referred to recycled fibers is usually negligeable, as many of the phases that produce these gases are not present when considering sustainable fibers instead of conventional ones [1].

In order to properly analyze materials and processes that must be included during the LCIA phase in FRC, Table 2 depicts the most common choices among the reviewed literature. These choices take into consideration what information has been included during LCA of the studied FRC mixes, regarding impacts and data from raw materials, transport, service life, and energy consumption, which has been divided in four sub-categories: raw material extraction, fiber production, fiber treatment, and mixing for concrete production.

From Tables 2 and it can be inferred that the vast majority of the studies refer to raw material and transport impacts as the main environmental burdens. They are always considered as these values can be easily retrieved. Service life is only considered in one third of the cases, mostly in studies where the FU is a full structure as its maintenance, repair, rehabilitation, and reconstruction can be crucial to its environmental impact [79,89]. The energy consumed during raw material extraction, due to mining and manufacturing [85], is considered in about half of the studies. The energy used for fiber production is included in more than half of the studies, while the energy needed in treatments to achieve FRC-suitable fibers from sustainable fibers [87] is taken into account in all studies involving such processes. Finally, the energy required for mixing the raw materials for concrete production is considered in about 56 % of the studies.

4. Composition of FRC mixes, sustainability and performance evaluation

In the present section, the characteristics of the FRC upon which an LCA was performed, as well as the main points of this analysis, are addressed. First, a set of potential aims for LCA on FRC is presented (**Section 4.1**), followed by a brief analysis of the raw materials commonly used in FRC production (**Section 4.2**), and a description of the main results on mechanical testing and environmental indicators (**Section 4.3**).

4.1. Aim

Research on FRC was conducted to evaluate a wide variety of concrete properties that different fiber types can affect, from environmental design through LCA to mechanical properties. In general, they were all intended to understand the ups and downs of each solution, while taking advantage of LCA as a decision tool [63]. These studies were categorized in three different groups based on their final aim, as can be seen in Table 1.

The first group of articles (1 in Table 1) involved the environmental impact of well-established fibers. Most of the studies were focused on the manufacturing of FRC batches with different conventional types or quantities of fibers and evaluating their impact categories, in order to achieve the best mix in LCA terms. No natural fibers or recycled fibers were compiled in this group. Very few studies emphasized the mechanical properties of the concrete, so as not to be diverted from the most important environmental issues.

The second and largest category (2 in Table 1) covered sustainable or recycled fibers. This group was focused on development and research into new fibers, mostly from recycled by-products or the treatment of plants. The fibers were characterized, and their main advantages and disadvantages for FRC production were discussed. These studies highlighted both the environmental burdens through LCA and the mechanical performance of FRC and sometimes even durability. FRC manufacturing with those fibers was innovative, so a full understanding of how they enhanced or weakened all concrete dimensions was sought.

The last category (3 in Table 1) was the analysis of mechanical and environmental enhancement of fiber use. The main concern was to define the best mechanical and structural solutions for different FRC elements, without forgetting the environmental impacts with which LCA can help, and the full-service-life performance. The articles within that category were not focused on raw-materials and their impact on LCA, but the whole process or element under study. The FUs attempted to show a full picture of the elements, such as full intervention, rehabilitation, and structural components, instead of focusing on the mix design.

4.2. Raw materials

As explained in **Section 3.2.2**, the most widely used approach in LCA on FRC was cradle-to-gate, where the raw materials and manufacturing process were the most important inputs [91]. In the present section, an LCA evaluation of the raw materials for FRC is set out.

4.2.1. Binders

It is widely known that cement is the most polluting raw material in concrete manufacturing [5]. It is, in fact, responsible for over 75 % of GWP produced in FRC [71,92]. However, performance depends on the cement type [5]. Ordinary Portland Cement (OPC), which is the most polluting one due its minimum clinker content of 95 %, was the most common. Nevertheless, the choice of a more sustainable cement than OPC [45], such as blast-furnace cement [45,89] with a clinker content of 35–64 %, reduced GHG emissions [45].

The cement type and quantities can be seen in Table 3. They mainly depended on the performance requirements of the concrete, all the cement contents being above the minimum established in the current regulations [56,118]. When more binder was necessary to achieve the desired specifications, *i.e.,* HPFRC/UHPFRC, by-products of other industrial processes were added as Supplementary Cementitious Materials (SCM). With no economic value and no contaminating flows associated with the LCA [57], those binders contributed to concrete sustainability.

- Fly ash was the most common SCM, with amounts around 100–200 kg/m^3. Fly ash was advantageous in so far as the shape of its particles ensured concrete workability [71].
- Steel slag, added in amounts of 100–320 kg/m^3 [63,81], demonstrated pozzolanic characteristics [119], while remaining hard and having proper adhesion to the cementitious matrix [120]. Replacing cement by both fly ash and steel slag could reduce the GWP to 0.81 kgCO$_2$e *per* kilogram of cement [121].
- Silica fume was also very common, added in amounts of 178–250 kg/m^3. It had pozzolanic characteristics [82], resulting in higher strength in concrete at older ages and a dense and compact cementitious matrix.

4.2.2. Water

Regular potable water was mostly used for FRC production, as it had no chemical interaction with its other raw materials, unlike seawater, which could be interesting from an environmental standpoint [122], but can corrode the fibers or other components of the mix [123]. The amount of tap water and cement in the mixtures can be seen in Fig. 6: the first nine studies beginning from the left were focused on FRC, the tenth was focused on FRSCC, and the last three were focused on HPFRC/UHPFRC. The water content ranged between 150 and 340 kg/m^3 and the water/cement ratio between 0.14 and 0.70, due to the presence of recycled materials and different kinds of fibers, aided by the addition of binders other than cement.

4.2.3. Aggregates

About 52 billion metric tons of aggregates are extracted annually all over the world for construction purposes [124], which heavily affects rivers, coastal and marine ecosystems, and quarries [125]. Aggregates also impacted the LCA of FRC, as they were the most abundant raw material in all the mix reviews [45]. A large number of those mixes had over 1000 kg/m^3 of aggregates from different natures. The use of Recycled Concrete Aggregate (RCA) [83] has therefore become a sustainable option, even combined with fibers [126], as it can reduce the embodied carbon of the concrete by 10–30 % [92].

4.2.4. Admixtures

The addition of fibers interferes with concrete workability [79]. Therefore, admixtures were often used in FRC [71,82] to maintain proper fresh performance without hindering mechanical properties and critically increasing the water/binder ratio [79]. They were added in a wide range of quantities from 1.7 to 55.0 kg/m^3, depending on the fiber content. The average admixture dosage was about 13.8 kg/m^3. Most were either superplasticizers or water-reducer admixtures.

4.2.5. Fibers

FRC can avoid the energy-intensive works related to laying out steel reinforcement [44], but it increases the energy in terms of the manufacturing process of fibers, affecting the LCA [71]. Table 3 lists the main characteristics of fibers, including the FUs for the analysis.

Fibers could be categorized according to their size [127]: micro-fibers (6–20 mm), which stitch potential and initial cracks within the concrete [127], and macro-fibers (usually over 30 mm), which start working after this initial phase and are responsible for ductility and reducing crack width [128]. Fiber lengths for the reviewed articles can be seen in Table 3, and their average lengths and tensile strengths can be observed in Table 4 and Table 5, respectively. Another way to categorize fibers is by their origin, as the fibers are categorized in **Section 4.2.5.1** and **Section 4.2.5.2**, for FRC in terms of the sustainability of their raw materials and manufacturing process. In Fig. 7, the most common kinds of fibers used on FRC that underwent LCA can be seen: steel fibers were the most used,

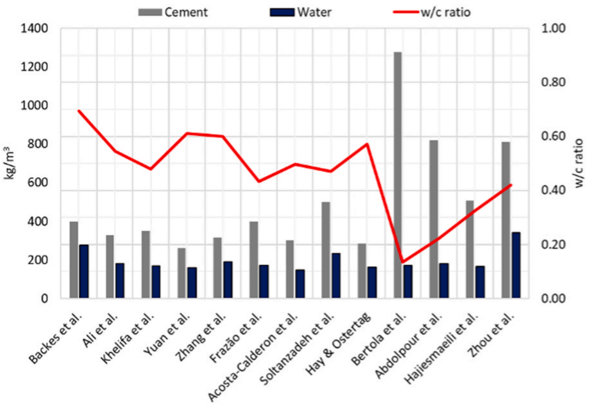

Fig. 6. Cement content, water content and water/cement ratio of the reviewed mixes [1,44,45,54,63,71,82–87,89].

Table 4
Average fiber lengths [1,44,54,55,63,71,77,80–87].

Material	Steel	Glass	Synthetic	Natural	Basalt	Recycled
Average (mm)	22	12	21	17	32	32
Standard deviation	13.16	0.35	18.13	4.07	19.09	11.38
Variance	1.73E+02	1.25E-01	3.29E+02	1.66E+01	3.65E+02	1.30E+02
Coeff. of variation	0.60	0.03	0.86	0.24	0.61	0.36

Table 5
Average tensile strengths of most frequently used fibers [1,44,45,55,71,80,83,84,86].

Material	Steel	Synthetic	Recycled
Average (MPa)	1371	1296	1512
Standard deviation	780.87	1884.09	1607.25
Variance	6.10E+05	3.55E+06	2.58E+06
Coeff. of variation	0.57	1.45	1.06

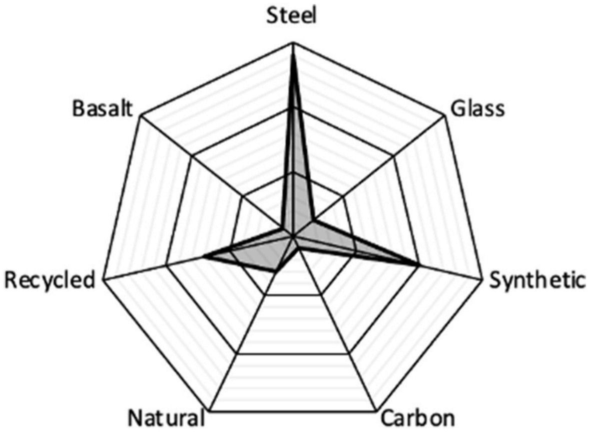

Fig. 7. Most common fibers used in FRC that underwent LCA [1,44,45,54,55,63,71,77–87].

followed by synthetic fibers and recycled fibers from various origins. Other materials that were implemented into the concrete mix such as fibers can be glass, carbon, basalt, and different kinds of natural fibers.

4.2.5.1. Conventional fibers. The term conventional fiber refers to those fibers that have been frequently used over the last decades for FRC development [129]. The fibers that were usually included in this group [80] are made out of steel, synthetic materials, glass, carbon, or basalt.

Steel fibers were the most common, as they showed the highest mechanical performance enhancement in FRC. However, those fibers are also the most energy and environmentally challenging [55,130], due to the consumption of natural resources and high temperatures needed for their manufacturing [131], besides also being an expensive alternative (around 700 €/t) [53]. Steel fibers are known for being prone to undergo corrosion [78], so more environmentally friendly FRC solutions with longer service lives have been sought [132,133].

Synthetic fibers were also frequently used, which are made out of a wide range of plastic materials [134,135], such as polypropylene (PP), polyolefin, Polyvinyl Alcohol (PVA), and Polyethylene (PE) [136]. They have no corrosion issues [137], their mechanical properties are similar to steel fibers [138], and they are much lighter [74]. Nevertheless, their adhesion to the cementitious matrix is usually poor, due to its surface characteristics and water-related behavior [77]. Their manufacturing process is also complex, as they require raw materials and processes that are highly polluting [86], though not as environmentally demanding as for steel fibers [134], and their use implies a less expensive product [139]. Besides, synthetic materials are one of the most polluting materials when the service life of elements incorporating them ends [140].

Glass fibers were less commonly used for FRC production [44]. Those fibers, with a wide range of shapes and lengths [127], presented a high rupture strength and were lightweight [141], although they had a brittle behavior and a low capability to withstand alkalis [141]. Furthermore, their high environmental impacts, resulting from their manufacturing process and related chemicals of their production, were even higher than cement *per* unit of mass [87]. Alternatively, carbon fibers could be used [45], as they do not rust, have low density and proper mechanical properties [45]. However, they require high amounts of electricity and thermal energy for their manufacture and are derived from petroleum [45], which emits large amounts of GHG during its refining process, so they do not perform well under LCA.

The last group of FRC fibers was basalt fibers [80,85]. FRC fibers show high tensile strength and withstand high strain levels, are of low density, and temperature resistant [142]. Moreover, they are usually reasonably priced and have environmental impacts similar to

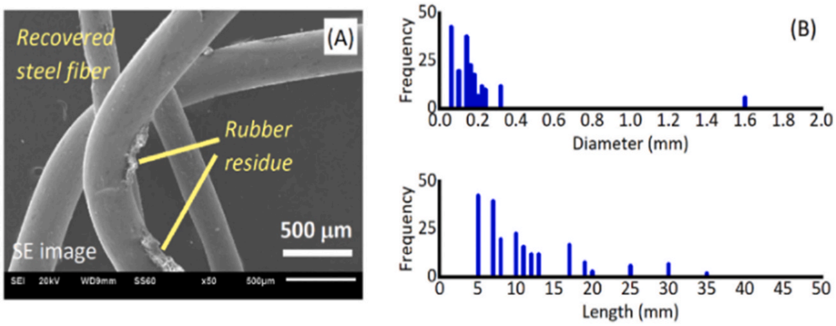

Fig. 8. (A) SEM image from recycled fibers from scrap tires showing rubber attached to their surface; (B) histogram with the diameter and length of the recovered scrap tire fibers [82].

glass fibers [143–145]. Nevertheless, there is not much literature available regarding datasets on their real environmental loads [80], as the vast resources for their production are very location-limited [146], which hinders LCA evaluation.

4.2.5.2. *Sustainable fibers.*

Sustainable fibers have low or no environmental impacts, due to their nature or the fact that no burdens are taken into the LCA, as they are by-products of other industrial processes [60]. There are two main groups: natural fibers and recycled fibers.

Natural plant fibers [80], such as alfa [54], sisal [86], and kenaf [87], are used for the production of FRC that then underwent LCA. These fibers are usually low cost, low density, and use 45 % less energy during production than conventional fibers [147], even though plant treatments can sometimes be quite energy demanding and result in highly polluting processes [148]. In addition, natural fibers are fully biodegradable, so the impacts in EoL scenarios are minimal [149]. As negative points their high trend to absorb water affects the workability of the mix and their weaker mechanical properties can be highlighted [150–152]. Natural fibers must be under 50 mm in length to contribute to good mechanical behavior in FRC [153].

Recycled fibers are extracted from EoL scenarios and from other products or processes, thus avoiding the impacts associated with them. There is a wide variety of recycled fibers, but the most common for LCA were steel fibers from scrap tires, and recycled synthetic materials.

- Steel recycling is easy and cost-efficient [55], so recycled steel fibers show high mechanical properties, due to the requirements needed for their previous use, and are usually inexpensive (50–200 €/t) [154]. The steel fibers recovered from recycled tires avoids landfilling these elements [155–157]. Moreover, the fibers usually have rubber from tires attached to their surface, and a wide variety of shapes and lengths [82], which improves their adhesion to the cementitious matrix [1], as depicted in Fig. 8.
- Also easy to recycle, due their high recovery rate [158], synthetic materials reduce the significant environmental impacts of the plastic disposal phase [55]. These fibers usually maintain high mechanical properties, and their length is scattered, from 10 to 40 mm [159], which provides an optimal coverage of all fracture mechanisms [160]. The recycling of the synthetic material can be industrialized or domestic, further reducing the environmental impact of the recycling process [55].

4.3. *Studied indicators*

Different indicators can be chosen to evaluate the environmental and mechanical performance of FRC mixtures, described in Table 1 for the reviewed articles. The most commonly used environmental indicators for FRC were already discussed in **Section 3.2.4**, whose results are then examined in **Section 4.3.1**. The mechanical properties of the FRC mixes are reviewed in **Section 4.3.2**, in order to assess how they behave in the hardened state.

4.3.1. *Environmental indicators*

4.3.1.1. *Global warming potential (GWP).*

The most important environmental impact in the vast majority of the studies was Global Warming Potential (GWP), also known as Climate Change or Greenhouse Effect, as depicted in Table 1 and Fig. 4e. The material that contributed most to GWP in FRC manufacturing was always the cement, as concrete without fibers had an average GWP of 320 $kgCO_2e/m^3$ [92]. The GWP associated with conventional fibers was also high, with steel fibers reaching values of 2.6 $kgCO_2e/kg$, three times higher than the GWP associated with the cement [124,147]. However, the overall GWP attributed to FRC was not usually higher, as the fiber content was much lower than that of cement, which caused most of the impacts, and the required admixtures [1].

Most FRC mixtures therefore usually achieved lower GWP values than the reference ones used for comparison, as higher levels of sustainability were usually sought, by selecting certain fiber types or changing the fiber manufacturing process.

- The fiber nature was changed in the studies that were focused on fiber type, to achieve better GWP results. Different materials required different processes for fiber manufacturing, that resulted in less pollution and energy demand [45].
- The studies focused on the fiber manufacturing process used the same raw material for the fibers of both the studied and the reference mixes but attempted to evaluate the effect on GWP of using recycled materials [55,71]. The results were sometimes encouraging, although in other cases they were not clear [45,86], as the processing of the sustainable fibers added no clear and precise enhancements to the environmental performance of FRC [86].

A few studies showed that some FRC mixes can lead to higher GWP than their reference mixes. In the case of UHPFRC, and if a cradle-to-gate system boundary is selected, the impacts could be increased due to its high binder requirements [79]. The GWP impacts were lower than the reference mix when considering the whole service life and a cradle-to-grave system boundary [84]. Nevertheless, assumptions on the impacts related to UHPFRC recycling in this analysis were needed. It is not yet fully determined, and a lot of energy was required for its removal due to its high mechanical properties, so its disposal doubled the GWP of conventional concrete [79]. Another example of higher GWP was when a non-sustainable treatment for appropriate use of some by-products was needed [81], although it was lower than the impacts related to landfill or waste processing [81].

The other most common environmental indicator values, depicted in **Section 3.2.4**, were directly proportional with GWP values, as highlighted below. The exception was water use where the need for cleaning and washing of recycled and natural fibers increased demand [55].

4.3.1.2. Abiotic depletion potential for fossil resources (APDf). As can be seen in Fig. 4e, other relevant environmental indicator is Abiotic Depletion Potential for Fossil resources (APDf), being among the most common between FRC LCA practitioners [1,45,71].

APDf refers to the usage of the non-renewable and non-biological resources that are fossil fuels and their scarcity, that play an important role for the energy and manufacturing process involved in FRC [112]. The results of conventional fibers in concrete often led to higher APDf than when using sustainable fibers because of the manufacturing processes of conventional fibers [1,71]. This difference was as high as 429 % due to electricity and fuel usage obtained from fossil resources [55]. Also, the APDf contribution of cement and fiber production present in FRC could take up to 84 % of the total impact [71].

This environmental indicator was usually, along GWP, the one that was reduced the most by the incorporation of sustainable fibers, especially when using recycled ones [1]. Therefore, the addition of recycled fibers to concrete not only allows recovering a by-product that needs a second life, but it also highly prevents emissions related to fossil fuel combustion that have an important influence in today's pollution issues, impacting large populations all over the world [161].

4.3.1.3. Acidification potential (AP). Acidification Potential (AP) is another relevant environmental indicator usually studied in FRC (Fig. 4e). Acidification takes places when acidic gases are emitted within the atmosphere. They pollute the water stored in it and form acid rain that can be deposited in surface soil and water. Acid rain can travel large distances and can cause impairment of numerous ecosystems, mainly due to nitrogen and sulfur oxides [71,112].

AP of land and water can be reduced up to 40 % when using sustainable fibers [1], as the mentioned gasses are mainly produced during conventional fiber and cement manufacturing process, not being as present when recycling is introduced [71,162]. Cement can represent up to 64–83 % of the AP impact of FRC, while industrial production of steel fibers can make up for up to 18 % of the AP impact, natural fibers up to 15 %, and glass fibers up to 29.6 %. The most important phase to AP in FRC is the production of raw materials [71,86].

4.3.2. Hardened behavior indicators

FRC can outperform RC in several fields [44], as fiber additions create a three-dimensional reinforcement in the concrete matrix, while steel reinforcements usually form discrete reinforcements in the concrete element cross-section [44]. Thus, compression [44,85,86], and flexural behavior [63,86] is enhanced within the concrete. Cracking is also reduced, due to the stitching effect of the fibers [44,78,85], even in terms of drying and plastic shrinkage [71,163]. Tensile strength is improved [86] and post-cracking load bearing capacity [54,71] that helped avoid a sudden and brittle structural failure [82,164]. It also enhanced the durability of concrete [63,85,89], which indirectly increased sustainability, by prolonging the service life of the concrete element [165]. FRC performs well under extreme conditions [44,86] and adequately resists fatigue and spalling [54], so the need for rehabilitation and repair becomes less important and the life cycle of the structural components can be lengthened [78,79,89]. FRC also showed some significant disadvantages, mainly related to the loss of compressive [1,166] and flexural [1,87] strengths when using sustainable fibers, due to poor bonding within the cementitious matrix [1,54].

In some cases, such as metallic fibers [71], these factors have been studied and investigated for longer periods of time and

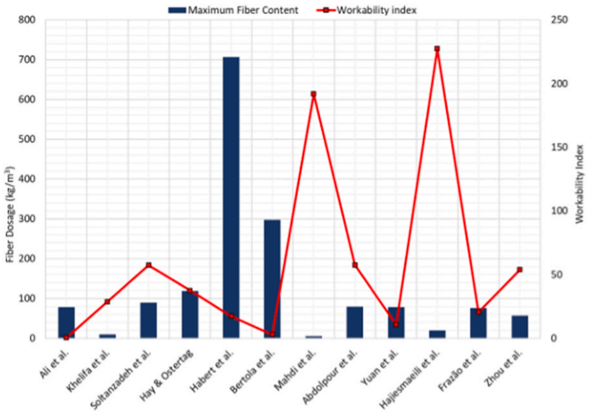

Fig. 9. Workability evaluation based on fiber content [1,44,45,54,63,71,79,81–84,89].

considered for structural design [71,167,168]. Nevertheless, these aspects for new recycled types of fibers are yet to be fully investigated, as they are recently being developed and implemented in the concrete mix [28,129,147]. It might be expected that these fibers could be beneficial from a structural perspective, as their heterogeneity in geometry and surface characteristics can provide various strengthening mechanisms to FRC [169,170], beyond merely economic and environmental advantages [71].

5. Discussion

In order to be able to find the key differences and findings from each scientific article, the descriptive analysis conducted needs to be complemented with the analysis of indexes to achieve an overall evaluation of environmental and mechanical performance of the FRC mixtures [83], to later perform a proper discussion from the obtained values. The GWP values were considered for these indexes, developed by the authors, and compared to concrete characteristics, either workability (**Section 5.1**), composition (**Section 5.2**) or mechanical properties (**Section 5.3**).

5.1. Workability index

As previously indicated, the workability of FRC mainly depended on the added amounts of water, admixtures and fibers. A Workability Index (*WI*), shown in **Equation (1)**, was implemented and is graphically represented in Fig. 9, to evaluate the workability of FRC in relation to the environmental damage caused by the high usage of water and admixtures, and the amount of fibers added into the mix. This index represented the amount of admixture and water needed to achieve the desired workability *per* kilogram of fibers: by multiplying both the water and the admixture quantity together, both factors are considered, and their interaction is clearly visible in the workability of the concrete. The higher the *WI*, the more workable the FRC, but the higher the content of water and admixture as well, which in turn leads to a higher environmental impact.

$$WI = \frac{ADM * W}{MaxF} \tag{1}$$

The highest *WI* was achieved by a UHPFRC mixture incorporating a low amount (19.6 kg/m^3) of polyethylene fibers [84], but high amounts of water-reducing admixture (27 kg/m^3), thus avoiding the negative effect of fibers towards workability and avoiding higher water/binder ratios. The second highest *WI* involved a very low dosage of polypropylene fibers (5 kg/m^3) and recycled cardboard (up to 24 kg/m^3) [81], which needed high amounts of water (up to 240 kg/m^3) and regular quantities of admixture (4 kg/m^3), which hindered the mechanical performance of the mix. The lowest values among studies [44,89] were due to high amounts of fibers (78–298 kg/m^3) with average amounts of water (below 180 kg/m^3) and plasticizers (up to 5 kg/m^3), which could have hindered the fresh state performance of the mixes.

5.2. Sustainability index

The next factor studied in this research was a Sustainability Index (*SI*), expressed in **Equation (2)**, and which divided the percentile (%) variation of GWP of the sustainable mix with regard to the reference mixture, by the cement content of that sustainable mix (kg/m^3). The *SI* represents an evaluation of mix sustainability relating to the most polluting raw material in the mix and to determine whether its enhancement or detriment was dependent on the cement amount. The higher the reduction in GWP and the lower the cement content of the sustainable mix, the better the performance in terms of *SI*. Therefore, the best *SI* results were achieved when the index was negative, and its absolute value was the highest.

$$SI = \frac{\Delta GWP}{CEM} \tag{2}$$

The different *SIs* obtained by the reviewed articles can be seen in Fig. 10, as well as the cement content of the mix. The two best performing mixtures were not the ones with the lowest cement content [45,84], but the ones in which fiber manufacturing did not imply such high energy demand (GWP variation of −67 %) [45] and in which conventional fibers were replaced by recycled ones (GWP variation of −70 %) [84]. In fact, the worst performance was found in the mixture with the lowest cement content [81], because it incorporated recycled carboard fibers, which were subjected to a high energy demanding treatment and increased the GWP compared to the reference mix. These findings highlighted the relevance of adequate fiber selection for FRC from a sustainability viewpoint, as it can completely modify the environmental performance of concrete both in positive and negative terms.

5.3. Mechanical and environmental indexes

Another two indexes were also evaluated to analyze the balance between the environmental and functional efficiency of FRC, considering its most relevant mechanical properties [88,171,172]: Flexural Sustainability Index (*FSI*) and Compressive Sustainability Index (*CSI*).

FSI, expressed in **Equation (3)** and graphed in Fig. 11a, served to evaluate the variation in GWP (kgCO$_2$e) *per* unit of flexural strength (MPa) between the reference and the sustainable mixes. The best performing mixtures in *FSI* terms were the ones with higher values, meaning that both mixes showed the same flexural strength, while the GWP of the sustainable mix was considerably lower.

$$FSI = \Delta\left(\frac{GWP}{FS}\right) = \frac{GWP_{REF}}{FS_{\ REF}} - \frac{GWP_i}{FS_{\ i}} \tag{3}$$

In addition, *CSI*, expressed in **Equation (4)** and shown in the graph in Fig. 11b, was obtained in the same way as *FSI*, but

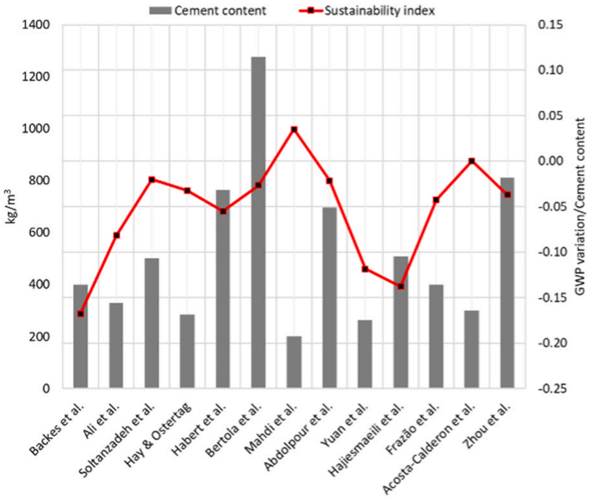

Fig. 10. Evaluation of concrete mixture sustainability levels based on their cement content and their GWP [1,44,45,52,63,71,79,81–84,86,89].

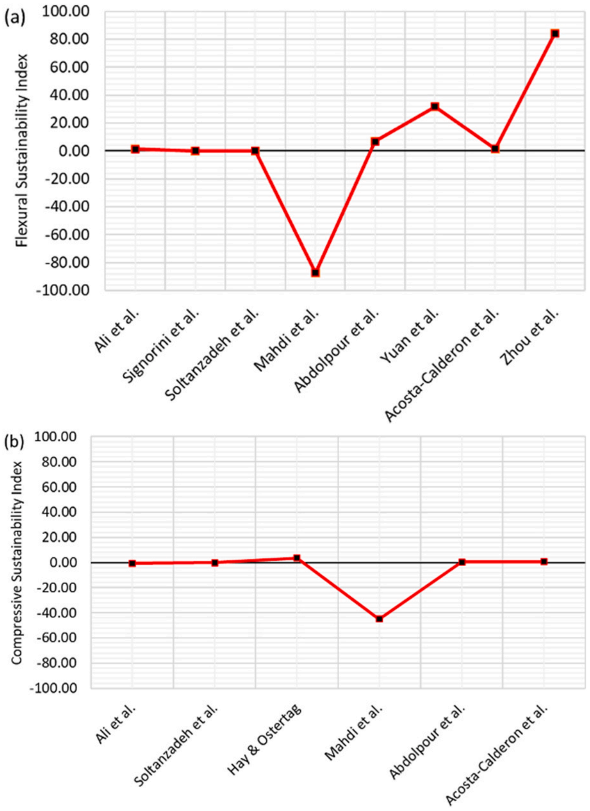

Fig. 11. Evaluation of the sustainability of the different concrete mixtures based on mechanical testing: (a) Flexural sustainability index; (b) Compressive sustainability index [1,44,63,77,81–83,86,87].

interchanging flexural strength for compressive strength.

$$CSI = \Delta\left(\frac{GWP}{CS}\right) = \frac{GWP_{REF}}{CS_{REF}} - \frac{GWP_i}{CS_i} \tag{4}$$

Most of the sustainable mixtures had *FSI* and *CSI* close to zero (Fig. 11), meaning that their flexural and compressive strengths and GWP were similar to those of the reference mix. Thus, the use of fibers had no great effect on the mechanical properties of concrete but reduced their GWP impact [77]. In fact, one mixture even outperformed the others in *FSI* terms [87], as the natural (kenaf) fibers that it incorporated rather than glass fibers, lowered the GWP by 10 % and enhanced flexural behavior by 16 %. The second-best performing study [83] in terms of *FSI* increased FRC sustainability by using RCA and incorporated a low cement content, while maintaining similar mechanical behavior. Finally, the same FRC mix [81] with poor *SI* values, also had the lowest values for both *FSI* and *CSI*, as recycled carboard fibers were slightly detrimental in terms of flexural and compressive behavior.

6. Conclusions

The aim of this systematic review paper has been to analyze the current literature on FRC that had undergone an LCA, understanding the methodology followed to conduct the LCA, and to evaluate the environmental and mechanical results. The following conclusions can be drawn from the LCA analysis.

- The authors of the studied articles defined their own FU and system boundaries of the LCA, which were difficult to compare between studies. The FUs were usually related to raw materials, while the most common system boundary was cradle-to-gate, assessing the impacts from early stages of FRC production. Cradle-to-grave system boundaries were used when evaluating the full-service life of the elements, which implied the whole intervention or rehabilitation of a structure or building. This system boundary gives a more complete overview of the environmental issues related to the concrete element.
- The Ecoinvent database was the most used along with SimaPro software. Other databases were used for specific data from a process related to a unique location or taken from the relevant industries, where the specifications of these processes or materials were crucial to the LCA. The most habitual methodologies used in LCA were CML and ReCiPe.
- The most used indicator was always GWP, which was able to show the main differences and environmental enhancements from the reference mixes and was closely related to ODP. Besides, ADPf and AP were also commonly studied, and were quite important when related to fiber production and cement use. Therefore, they need to be carefully analyzed to avoid the most common issues regarding FRC. Other environmental impacts were directly related to GWP results, except for water use, which greatly depended on the need for treatment of the sustainable fibers and their washing.

Regarding raw material choices, binders, aggregates, supplementary cementitious materials and water were all common, while the most widely used fibers for concrete use were steel and synthetic fibers, respectively. Both fiber types had high environmental impacts, so recycled fibers from different materials and processes were implemented to achieve higher sustainability in FRC, thus reducing and avoiding a high number of environmental impacts.

Indexes were established to assess all the performance dimensions of the concrete specimens simultaneously. It was concluded that sustainable fibers can be added to achieve considerable reductions of GWP, without hindering the mechanical performance of FRC. The indexes also showed the importance of treatment and processing of the sustainable fibers, which can be a key factor, in order to obtain a product with a good mechanical performance and environmental rating.

As a summary, it has been found from this systematic review that the use of sustainable fibers is rising considerably, as they tend to maintain or even enhance the mechanical properties of concrete while avoiding high environmental impacts. These impacts in conventional fibers are related to their manufacturing process, which for the most common fibers (steel or glass fibers) constitute a major part of their environmental damage, as shown by GWP, ADPf, and AP indicators. Recycled fibers from various origins can be used in concrete with encouraging results, as their retrieving process is carefully being improved while the impacts from landfill or waste processing are being avoided.

This systematic review contributes to establish a more comparable LCA framework for FRC. Thus, the reader can easily know the process followed to conduct the LCA of different FRC mixes and link its results with their composition and mechanical performance of FRC. A more proper balance between all these aspects can therefore be achieved in this way when producing FRC.

Future outlook

In upcoming years, sustainability will be a determining factor for construction and building solutions [2]. FRC can count on the advantages and the versatility of concrete, its mechanical properties and durability and the increased sustainability of having added fibers [44]. The environmental performance of FRC can be analyzed by LCA, but some aspects have to be addressed in future research.

- First, a more standardized methodology and framework needs to be developed for LCA. Besides, further investigation needs to be done to achieve results that could be replicated across multiple locations and research facilities all over the world.
- Second, some fiber types are of recent development and are yet to be fully defined and described, such as natural fibers and most of the synthetic or steel recycled fibers that are retrieved. Therefore, a more profound characterization of the mechanical and environmental performance of the concrete mixes that incorporate them is needed. In this way, a proper balance between sustainability and mechanical behavior can be guaranteed.
- Finally, new materials can be revalued as concrete fibers, as the impacts derived from landfill and waste management are growing exponentially [140]. Their suitability for this use should be verified through LCA and mechanical testing.

On a closing note, further research towards the optimization of the FRC mix design is needed, to define fully and to minimize its inherent environmental burdens. That research path offers a promising future leading towards the circular economy in the field of FRC.

CRediT authorship contribution statement

Javier Manso-Morato: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Nerea Hurtado-Alonso: Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Víctor Revilla-Cuesta:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Marta Skaf:** Writing – review & editing, Methodology, Conceptualization. **Vanesa Ortega-López:** Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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

Data will be made available on request.

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