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Enhancing Circularity in the Construction Industry: Life Cycle Assessment of Recycled Fibers in Concrete Composites

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ABSTRACT

Nowadays, the construction sector accounts for a significant share of global energy consumption, carbon emissions, and resource depletion. To reduce its environmental impact, the entire sector must shift toward sustainable strategies, such as improving energy efficiency and using sustainable materials. In this context, fiber-reinforced concrete composites (FRCCs) made from recycled fibers are proposed as a possible solution. This research aims to evaluate the environmental impacts of sixteen formulations of reinforced concrete using different types of virgin or recycled fibers through Life Cycle Assessment. The findings showed that the environmental impacts of FRCCs depend strongly on both the fiber type and the recycling process adopted. Climate change impacts ranged from 218 to 926 kg CO_2 eq per m^3 of concrete composite. Compared with the conventional steel-fiber-reinforced concrete formulation, mechanically recycled fiber formulations reduced climate change impacts by 28%–61%, whereas the chemically and thermally recycled glass-fiber formulations increased them by 9% and 66%, respectively. Overall, virgin fibers and fibers recycled through thermal or chemical treatments showed higher environmental impacts across several categories due to the high energy demand and chemical inputs associated with these processes. In contrast, mechanically recycled fibers generally demonstrated lower environmental impacts, particularly for bio-based fibers. These results highlight the potential environmental advantages of mechanical recycling pathways compared to more energy-intensive recycling processes. This study contributes to the scientific literature by offering a new perspective on the use of recycled fibers in concrete composites.

Abbreviations	
BF	Basalt Fiber
CCs	Concrete Composites
C&DW	Construction and Demolition Waste
CF	Carbon Fiber
CTM	Concrete Traditional Mix
FRCCs	Fiber-reinforced Concrete Composites
GF	Glass Fiber
HF	Hemp Fiber
LCA	Life Cycle Assessment
OF	Bamboo Fiber
PF	Polypropylene Fiber
rcCF	Chemical Recycled Carbon Fiber
rcCFCC	Concrete Composite with Chemical Recycled Carbon Fiber
rcGF	Chemical Recycled Glass Fiber
rcGFCC	Concrete Composite with Chemical Recycled Glass Fiber

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Abbreviations	
BF	Basalt Fiber
rmCF	Mechanical Recycled Carbon Fiber
rmCFCC	Concrete Composite with Mechanical Recycled Carbon Fiber
rmBF	Mechanical Recycled Basalt Fiber
rmBFCC	Concrete Composite with Mechanical Recycled Basalt Fiber
rmGF	Mechanical Recycled Glass Fiber
rmGFCC	Concrete Composite with Mechanical Recycled Glass Fiber
rmHF	Mechanical Recycled Hemp Fiber
rmHFCC	Concrete Composite with Mechanical Recycled Hemp Fiber
rmOF	Mechanical Recycled Bamboo Fiber
rmOFCC	Concrete Composite with Mechanical Recycled Bamboo Fiber
rmPF	Mechanical Recycled Polypropylene Fiber
rmPFCC	Concrete Composite with Mechanical Recycled Polypropylene Fiber
rtCF	Thermal Recycled Carbon Fiber

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Abbreviations	
BF	Basalt Fiber
rtCFCC	Concrete Composite with Thermal Recycled Carbon Fiber
rtGF	Thermal Recycled Glass Fiber
rtGFCC	Concrete Composite with Thermal Recycled Glass Fiber
vBF	Virgin Basalt Fiber
vBFCC	Concrete Composite with Virgin Basalt Fiber
vCF	Virgin Carbon Fiber
vCFCC	Concrete Composite with Virgin Carbon Fiber
vGF	Virgin Glass Fiber
vGFCC	Concrete Composite with Virgin Glass Fiber
vHF	Virgin Hemp Fiber
vHFCC	Concrete Composite with Virgin Hemp Fiber
vOF	Virgin Bamboo Fiber
vOFCC	Concrete Composite with Virgin Bamboo Fiber
vPF	Virgin Polypropylene Fiber
vPFCC	Concrete Composite with Virgin Polypropylene Fiber

1. Introduction

The construction sector plays a crucial role in the global economy, making significant contributions to the development of infrastructure essential for social and technological progress (Huang et al., 2018; Islam, 2025; Pittri et al., 2025). Accelerated urbanisation and the ageing of existing infrastructure are leading to a continued increase in the demand of construction materials (Siddiqui et al., 2025). Globally, in 2022, the construction sector was responsible for the emission of approximately 10 Gigatons of CO_2 eq, representing 37% of total Greenhouse Gas emissions (United Nations Environment Programme, 2024). In addition, this sector also contributes to the depletion of primary resources, air and water pollution, and increased construction and demolition waste (C&DW) generation (Arpitha et al., 2025; Bayram et al., 2025; Zhu and Feng, 2025). C&DW represents one of the largest waste streams globally and therefore poses significant environmental and management challenges (Hao et al., 2020). Most C&DW is generated annually due to urban expansion, infrastructure renovation, and building demolition (Sun et al., 2025). Managing this waste is often complex due to its heterogeneous composition, which can include concrete, metals, polymers, composite materials, and other construction residues. Moreover, most C&DW is disposed in landfills, resulting in resource loss, land use, and additional environmental burdens (Alsheyab, 2022). Improving the recovery and valorisation of C&DW is a key priority for promoting circular economy strategies in the construction sector. In particular, reusing waste-derived materials in new construction products represents a promising way to reduce landfill disposal, decrease the demand for virgin raw materials, and mitigate environmental impacts.

In addition to C&DW disposal, the environmental impacts are primarily caused by the production and use of cementitious materials, particularly concrete (Dal Lago et al., 2025; Orozco et al., 2024). Therefore, achieving sustainable production and consumption in the construction sector has become a strategic priority (Hasan et al., 2024). This involves not only reducing carbon dioxide emissions and energy consumption, but also optimising resource use, promoting waste valorisation, and minimising environmental impact through the development of low-impact and high-performance alternatives to conventional concrete (Myint et al., 2025; Su et al., 2025). In this context, the use of fiber-reinforced concrete composites (FRCCs) can be strategic. FRCCs consist of a cementitious matrix containing randomly dispersed short fibers that significantly improve tensile strength, ductility, crack resistance, and overall durability (Sahani et al., 2025). These materials are particularly valuable for applications that require improved structural performance, seismic resilience, or reduced maintenance, such as precast elements, infrastructure repairs, and high-performance concrete (Aduwenye et al., 2024; Wang et al., 2024). Furthermore, FRCCs enable greater design optimisation of construction elements, thus reducing the overall material demand in construction (Bheel et al., 2024; Li et al., 2025; Scope et al., 2021). Short fibers improve the tensile strength, ductility, and energy absorption capacity of concrete (Liew et al., 2019). Therefore, FRCCs can optimise elements such as prefabricated panels, sewer pipes, thin shell roofs, and tunnel linings, potentially reducing conventional reinforcement requirements (Akbar and Liew, 2021).

However, the sustainability of FRCCs depends not only on their structural efficiency but also on the environmental impacts associated with their constituent materials, particularly the fibers. Traditionally, FRCCs include carbon fiber (CF), glass fiber (GF) or synthetic polymers such as polypropylene fiber (PF); despite their mechanical advantages, the production of these materials is often associated with high environmental impacts (Moutik et al., 2024). In this framework, increasing attention is being paid to the use of recycled fibers as a replacement for virgin fibers as a strategy to mitigate the environmental impacts related to the use of recycled finers in composite manufacturing. (Akbar and Liew, 2021; Ateeq et al., 2025). Recycled fibers can come from a wide range of industrial or post-consumer waste, including synthetic and biomass-based fibers recovered from packaging or textile waste, CF, GF, and basalt fiber (BF) recovered from end-of-life composite materials, for instance, in the automotive or aerospace sectors, or from wind turbine blade waste (Manso-Morato et al., 2025; Sobek et al., 2024; Tyurkay et al., 2024). Their integration into cementitious systems not only maintains many of the mechanical advantages offered by conventional fibers but also introduces additional environmental benefits (Prasad et al., 2024; Singh and Yadav, 2024). However, despite these potential benefits, several obstacles remain for the adoption of recycled fibers in FRCCs, including variability in fiber quality and uncertainties regarding long-term performance and sustainability (Kumar et al., 2025; Overhage and Gries, 2025). Furthermore, some recycling methods, such as thermal or chemical recycling, could present high environmental impacts (Caballero et al., 2025; Patre et al., 2025; Sobek et al., 2024). For these reasons, it is necessary to better evaluate the fiber recycling processes in comparison to the production processes for virgin fibers and their impacts on the the properties and sustainability of the results FRCCs.

This study aims to evaluate the environmental impacts of sixteen formulations of reinforced concrete using different types of virgin or recycled fibers. The analysis was conducted using the Life Cycle Assessment (LCA) approach, as outlined in ISO 14040:2006 and ISO 14044:2006. LCA is a systematic and rigorous method used to evaluate the environmental impacts associated with the life cycle of a product, service, or process. This methodology spans from the extraction of raw materials through production process, use, and final disposal. LCA is an essential tool necessary for evaluating sustainability and supporting decision-making (ISO, 2006a, 2006b).

Several studies evaluated the environmental performance of different types of recycled fibers for concrete composites (CCs). For instance, Sbahieh et al. (2023) assessed the environmental impacts of GF-reinforced polymer, CF-reinforced polymer and steel GF-reinforced polymer bars compared to conventional steel bars. Backes et al. (2022) evaluated the environmental impact range of end-of-life scenarios of steel-reinforced concrete and CF-reinforced concrete, determined as a future outlook for the next 50 and 100 years. The study of Singh et al. (2022) examined the suitability of using GF-reinforced polymer and CF-reinforced polymer waste in pervious concrete and quantified their environmental impacts through a LCA framework. The research of Manso-Morato et al. (2025) applied LCA to compare landfilling, incineration and mechanical recycling of wind turbine blade waste made in GF. Witik et al. (2013) compared the recycling of a CF epoxy composite via pyrolysis with modern incineration with energy recovery and disposal via landfilling as potential waste treatments for CF-reinforced plastic waste. Finally, Akbar and Liew (2021) evaluated and compared the performance of different FRCCs based on their mechanical strength, environmental impact potential, and cost.

However, the scientific literature lacks studies that primarily focus on comparing the environmental impact of the production process of virgin fibers compared to recycling treatments applied to various types of fibers. Although several attempts have been made, these often focus solely on virgin fibers or on a limited range of recycled fibers. Furthermore, recent studies lack comprehensive comparative analyses of FRCCs. Given growing environmental concerns, it is necessary to fill these gaps in order to understand the best solutions to mitigate environmental impacts.

This study seeks to fill this gap by analysing the environmental impacts of the production of six types of reinforced fibers, considering their different recycling processes, as reported in the materials and methods section. Specifically, the impacts of the different recycling methods were evaluated and compared to traditional production processes for carbon fibers (CF), glass fibers (GF), basalt fibers (BF), polypropylene fibers (PF), hemp fibers (HF), and bamboo fibers (OF). The study offers an overview of the impacts of FRCCs composed of the sixteen fibers mentioned.

This research contributes to the scientific literature by offering a new perspective on the environmental impacts of the use of recycled fibers in CCs, highlighting the importance of integrating recycled materials and exploring innovative approaches for managing fiber waste, thus improving the sustainability of the construction sector. The results of this study will be useful for both the scientific community and technical stakeholders involved in the production, development, and management of sustainable CCs.

2. Materials and methods

2.1. Materials and recycling processes description

The recycling processes for CF, BF, GF, PF, HF, and OF require various treatments that result in different material properties and characteristics. Recycling methods can be mechanical, thermal, and chemical, with mechanical recycling being applied to all types of fibers, while chemical and thermal recycling are considered only for CF and GF. The recycling processes described in the following sections can be targeted at various post-industrial and post-consumer waste streams. CF, BF and GF can potentially be recovered from manufacturing waste and end-of-life fiber-reinforced polymer composites, including components from the automotive, aerospace, construction, marine, and wind energy sectors. PF can be recovered from selected post-industrial or post-

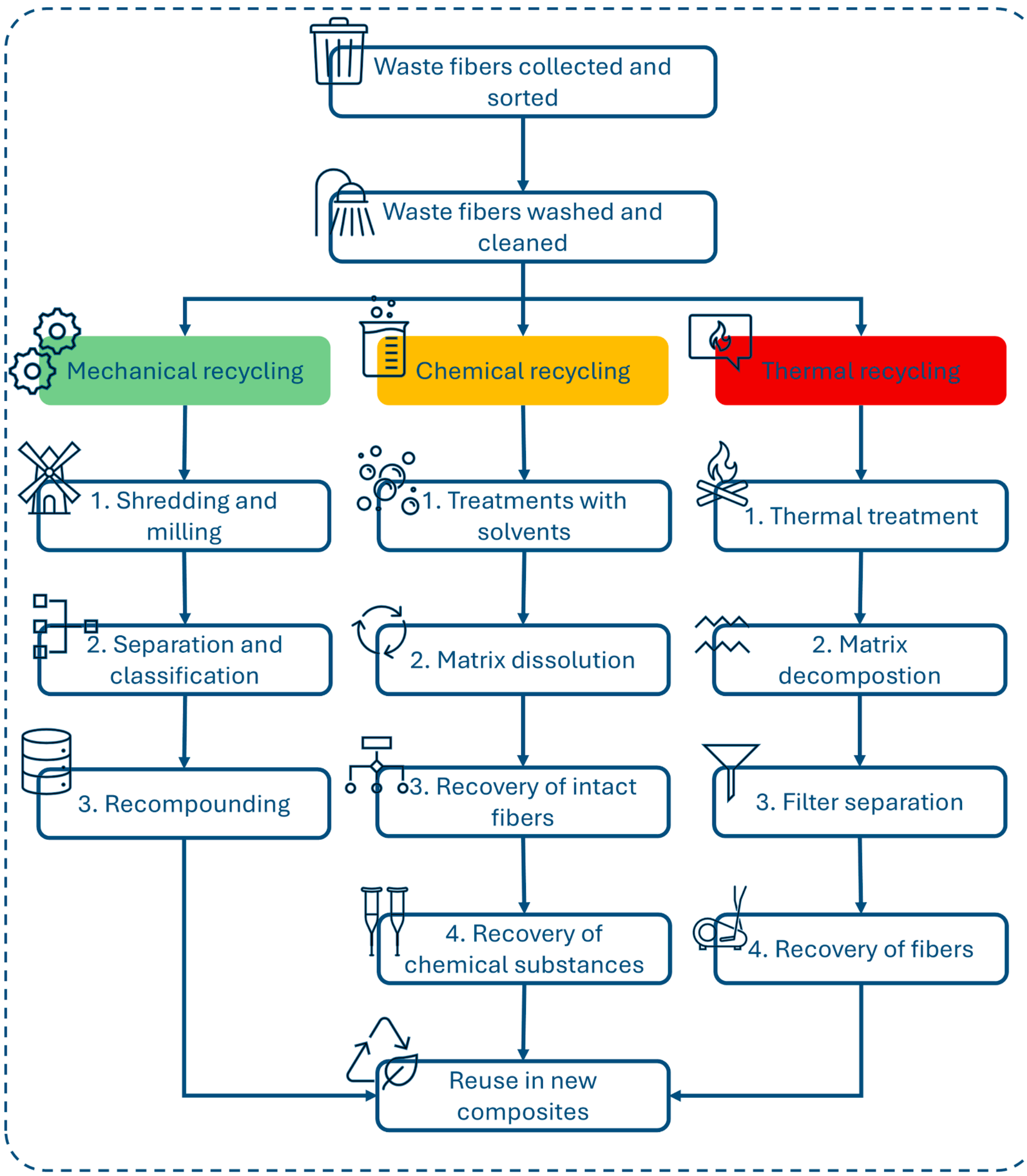

Fig. 1. Recycling processes flow diagram.

consumer plastic waste, particularly packaging and textile waste. HF and OF can be derived from agricultural residues and processing waste generated during fiber extraction and the production of textiles, biocomposites, furniture, and building products. The recycling methods, the technical challenges, the properties and the use of these types of fibers in CCs are summarised in Table S1, while the main features of the reinforced fibers are reported in Table S2. The flow diagram of the recycling processes is reported in Fig. 1.

2.1.1. Recycled Carbon Fiber (rCF)

Recycled Carbon Fiber (rCF) is obtained via mechanical, thermal, or chemical processes and retains high tensile strength (3,150–4,950 MPa) and elastic modulus (200–240 GPa), with only minor reductions compared to vCF (Aflaki Samani and Jabbari Lak, 2019; Akbar and Liew, 2020; Belli et al., 2018; Bhandari and Nam, 2024; de Souza Abreu et al., 2020; Faneca et al., 2018; Patrinou et al., 2022). It enhances both tensile and flexural performance in concrete, improves crack control, and enables to manufacture lightweight, high-performance structures. However, chemical and thermal recycling have high energy costs, and rCF may have surface residues (Borjan et al., 2021; Butenegro et al., 2021). In mechanical recycling, the process begins with the collection and sorting of post-industrial CFRP manufacturing scrap or end-of-life CFRP components, such as automotive, aerospace, and wind-energy products, followed by cleaning and the removal of contaminants (Akbar and Liew, 2021). After that, the cleaned material is shredded, milled, and sieved to recover shorter fibers. Then, fibers are separated, classified and finally recompounded. Thermal recycling involves pyrolysis which heats the waste at 400–1000 °C in low-oxygen conditions to decompose the resin. Chemical recycling with nitric acid breaks down the waste fiber into small pieces that are submerged in a solvent to dissolve the resin, producing clean fibers with properties similar to those of the original material. After that, the intact fibers and the chemical substances are recovered (Patre et al., 2025).

2.1.2. Recycled Basalt Fiber (rBF)

Recycled Basalt fiber (rBF) is a chemically stable fiber, exhibiting excellent chemical stability. When added to CCs, rBF improves crack control and offers excellent alkali durability (Chairi et al., 2025; Persico et al., 2022). Due to the lack of standardised mechanical data of rBF, the properties of vBF are commonly adopted as proxies, which may lead to an overestimation of the actual mechanical performance of the recycled fibers. In particular, vBF typically exhibits a tensile strength ranging from 2,950 to 4,500 MPa and an elastic modulus ranging from 88 to 115 GPa. Mechanical recycling of rBF may involve the collection of BF-reinforced polymer manufacturing end-of-life composite products, followed by cleaning, shredding, and milling to obtain short fibers (Fořt et al., 2021).

2.1.3. Recycled Glass Fiber (rGF)

Recycled Glass Fiber (rGF) can be obtained through mechanical, thermal, or chemical processes; however, its use faces challenges such as strength loss after thermal exposure and dust generation. Compared to vGF, rGF has lower tensile strength (1,050 MPa), a lower elastic modulus (72 GPa) and a lower density (2.53 g/cm^3) (Zhao et al., 2023). The rGF remains effective for crack control in concrete, though reduced performance limits its structural use (Chang et al., 2021; Gonçalves et al., 2022). Potential sources of rGF include GF-reinforced polymer manufacturing scrap and end-of-life composite products, such as automotive components, construction products, boats, and wind turbine blades. Mechanical recycling involves collecting and cleaning the waste, then shredding and milling it to produce short fibers (Howarth et al., 2014). Regarding chemical recycling, solvents are used to dissolve the polymer resin matrix of composite waste, enabling the recovery of intact fibers (Sobek et al., 2024). Thermal recycling, typically achieved through pyrolysis, heats the composite in low-oxygen conditions to decompose the matrix, leaving the glass fibers, which may require post-treatment to restore their original properties (Caballero et al., 2025).

2.1.4. Recycled Polypropylene Fiber (rPF)

Recycled Polypropylene Fiber (rPF), typically recovered mechanically, may have lower consistency and more potential impurities compared to vPF. Its tensile strength is 250 MPa with an elastic modulus of 5 GPa (Araya-Letelier et al., 2019). The rPF enhances plastic shrinkage crack control and contributes to the production of lightweight, cost-effective concrete, making it a valuable and sustainable option for non-structural and crack-control applications (Akça et al., 2015; Yin et al., 2015). Mechanical recycling of PF may target sorted post-industrial and post-consumer polypropylene waste, particularly packaging and textile waste. The waste is collected, sorted, cleaned, shredded and granulated into pellets or short fibers for reuse (Yin et al., 2015).

2.1.5. Recycled Hemp fiber (rHF)

Recycled Hemp Fiber (rHF) is mechanically derived and primarily used in bio-concrete due to its eco-friendly profile. It is lightweight, with a tensile strength of 857 MPa, elastic modulus of 58 GPa, fiber length of 20–40 mm, and a density of 1.50 g/cm^3 (Lu and Oza, 2013; Pickering et al., 2007; Zhang et al., 2022). The rHF increases concrete porosity and insulation, and when treated offers good durability (Manaia et al., 2019; Rissanen et al., 2023). Mechanical recycling of HF involves the collection and sorting of hemp cultivation and processing residues, including stalk residues and textile or biocomposite manufacturing offcuts, followed by cleaning to eliminate impurities. The material is then processed through mechanical shredding, reducing it into shorter fibers or fine particles, which can be further processed (Akbarian-Saravi et al., 2025).

2.1.6. Recycled Bamboo fiber (rOF)

Recycled Bamboo Fiber (rOF) is mechanically recovered and can be used dispersed or as strips in concrete. It provides tensile strength between 39–775 MPa, elastic modulus from 0.4 to 42 GPa and a density of 0.6–1.1 g/cm^3 (Huang and Young, 2019; Mousavi et al., 2022; Osorio et al., 2011; Phong et al., 2011; Rassiah et al., 2013). Although less uniform than vOF and susceptible to decay, rOF is renewable, CO_2 neutral, and effectively improves flexural strength and crack control in green and sustainable CCs (Liu et al., 2012; Muhammad et al., 2019). Mechanical recycling of OF consists of collecting and sorting bamboo harvesting and processing residues, including offcuts and scraps from furniture, panels and other construction products, followed by thorough cleaning to remove dirt and contaminants. The bamboo material is then mechanically shredded into shorter fibers or fine particles (Gan et al., 2022).

2.1.7. Concrete composites recipe mix

A total of sixteen CCs with virgin and recycled fibers were evaluated and compared to the Concrete Traditional Mix (CTM) with steel fibers that was used as a benchmark. The mix design adopted was based on Akbar and Liew (2021), who used the same cementitious matrix and a fiber volume fraction of 1% under identical experimental conditions. The additional recycling-route formulations were estimated by maintaining the same cementitious matrix and fiber volume fraction and calculating the corresponding fiber mass according to fiber density. This standardised basis was adopted to isolate the environmental influence of fiber type and recycling process; however, it should not be interpreted as demonstrating identical mechanical performance among all formulations. The quantity details are presented in Table S3. The sand/binder ratio was 1.5, and the admixture dosage was set at 0.25% by weight of the binder in the case of CTM, while it was increased to 3% for the FRCCs. Only sand was used, while coarse aggregates were not included. This formulation is consistent with typical fiber-reinforced composites, where the use of sand improves fiber dispersion and reduces the risk of fiber clustering during mixing. Furthermore, the higher amount of admixture was selected to prevent any loss of workability caused by fiber addition, which increases internal friction and reduces the flowability of the mix. The admixture used is a polycarboxylate-based superplasticiser. In accordance with the study of Kim et al. (2014), volumetric equivalence was used to estimate the dosage of steel fiber (Eq.1):

$$m_{steel} = \frac{m_{CF}}{\rho_{CF}} \bullet \rho_{steel} \quad (1)$$

where, m_{steel} is the mass of steel fibers (kg/m^3), m_{CF} is the mass of CFs (kg/m^3), ρ_{CF} is the density of CFs equal to 1,750 kg/m^3 and ρ_{steel} is the density of steel fibers and is equal to 7,850 kg/m^3. Eq. (1) was applied to estimate the mass of steel fibers corresponding to the same 1% volumetric fraction adopted for the other formulations. This assumption provides a consistent volumetric reference for CTM but does not establish mechanical equivalence between CTM and the other CC formulations.

2.2. Goal and scope

The goal of this study is to evaluate the environmental impacts of sixteen formulations of reinforced concrete using different types of virgin or recycled fibers, with the scope of understanding the impacts generated by the FRCCs. The comparison was standardised for a fiber volume fraction of 1% to investigate the influence of fiber type and recycling process.

The LCA analysis was carried out using SimaPro v9.6 software (Goedkoop et al., 2016) and Ecoinvent database v3.10 (Wernet et al., 2016). The Environmental Footprint 3.1 method was used as the impact assessment method (Andreasi Bassi et al., 2023).

To achieve the objective, the functional unit was defined as 1 m^3 of concrete composite. A cradle-to-gate approach was followed. The system boundaries consider the raw materials extraction and processing for the virgin materials and include the collection and waste management for the recycled fibers. Use and end-of-life phases of the concrete composites were excluded from the analysis.

2.3. Life Cycle Inventory

The Life Cycle Inventory data used in this study were collected from literature sources and proxy datasets available in the Ecoinvent database. Most datasets refer to European or global average conditions. The complete inventory data, including datasets, assumptions, and references are reported in Table S4. Specifically, vCF was based on the study of Akbar and Liew (2021), while rmCF data were taken from Howarth et al. (2014). For rcCF and rtCF, the data reported by the research of Patre et al. (2025) were used. Similarly, vBF were described following Akbar and Liew (2021), with the rmBF inventory based on Fořt et al. (2021). The data of vGF were also sourced from Akbar and Liew (2021). The data on the recycling processes for rmGF, rcGF and rtGF were obtained from Shuaib and Mativenga (2016), Sobek et al. (2024), and Caballero et al. (2025), respectively. The inventory for vPF came from Akbar and Liew (2021), while recycling data for rmPF were derived from the study of Arena et al. (2003). For natural fibers, vHF data were based on Akbarian-Saravi et al. (2025), while the rmHF dataset was described by González-García et al. (2010). Lastly, data on vOF were taken from Gan et al. (2022), with rmOF data from the research of Gu et al. (2018). Primary information regarding the specific origin of the composite waste (e.g., wind turbine blades, automotive parts, or construction waste streams) was not available. The recycling processes were therefore modelled considering generic composite waste streams represented in the database. Steel fibers were modelled using the Ecoinvent global market dataset for low-alloyed, hot-rolled steel, representing an average supply mix rather than a specific steel production route. As regards the concrete mix, the details of the recipes are given in section 2.1.7. According to the Ecoinvent database process "Building, multi-storey {RER}| building construction, multi-storey | Cut-off, U", an average value of 4.36 kWh/m^3 was considered for the mixing of the CCs (Wernet et al., 2016). The transport routes for each type of fiber are reported in Fig. 2, the datasets are reported in Table S5 and the details of distances and means of transport used are shown in Table S6.

3. Results and discussion

The results are presented and discussed focusing on six main impact categories that showed the most relevant variations among the analysed CC formulations: (i) climate change, (ii) ecotoxicity, freshwater, (iii) particulate matter, (iv) ozone depletion, (v) resource use, fossil and (vi) resource use, minerals and metals. All values for the other impact categories assessed, as well as the results of the environmental profile, are available in the supplementary materials.

3.1. Environmental impacts related to the manufacturing of the different types of concrete composites

The environmental impacts of the manufacturing of the different types of FRCCs considered in this study are reported in Fig. 3. For climate change (Fig. 3a), rtGFCC and rcGFCC had emissions higher than CTM by 66% and 9%, respectively. All the other formulations showed lower climate change impacts than CTM, with reductions ranging from approximately 1% to 61%. These results indicate that CCs with recycled fibers obtained through mechanical processes are generally associated to a lower carbon footprint compared to CTMs with steel fibers. This is mainly related to the absence of high-temperature treatments or solvent-based processes, which significantly increase energy demand and chemical inputs in thermal and chemical recycling processes. Fig. 3b shows that for ecotoxicity for freshwater systems only rcCFCC had an impact above CTM, with an increase of 19%. This was due to the use of solvents in chemical recycling processes. All the other formulations with positive impacts showed reductions ranging from approximately 47% to 96% compared to CTM. Negative values were obtained for rmCFCC and rmHFCC because of the environmental credits assigned to avoided virgin-material production. Regarding particulate matter (Fig. 3c), all the analysed formulations showed lower impacts than CTM. For the formulations with positive results, the reductions ranged from approximately 5% to 94%, while rmCFCC showed a net environmental credit. The higher impact of CTM was mainly associated with the steel-fiber production process. In contrast, regarding ozone depletion impacts (Fig. 3d), seven formulations showed higher impacts than CTM, with increases ranging from approximately 20% to 366%. The highest increases were observed for rcGFCC and rtGFCC, which exceeded CTM by 324% and 366%, respectively. The remaining formulations with positive impacts showed reductions of approximately 4%–66%, while rmCFCC showed a negative value. As concerns resource use for the fossil category (Fig. 3e), three formulations showed higher impacts than CTM: vCFCC, rcGFCC, and rtGFCC, with increases of approximately 49%, 52%, and 67%, respectively. The remaining formulations with positive results showed reductions ranging from approximately 5% to 64%, while rmCFCC showed a net environmental credit. The production of raw materials, particularly carbon fiber and glass fiber, generated the majority of impacts. In fact, the production processes of both carbon fiber and glass fiber are energy-intensive. Finally, Fig. 3f shows the comparison in terms of resource use, minerals and metals. In particular, only vGFCC showed an impact 656% higher than CTM, while all the other formulations with positive results showed reductions ranging from approximately 66% to 78%. Three FRCCs had negative impacts: rmGFCC, rtGFCC and rcGFCC. The virgin glass fiber process production remains the main cause of the large impact of virgin glass fiber in this category. The values of all impact categories assessed are available in Table S7. On balance, the results show that CCs made with recycled fibers, especially those from mechanical recycling, may have lower

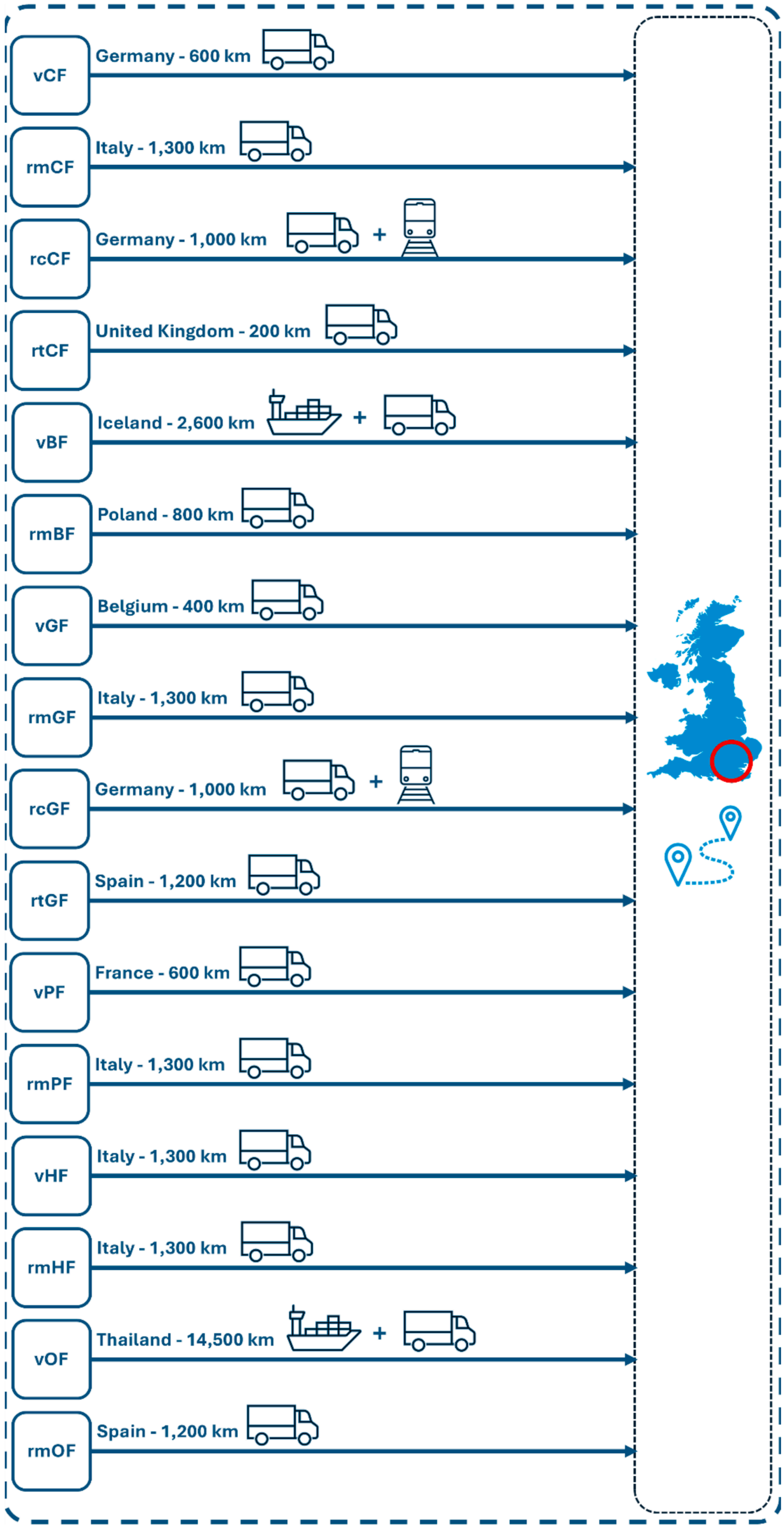

Fig. 2. Transport routes and modes for fibers included in the Life Cycle Inventory.

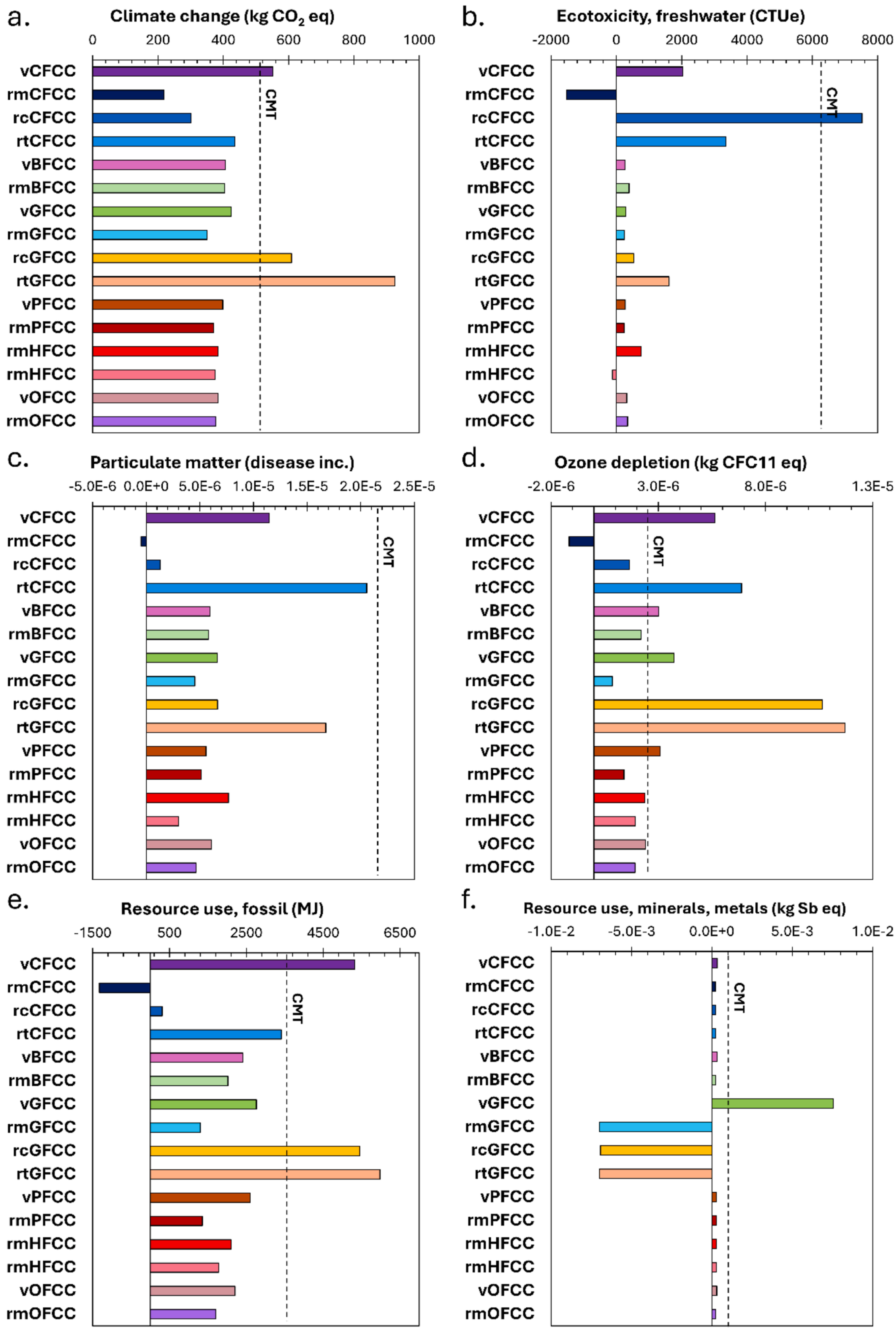

Fig. 3. Impact categories of 1 m^3 of concrete composite: a. Climate change (kg CO_2 eq); b. Ecotoxicity, freshwater (CTUe); c. Particulate matter (disease inc.); d. Ozone depletion (kg CFC11 eq.); e. Resource use, fossil (MJ); f. Resource use, minerals, metals (kg Sb eq.).

impacts than traditional and virgin fiber mixes. However, recycled fibers from thermal and chemical processes often have higher impacts. The findings align with the proposal by Akbar and Liew (2021), which highlights the benefits of using mechanically recycled material. The negative values observed for some indicators are related to the avoided burden associated with the recycling process. In these cases, avoided impacts due to the substitution of virgin materials are considered resulting in a net environmental benefit. Detailed results for each type of

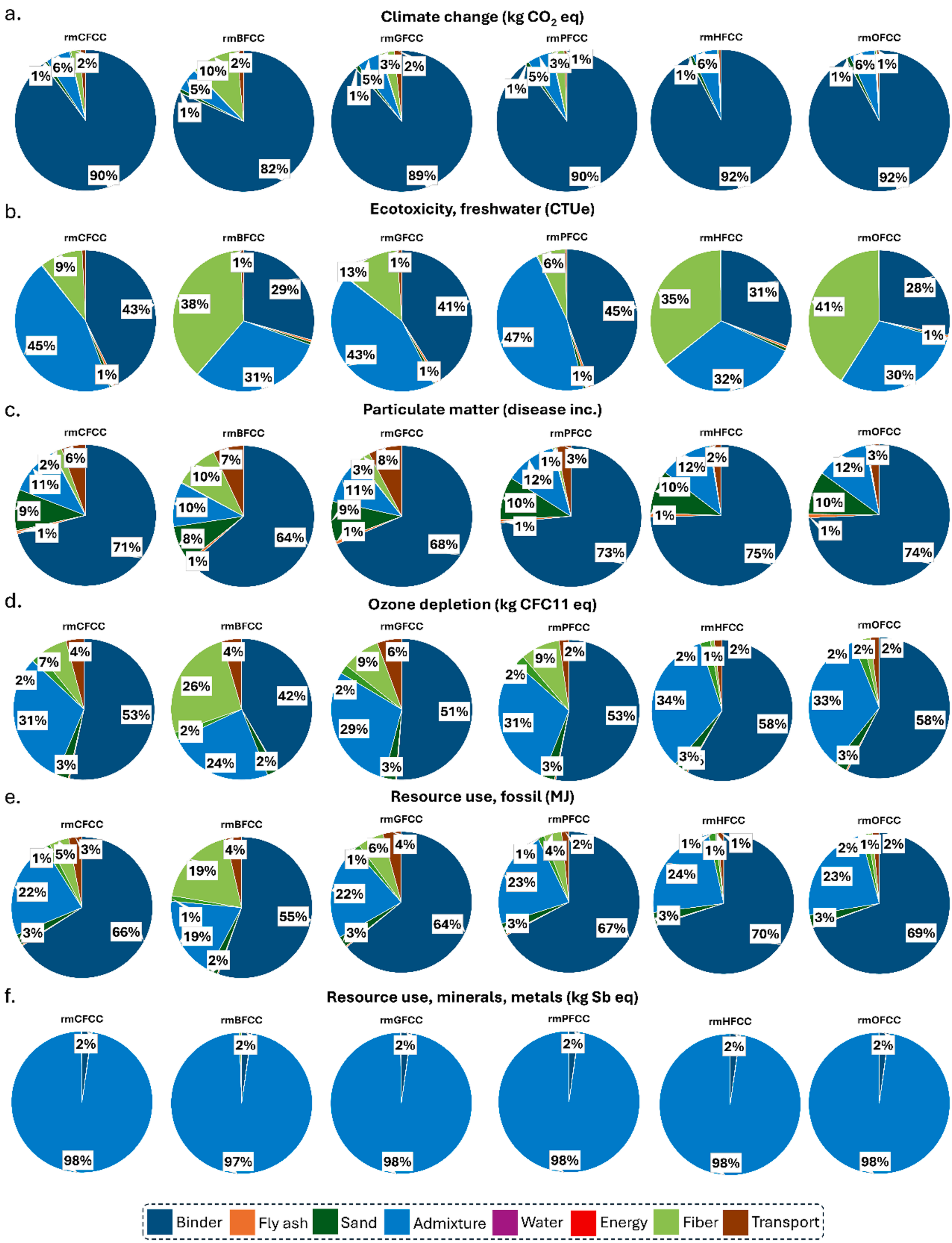

Fig. 4. Materials impacts share of 1 m^3 of concrete composites: a. Climate change (kg CO_2 eq); b. Ecotoxicity, freshwater (CTUe); c. Particulate matter (disease inc.); d. Ozone depletion (kg CFC11 eq.); e. Resource use, fossil (MJ); f. Resource use, minerals, metals (kg Sb eq.).

fiber are reported in Fig. S1.

Fig. 4 shows the percentage contributions of the main materials and processes to the six selected impact categories for the CCs containing mechanically recycled fibers. Contributions below 1% are not labelled. The complete results are reported in the supplementary material (Fig. S2). Regarding climate change (Fig. 4a), the binder was the main contributor for all the CCs, accounting for 82%–92% of the total impact. The admixture contributed approximately 5%–6%, while the contribution of the fibers ranged from 1% to approximately 11%. Transport accounted for approximately 1%–2%, whereas the remaining components individually contributed about 1% or less. As for ecotoxicity to freshwater organisms (Fig. 4b), the admixture and binder were the principal contributors, accounting for 30%–47% and 28%–45% of the total impact, respectively. The fiber contribution varied substantially among the formulations, ranging from 6% to 41%, while the remaining components generally contributed approximately 1% or less. The contributions to the particulate matter indicator are represented in Fig. 4c. The impacts of this category were mainly associated with the binder, which contributed 64%–75%, followed by the admixture, accounting for 10%–12%. Sand contributed 8%–10%, while the contributions of the fibers and transport ranged from less than 1% to 10% and from 2% to 8%, respectively. For ozone depletion impacts (Fig. 4d), the binder was the principal contributor, accounting for approximately 42%–58% of the total impact, followed by the admixture, which contributed 24%–34%. The fiber contribution ranged from approximately 1% to 26%, while transport and sand contributed 2%–6% and 2%–3%, respectively. Energy accounted for approximately 2%, whereas the remaining components provided negligible contributions. For fossil resource use (Fig. 4e), the binder was also the dominant contributor, accounting for approximately 55%–70% of the total impact, while the admixture contributed 19%–24%. The contribution of the fibers ranged from approximately 1% to 19%, whereas sand, transport, and energy contributed 2%–3%, 1%–4%, and 1%–2%, respectively. Finally, resource use, minerals and metals (Fig. 4f) was almost entirely associated with the admixture, which accounted for approximately 97%–98% of the total impact. The binder contributed approximately 2%, while all other components individually accounted for less than 1%. The dominant contribution of the binder to climate change, particulate matter, ozone depletion, and fossil resource use was consistent with previous LCA studies on cement-based materials, in which clinker production is commonly identified as a major source of environmental impacts because of the calcination process and its high thermal energy demand.

3.2. Policy implications

The results clearly show that using recycled fibers may bring environmental benefits. While this may seem obvious, given that using recycled material already has environmental benefits, this study demonstrates that this is not always the case. The chemical and thermal recycling of CF and GF often has a much greater impact, even compared to the respective virgin materials. This means that mechanical recycling may be the most sustainable way to recycle the analysed fibers. Further research and investment are needed to optimise recycling technology, improve quality and consistency of the recovered fibers, and overcome the barriers limiting their use in CCs. Incentives to support mechanical recycling technologies could accelerate the adoption of low-impact recycling pathways in the construction sector. Furthermore, the development of technical standards that promote or mandate a minimum recycled fiber content in cementitious composites could facilitate their market uptake while ensuring consistent material performance. Furthermore, even partial substitutions should be considered to maintain physical characteristics and increase sustainability, particularly for bio-based fibers. Another aspect to be developed is the introduction of recycled materials into prefabricated building materials. From an economic perspective, mechanical recycling is generally associated with lower operating costs than chemical or thermal recycling processes that typically require greater energy input and more complex technologies. Therefore, mechanically recycled fibers may represent not only an environmentally preferable option, but also a more economically feasible solution for industrial application.

3.3. Limitations and future development

This study highlights some limitations inherent to the LCA methodology. Firstly, there is a constraint related to the use of data from the literature: it would be preferable, in future research, to use primary data specific to the system under investigation. Furthermore, this is a preliminary assessment that should be supported by additional experimental testing and laboratory analyses in order to validate and strengthen the results obtained. Another source of uncertainty concerns the variability of key parameters assumed to define the inventory data. Another limitation concerns the absence of consistent experimental mechanical data for all virgin and recycled fiber scenarios. Although the 1% fiber volume fraction provides a standardised formulation basis, it does not guarantee equivalent mechanical performance because recycling may alter fiber length, surface conditions and tensile properties. Therefore, the results should be interpreted as a comparative environmental screening of formulations intended to provide the same general reinforcing function, rather than as a comparison of mechanically equivalent structural products. Future experimental studies should determine the appropriate dosage range for each fiber type required to meet common mechanical and technical targets, including flexural and tensile strength, ductility, crack resistance, and durability, and subsequently update the LCA comparison. Future studies should experimentally determine the maximum dosage of each recycled fiber that can be incorporated while meeting the required workability, tensile and flexural performance, crack resistance, durability, and other technical requirements. Future studies should also extend the present analysis by addressing the economic and social dimensions through Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) within a Life Cycle Thinking (LCT) perspective. Following the study of Baltrocchi et al. (2023), this would enable a comprehensive assessment of the three pillars of sustainability according to Purvis et al. (2019): the environment, economy, and social dimensions. Furthermore, it would be appropriate to focus on biomass fibers in the future, whose environmental performance may vary substantially depending on feedstock origin, cultivation practices, processing requirements, transport, and end-of-life management.

4. Conclusions

This study evaluated the environmental impacts of sixteen formulations of reinforced concrete using different types of virgin or recycled fibers. The results revealed that the environmental impacts of CCs strongly depend on the type of fiber and on the recycling process adopted. All mechanically recycled fiber formulations reduced climate change impacts by 28%–61% compared with the steel-fiber benchmark. In contrast, chemically and thermally recycled glass-fiber formulations increased climate change impacts by 9% and 66%, respectively. Mechanical recycling, particularly for hemp and bamboo fibers, provided the most consistent environmental advantages across several impact categories. These findings highlight the potential environmental advantages of mechanical recycling pathways compared to more energy-intensive recycling technologies. On balance, the results confirm that the integration of recycled fibers, particularly those obtained through mechanical recycling, can contribute to improving the environmental sustainability of CCs and support circular economy strategies in the construction sector. This study contributes to the scientific literature by offering a new perspective on the use of recycled fibers in CCs. This research highlights the importance of incorporating recycled materials and exploring innovative approaches to managing waste from virgin fibers, thereby enhancing the sustainability of the construction sector.

Future research should extend the present cradle-to-gate assessment to a cradle-to-grave perspective, including service life, maintenance, durability-related effects, demolition, recycling, and final disposal of the CCs.

CRediT authorship contribution statement

Alberto Pietro Damiano Baltrocchi: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Shafique:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization. **Vincenzo Torretta:** Writing – review & editing, Validation, Supervision, Conceptualization.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2026.115812.

Data availability

All data generated or analysed during this study are included in this published article.

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