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Circular pathways in construction: environmental life cycle assessment of bio-based fiber-reinforced building component

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The construction sector is one of the most significant contributors to global environmental impacts, particularly due to its high material and energy demands. Developing sustainable alternatives to conventional building materials is, therefore, a critical step toward reducing the environmental impact of this sector. The integration of recycled bio-based fibers with traditional reinforcement is proposed as an alternative solution to mitigate environmental impacts. This study evaluated the environmental benefits of replacing traditional steel reinforcement with recycled bio-based hemp and bamboo fibers in a reinforced concrete beam using the Life Cycle Assessment (LCA) methodology, excluding the evaluation of the mechanical performance of the replacement materials from its scope. The results show that, overall, replacing steel has significant benefits for several impact categories even at low replacement rates for the reinforced concrete beam. For instance, in terms of global warming potential (GW), the emissions decrease from 362 kg CO_2 eq for beam for the steel-reinforced concrete to 324 kg CO_2 eq for beam for 30% steel replacement with recycled hemp and 312 kg CO_2 eq for beam for 30% steel replacement with recycled bamboo fiber. Therefore, the GW emissions decrease by around 14% for the reinforced concrete beam. This study contributes to the scientific literature by providing concrete data on the benefits of using bio-based recycled fibers even at low replacement rates. This research suggests that utilizing recycled bio-based materials could be a practical approach to enhancing the sustainability of construction materials from a circular economy perspective.

KEYWORDS

resource efficiency, life cycle assessment, environmental impacts, bio-based materials, fiber-reinforced concrete

1 Introduction

The construction sector emitted nearly 10 Gt of CO_2 eq in 2022, representing ~37% of global greenhouse gas (GHG) emissions (United Nations Environment Programme, 2024). Most emissions are associated with the production of building materials and reinforcement systems, particularly concrete and steel (Al Omar and Abdelhadi, 2024; Orozco et al., 2024; Lin et al., 2025). For these reasons, it is necessary to intervene by proposing alternative strategies to mitigate impacts. Currently, most solutions aim to optimize processes, identify more sustainable raw materials, and optimize design in order to reduce material consumption (Dierks et al., 2024; Tripathi et al., 2024; Dal Lago et al., 2025). However, within this framework, bio-based reinforcement fibers and agro-waste as replacements for materials such as steel, carbon fiber, and glass fiber are proposed as an alternative to mitigate impacts, enhance resources, and improve waste management (Myint and Shafique, 2024; Kumbasaroglu and Kumbasaroglu, 2025; Nwankwo and Mahachi, 2025).

Bio-based materials, derived from renewable resources such as hemp or bamboo, can help reduce dependence on non-renewable and energy-intensive raw materials (Gibson, 2025; Memari et al., 2025; Przybek, 2025). Furthermore, their integration into construction systems is consistent with the principles of the circular economy, as they are often compatible with recycling and upcycling pathways (Pacheco-Torgal, 2025). However, barriers to the widespread adoption of recycled and bio-based fibers remain, including variability in fiber quality, uncertainties about long-term durability, and the environmental costs associated with recycling technologies (Salazar Sandoval et al., 2024). For these reasons, it is necessary to evaluate the sustainability performance of bio-based and recycled materials compared to conventional reinforcements and to identify the conditions under which these alternatives can offer tangible environmental benefits (La Rosa et al., 2014).

Several studies have highlighted that bio-based fibers such as hemp, bamboo, sisal, flax and jute offer significant environmental advantages over conventional plastics and mineral reinforcement fibers (Madhu et al., 2022; Maiti et al., 2022; Santos et al., 2022; Kozlowski and Muzyczek, 2023). Furthermore, bio-based fibers are biodegradable, which reduces the long-term impact on landfills and limits waste (Okolie et al., 2023). By offering a renewable and less resource-intensive alternative, bio-based materials represent an important path toward reducing the environmental impact of construction (Suttie et al., 2017; Yadav and Agarwal, 2021). In addition to sustainability considerations, bio-based fibers have also demonstrated promising mechanical performance (Shelly et al., 2025). For these reasons, integrating bio-based reinforcement fibers into the construction sector is essential. Furthermore, recycled bamboo and hemp fibers are particularly relevant. On the one hand, mechanical recycled bamboo fibers (density: 0.6–1.1 g/cm^3, Young's modulus 0.4–42 GPa, tensile strength 39–775 MPa) are sustainable reinforcements that enhance flexural strength but exhibit variability due to their natural heterogeneity (Osorio et al., 2011; Rassiah et al., 2013; Tran et al., 2013; Mousavi et al., 2022). On the other hand, recycled hemp fibers (density 1.50 g/cm^3, Young's modulus 58 GPa, tensile strength 857 MPa) are eco-friendly alternatives with high mechanical performance, though their porosity and need for surface treatment influence durability and interfacial bonding in cementitious composites (Pickering et al., 2007; Ghosn et al., 2020; Zhang et al., 2022).

The analysis was conducted using Life Cycle Assessment (LCA), in accordance with ISO 14040:2006 and ISO 14044:2006 standards (ISO, 2006a,b). This approach allows for a systematic and rigorous evaluation of the environmental impacts associated with the life cycle of a product, service, or process (Ferronato et al., 2023; Baltrocchi et al., 2025a). This is achieved by evaluating the entire production process, from raw material extraction to use and final disposal (Romagnoli et al., 2024). LCA is an essential tool for supporting decision-making in sustainable design, with a focus on the circular economy (Shafique et al., 2022; Baltrocchi et al., 2025b).

Several studies in the literature have investigated the environmental impacts of alternative reinforcing fibers in the replacement of steel in reinforced concrete using the LCA approach. For instance, Akbar and Liew (2021) evaluated and compared several fiber-reinforced cementitious composites made of different materials in terms of mechanical performance, potential environmental impact, and cost. The research of Singh et al. (2022) explored the potential of waste incorporation in glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) by quantifying their environmental impacts. Again, Backes et al. (2023) conducted an environmental analysis of carbon-reinforced concrete (CRC) and steel-reinforced concrete (SRC); in term of climate change (CC), CRC double-wall ranges from 453 to 754 kg CO_2 eq per component, depending on concrete mix and fiber configuration. The study of Santos et al. (2022) evaluated the environmental performance of concrete composites reinforced with sisal fiber, reporting 6.32 and 5.89 kg CO_2 eq per m^2 for concrete composites with 2 and 0.4% fiber content, respectively. Furthermore, Sbahieh et al. (2023) evaluated the environmental impacts of GFRP- and CFRP-reinforced beam compared to traditional steel-reinforced beam, reporting a CC of 322 kg CO_2 eq for GFRP-reinforced beam, 401 kg CO_2 eq for CFRP-reinforced beam, and 417 kg CO_2 eq for steel-reinforced beam. Finally, Ghali et al. (2023) investigated the environmental performance of a reinforced concrete beam containing different types of fibers; the GW values ranging from 373 kg CO_2 eq (polypropylene) to 392 kg CO_2 eq (glass), with intermediate values of 384 kg CO_2 eq (basalt) and 382 kg CO_2 eq (steel).

This study aims to evaluate and compare the environmental impacts of a reinforced concrete beam designed with traditional steel reinforcement and with the introduction of two recycled bio-based fibers, hemp and bamboo, at different replacement rates in substitution of the steel. This in order to understand the environmental benefits resulting from the introduction of the more sustainable bio-based materials. The research aims to answer three main questions: (i) what is the contribution of materials to the environmental impacts of a reinforced concrete beam? (ii) What are the environmental impacts of the recycling process of bio-based reinforcement fibers? (iii) What are the benefits derived from the replacement of steel reinforcement with bio-based mechanical recycled fibers in different rates for a reinforced concrete beam?

Abbreviations: CC, Climate change; CFRP, Carbon fiber reinforced polymer; EoL, End-of-life; FC, Freshwater ecotoxicity; FE, Freshwater eutrophication; FR, Fossil resources scarcity; FU, Functional unit; GFRP, Glass fiber reinforced polymer; GHG, Greenhouse gas; GW, Global warming potential; HC, Human carcinogenic toxicity; HN, Human non-carcinogenic toxicity; IR, Ionizing radiation; LCA, Life cycle assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment method; LU, Land use; MC, Marine ecotoxicity; ME, Marine eutrophication; OD, Stratospheric ozone depletion; OF, Ozone formation; PM, Fine particulate matter formation; rBF, Recycled bamboo fiber; rHF, Recycled hemp fiber; SB, System boundaries; S0, Scenario 0; S1, Scenario 1; s2, Scenario 2; s3, Scenario 3; TA, Terrestrial acidification; TE, Terrestrial ecotoxicity; WC, Water consumption.

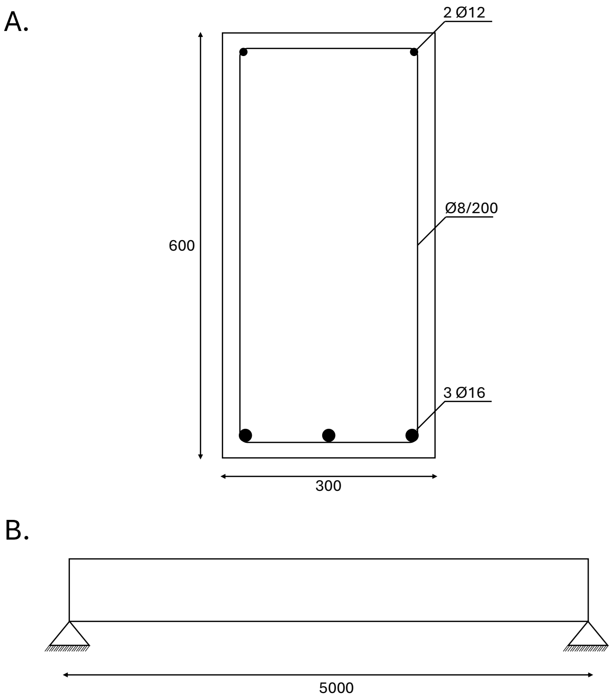

FIGURE 1
Reinforced concrete beam features: **(A)** cross section and **(B)** longitudinal view. The dimensions are reported in millimeters.

Despite growing interest in sustainable building materials, the current scientific literature presents several gaps in studies evaluating the benefits of replacing conventional steel reinforcement with recycled bio-based fibers. Existing studies have primarily focused on virgin, non-bio-based fibers, often overlooking the potential of natural fibers in structural concrete applications. Furthermore, few studies evaluate the environmental benefits of using recycled material. This study differs by quantifying LCA at structural scale rather than material scale. This research critically examines the replacement of steel reinforcement with two recycled bio-based fibers, hemp and bamboo, in reinforced concrete beams to address these gaps. This research provides new insights into the environmental performance of these replacements, thus contributing to a more comprehensive understanding of cement composites reinforced with recycled bio-based fibers in structural contexts.

2 Materials and methods

2.1 Reinforced concrete beam

A precast reinforced concrete beam was designed in accordance with Eurocode 2 (European Committee for Standardization, 2004) and adopted as a representative structural element for industrial applications to assess material requirements and sustainability implications. The beam was assumed to be simply supported, with a span length of 5.0 m and a rectangular cross-section of 0.30 × 0.60 m, corresponding to a concrete volume of ∼0.90 m^3 (Figure 1A). The concrete was specified as strength class C30/37 (CEM II 42.5R), while reinforcement was assumed to be steel B450C. Reinforcement detailing followed standard industrial practice, with three Ø16 bars at the bottom and two Ø12 bars at the top. Shear reinforcement was provided by Ø8 stirrups at a 20 cm spacing, reduced to 10 cm in the support regions (Figure 1B). The total amount of steel reinforcement required for one beam was estimated to be ∼35.1 kg in the form of rebars. Table 1 reports the quantities for (i) 1 m^3 of concrete and for (ii) the whole beam.

TABLE 1 Materials quantities per 1 m^3 of concrete and for the whole beam.

Material	Amount per 1 m^3	Amount for beam (0.9 m^3)
Cement	350 kg	315 kg
Water	175 L	158 L
Sand	700 kg	630 kg
Gravel	1,100 kg	990 kg
Superplasticizer	5 kg	4.5 kg
Steel reinforcement	39 kg	35.1 kg

2.2 Goal and scope

The goal of this study is to compare the environmental impacts of a reinforced concrete beam designed with traditional steel reinforcement and with the introduction of recycled bio-based fiber reinforcement at different replacement rates in substitution of the steel. The scope of the analysis is to understand the environmental benefits resulting from the introduction of the bio-based materials, excluding the evaluation of the mechanical performance of the replacement materials. The analysis wants to answer three questions:

(i) What is the contribution of materials to the environmental impacts of a reinforced concrete beam?
(ii) What are the environmental impacts of the recycling process of bio-based reinforcement fibers?
(iii) What are the benefits derived from the replacement of steel reinforcement with bio-based mechanical recycled fibers in different rates in a reinforced concrete beam?

The analysis was performed using Simapro v9.6 software (Goedkoop et al., 2016) and Ecoinvent v3.10 database (Wernet et al., 2016). SimaPro software was chosen for its consistency, functional graphical interface, and effective uncertainty analysis, while Ecoinvent database is recognized as the world's largest database of Life Cycle Inventory (LCI) for unit processes. ReCiPe 2016 v1.09 midpoint, Hierarchist perspective was used as the Life Cycle Impact Assessment (LCIA) method. This method provides a state-of-the-art method for converting inventory data into environmental impact scores at the midpoint and endpoint levels (Goedkoop et al., 2009).

TABLE 2 Challenges, features, and applications in cement composites of bamboo and hemp fibers.

Fiber	Use in cement composites	Properties of fibers	Main challenges	Ref.
Bamboo	• Mainly used in polymer composites. • Potential replacement for glass/synthetic fibers. • Sustainable natural reinforcement.	• High strength. • Good stiffness • Favorable strength-to-weight performance.	• Variable fiber length and quality. • Moisture sensitivity • Poor interfacial adhesion.	Liu et al., 2012; Muhammad et al., 2019
Hemp	• Bio-concrete. • Thermal insulation. • Sustainable construction.	• Low density, high specific stiffness and strength. • Less abrasive to processing equipment than synthetic fibers. • Recyclable via chemical dissolution and fiber regeneration.	• Lower strength compared to synthetic fibers. • High moisture absorption. • Flammable, sensitive to UV, microbial, and fungal degradation.	Manaia et al., 2019; Rissanen et al., 2023

The Functional Units (FUs) are (i) 1 m^3 of reinforced concrete, (ii) 1 kg of recycled fiber, (iii) the whole beam, consisting of 0.9 m^3. The System Boundaries (SB) follow the cradle-to-gate approach and include raw material production, transportation, mechanical recycling process, and beam production. The geographical boundaries are the United Kingdom, and in particular, most of the products are supplied from Europe, wherever possible.

This research used data from (i) literature and (ii) Ecoinvent database. Regarding the fibers, the virgin hemp data are based on Akbarian-Saravi et al. (2025), while the mechanical recycled hemp dataset was described by González-García et al. (2010). The virgin bamboo data were taken from Gan et al. (2022), with the mechanically recycled bamboo data from the research of Gu et al. (2018). Table 2 reports the use of recycled fibers in cement composites, the features of these fibers, and the main challenges associated with bio-based fibers. Furthermore, according to Ecoinvent database process *"Building, multi-story {RER}| building construction, multi-story | Cut-off, U"*, an average electricity consumption of 4.26 kWh/m^3 was considered for the concrete mixing (Wernet et al., 2016). The complete database is available in Supplementary Table S1.

2.3 Bio-based recycled, reinforced fibers

Recycled bamboo fiber (rBF) and recycled hemp fiber (rHF) were considered. This study aims to conduct an LCA of the recycling process of hemp and bamboo fibers that have been previously discarded. In accordance with the defined scope of the analysis, the previous use phase of the fibers is excluded. The gate of the system is defined as the collection and sorting of materials that have already been designated as waste. The mechanical recycling of bio-based fibers that are considered in this analysis follows a standardized sequence of operations that is reported in Figure 2. Waste fibers are (1) first collected and sorted, followed by (2) washing and cleaning. The material is then subjected to mechanical size reduction through (3) shredding and milling, producing shorter fibers. These fractions are subsequently (4) separated and classified according to particle size before being (5) recompounded. In the final stage, the recycled fibers are reused in the (6) production of new materials (Gan et al., 2022; Akbarian-Saravi et al., 2025). Furthermore, the avoided impacts associated with the use of virgin hemp and bamboo fibers were also taken into consideration. In this context, avoided impacts refer to the potential environmental impacts that are prevented by substituting conventional materials with more sustainable alternatives, as quantified negative in LCA analysis. The main features of the recycled fibers are reported in Table 3.

2.4 Recycled bio-based fibers scenarios analysis

In order to assess the environmental impact of substituting conventional steel reinforcement in the form of rebars with bio-based mechanically recycled fibers, a mass replacement scenarios were developed. The modeling approach involved progressively replacing a defined proportion of the total steel reinforcement mass with equivalent masses of recycled hemp and bamboo fibers. Three substitution rates were simulated to evaluate the environmental benefits of introducing bio-based materials. Scenario 0 (S0) represents the baseline configuration, where all reinforcement is conventional steel in the form of rebars, and no bio-based fibers are used. In Scenarios 1 (S1), Scenario 2 (S2) and Scenario 3 (S3), a defined proportion of the total mass of steel reinforcement in the whole beam is substituted with an equivalent mass of mechanically recycled bio-based fibers (hemp or bamboo) at substitution rates of 10, 20 and 30% of the original steel mass, respectively. The substitution is performed on a mass basis: for a given beam, the mass of bio-based fiber added equals the targeted replacement fraction of steel reinforcement. The total material mass and all other component quantities for the beam are held constant and are equal to the values reported in Table 1; the exact replacement fractions used in each scenario are reported in Table 4. Note that the substitution is defined by mass, not by identical mechanical properties; any mechanical or structural performance differences between steel and the bio-based fibers are addressed separately.

3 Results

The results are structured to illustrate the rationale and effects of replacing steel reinforcement with recycled bio-based fibers. First, the environmental impacts of all materials in the beam are compared. Next, the environmental impacts of the recycled fibers and the resulting benefits of their use as substitutes for steel are presented. For paragraphs 3.2 and 3.3, the findings are discussed for six main indicators: Global warming potential (GW), Ozone formation (OF), Human carcinogenic

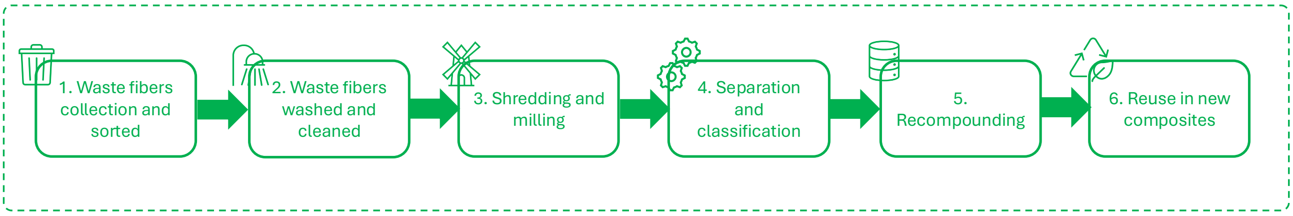

FIGURE 2
Bio-based fibers mechanical recycling process diagram.

TABLE 3 Main features of mechanical recycled bio-based fibers.

Fiber	Fiber length (mm)	Fiber diameter (μm)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Density (g/cm^3)	Ref.
Bamboo	—	90–583.8	0.4–42	39–775	1.7–9.8	0.6–1.1	Osorio et al., 2011; Phong et al., 2011; Rassiah et al., 2013; Huang and Young, 2019; Mousavi et al., 2022
Hemp	20–40	19–38	58	857	—	1.50	Pickering et al., 2007; Ghosn et al., 2020; Zhang et al., 2022

TABLE 4 Replacement rates of steel reinforcement with bio-based mechanical recycled fibers for scenarios analysis for the reinforced concrete beam.

Scenario	Steel reinforcement, (kg)	Bio-based bamboo or hemp fiber, (kg)
Scenario 0 (S0)	100%, (35.1)	0%, (0.0)
Scenario 1 (S1)	90%, (31.6)	10%, (3.5)
Scenario 2 (S2)	80%, (28.1)	20%, (7.0)
Scenario 3 (S3)	70%, (24.6)	30%, (10.5)

toxicity (HC), Fossil resources scarcity (FR), Fine particulate matter formation (PM) and Water consumption (WC). All values for the other impact categories assessed are available in Supplementary Table S2, while the results for one whole beam are reported in Supplementary Table S3.

3.1 Environmental impacts of the beam materials

Figure 3 presents the distribution of environmental impacts for the beam materials components across seventeen indicators, offering insights into which materials are responsible for the highest loads. Presenting the results obtained for the beam composed of conventional materials allows for a deeper understanding and justifies the need to modify the material composition of the reinforcing bars. In fact, steel and concrete emerge as the most influential, accounting for the majority of the impacts. Steel demonstrates a predominant role in several impact categories, reflecting its intensive manufacturing processes. Specifically, it accounts for the majority of Freshwater eutrophication (FE) (54% of the total), Marine eutrophication (ME) (76%), Terrestrial ecotoxicity (TE) (98%), Freshwater ecotoxicity (FC) (93%), Marine ecotoxicity (MC) (98%), Human carcinogenic toxicity (HC) (89%), and Mineral resource scarcity (MR) (67%). These results highlight the significant environmental pressures associated with the use of steel. In addition to being the primary impact factor, steel often ranks second in several categories. It ranks second in terms of Global warming potential (GW) (21%), Stratospheric ozone depletion (OD) (39%), Ionizing radiation (IR) (20%), Ozone formation (OF) (24%), Fine particulate matter formation (PM) (44%), Terrestrial acidification (TA) (33%), Human non-carcinogenic toxicity (HN) (18%), Land use (LU) (21%), and Fossil resource scarcity (FR) (39%). Consequently, steel emerges as one of the two materials with the most significant impact in sixteen out of seventeen indicators, underscoring its dominant role. Cement also plays an important role in the beam's environmental impacts. It has the highest contribution in terms of GW (75%), OD (46%), IR (61%), OF (67%), PM (50%), TA (61%), and FR (50%). These results reinforce the importance of cement as the primary factor contributing to environmental impact. In addition to these primary contributions, cement also ranks second in several indicators. For example, it follows steel in FE (42%), ME (18%), TE (1%), FC (5%), MC (1%), HC (8%), and MR (33%). This consistency across categories underscores the broad environmental relevance of cement as a construction material. Other materials, although less dominant, play a role in specific categories. Gravel is particularly relevant for LU (32%) and Water consumption (WC) (37%), while superplasticiser has a substantial influence on HN (63%). These results demonstrate that, although steel and concrete are the dominant materials, complementary materials can also make significant contributions to specific impact categories.

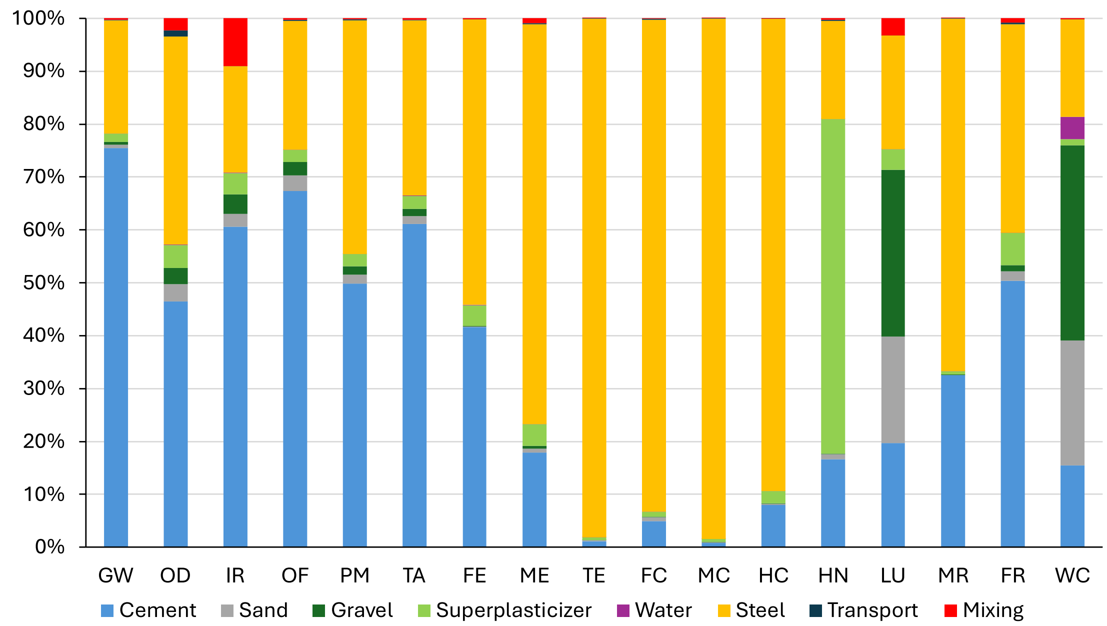

FIGURE 3
Environmental impacts contribution of the beam materials.

3.2 Environmental performance of recycled bio-based fibers

Figure 4 presents the environmental impacts associated with recycling bio-based fibers, comparing bamboo (rBF) and hemp (rHF). Regarding Global warming potential (GW) (Figure 4A), rBF generates 0.066 kg of CO_2 eq per kg, while rHF generates 0.042 kg of CO_2 eq. This represents a 36% reduction compared to hemp, indicating its lower climate impact. Ozone formation (OF) (Figure 4B) is another important category, as it reflects precursor emissions that contribute to air quality degradation. In this case, rBF emits 2.34E-04 kg of NO_X eq, 36% more than rHF, which emits 1.50E-04 kg of NO_X eq. These results further highlight the environmental benefits of rHF in recycling. Human carcinogenic toxicity (HC) indicator (Figure 4C) reflects the potential harm to human health resulting from emissions. In this case, the difference between the two fibers is smaller. rBF produces 7.00E-04 kg 1,4-DCB eq, or only 2% more than rHF, which produces 6.88E-04 kg 1,4-DCB eq. This suggests that the toxicity impacts are comparable for both recycling processes. This is mainly due to the use of energy-intensive processes and the limited use of chemical agents. Fossil resources scarcity (FR) (Figure 4D) is a key measure of non-renewable energy demand. The results show a clear difference between the two fibers, with rBF emitting 2.36E-02 kg oil eq compared to 1.51E-02 kg oil eq for rHF. This corresponds to a 36% increase for bamboo recycling. Fine particulate matter formation (PM) (Figure 4E) represents emissions that contribute to air pollution and respiratory health risks. The reported values are 3.17E-05 kg $PM_{2.5}$ eq for rBF and 2.03E-05 kg $PM_{2.5}$ eq for rHF. This once again confirms a 36% greater impact for bamboo compared to hemp recycling. Finally, Water consumption (WC) (Figure 4F) provides information on resource efficiency in recycling. rBF requires 3.33E-04 m^3, while rHF consumes 2.13E-04 m^3, a 36% increase for bamboo. Overall, across all indicators, rBF shows systematically greater impacts, on average 36% higher, primarily due to its more energy-intensive recycling process and longer transport distances.

3.3 Environmental benefits of steel replacement scenarios

Figure 5 shows the comparison of the environmental impact categories for the four modeled scenarios: Scenario 0 (S0), the reference case with 0% steel replacement, and Scenario 1 (S1), Scenario 2 (S2), and Scenario 3 (S3), which correspond to progressive mass-based substitutions of conventional steel reinforcement with mechanically recycled hemp (rHF) and bamboo (rBF) fibers at rates of 10, 20, and 30%, respectively, for the reinforced concrete beam. Global warming potential (GW) indicator (Figure 5A) quantifies GHG emissions and is essential to assess the impact of CC. In the reference scenario (S0_SF), emissions reach 362 kg CO_2 eq. However, progressive substitution with rHF or rBF reduces this impact, reaching the maximum benefit of 14% in S3_rBF (312 kg CO_2 eq). Similarly, Ozone formation (OF) (Figure 5B), measured in NO_X equivalents and related to smog-related health risks, also shows a decrease. Values decrease from 0.6 kg NO_X eq in S0_SF to 0.4 kg NO_X eq in S3_rBF, equivalent to a 33% reduction. This confirms that recycled fibers not only reduce climate impact but also improve air quality. Human carcinogenic toxicity (HC) (Figure 5C)

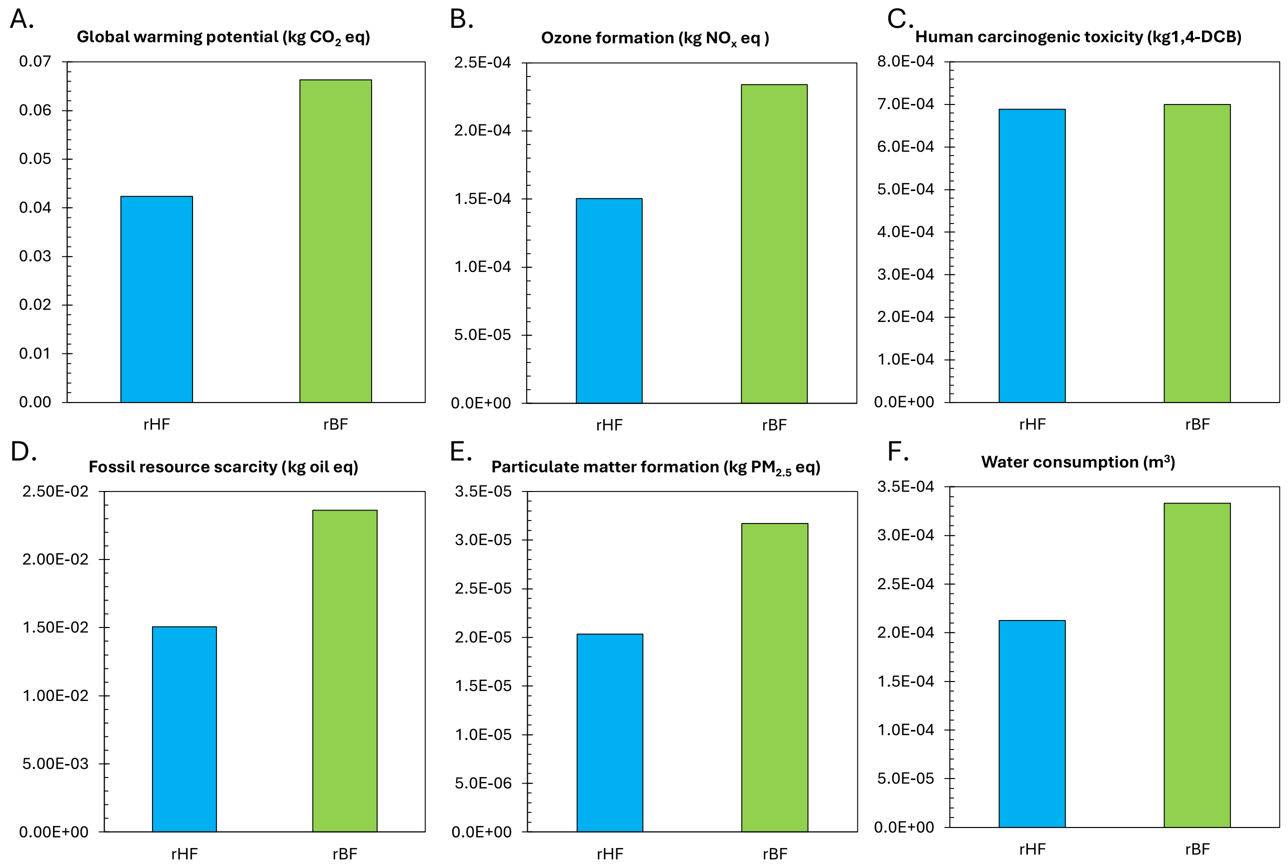

FIGURE 4
Environmental impacts for 1 kg of recycled hemp fiber (rHF) and recycled bamboo fiber (rBF): **(A)** Global warming potential (kg CO_2 eq), **(B)** Ozone formation (kg NO_x eq), **(C)** Human carcinogenic toxicity (kg 1,4-DCB eq), **(D)** Fossil resource scarcity (kg oil eq), **(E)** Fine particulate matter formation (kg $PM_{2.5}$ eq), and **(F)** Water consumption (m^3).

further highlights the benefits of substitution. While the reference scenario (S0) records 1.6 kg of 1,4-DCB, substitution with rHF reduces this value by 27% in S3_rHF (1.1 kg of 1,4-DCB). Even greater benefits are achieved with rBF, which achieves a 62% reduction in S3_rBF (0.6 kg of 1,4-DCB), indicating more significant mitigation effects on human health. A similar trend is observed for Fossil resources scarcity (FR) impact category (Figure 5D), which shows the use of non-renewable resources. The reference scenario (S0) (43 kg oil eq) steadily decreases at all substitution levels, with S3_rBF reaching 33 kg oil eq (-23%). Therefore, fiber recycling not only reduces emissions and toxicity but also reduces pressure on fossil resources. Fine particulate matter formation (PM) indicator (Figure 5E) reinforces this positive trend. The results show a decrease from 0.23 kg $PM_{2.5}$ eq in S0_SF to 0.15 kg $PM_{2.5}$ eq in S3_rBF, corresponding to a 37% reduction. This result highlights the potential of recycled fibers to mitigate respiratory health risks associated with air pollution. Finally, Water consumption (WC) (Figure 5F) also decreases with substitution, highlighting an increase in resource efficiency. While S0_SF records 3.8 m^3, substitution with rHF and rBF reduces the impact, reaching 3.5 m^3 in S3_rHF (-24%). Together with the other impact categories, these results confirm that recycled fibers offer substantial reductions in WC. On balance, across all six indicators, replacing steel reinforcement with rHF and rBF results in consistent environmental improvements. rBF offers the most obvious benefits, also thanks to the reduced impact of the more energy-intensive bamboo fiber production process. These results demonstrate that recycled fiber reinforcement significantly improves the environmental performance of reinforced concrete beams, while also reducing pressure on the climate, health, and natural resources. All values for the other impact categories assessed are available in Supplementary Table S2, while the results for one whole beam are reported in Supplementary Table S3.

4 Discussion

4.1 Consideration about the results

The results of this study confirm that steel and concrete are primarily responsible for most environmental impact categories, according to the studies of Sbahieh et al. (2023) and Backes et al. (2022). However, the introduction of recycled bio-based fibers shows clear environmental benefits across several indicators. In particular, the reduction in GW (up to −14% with rBF) and FR indicator demonstrates the potential of the bio-based fibers to

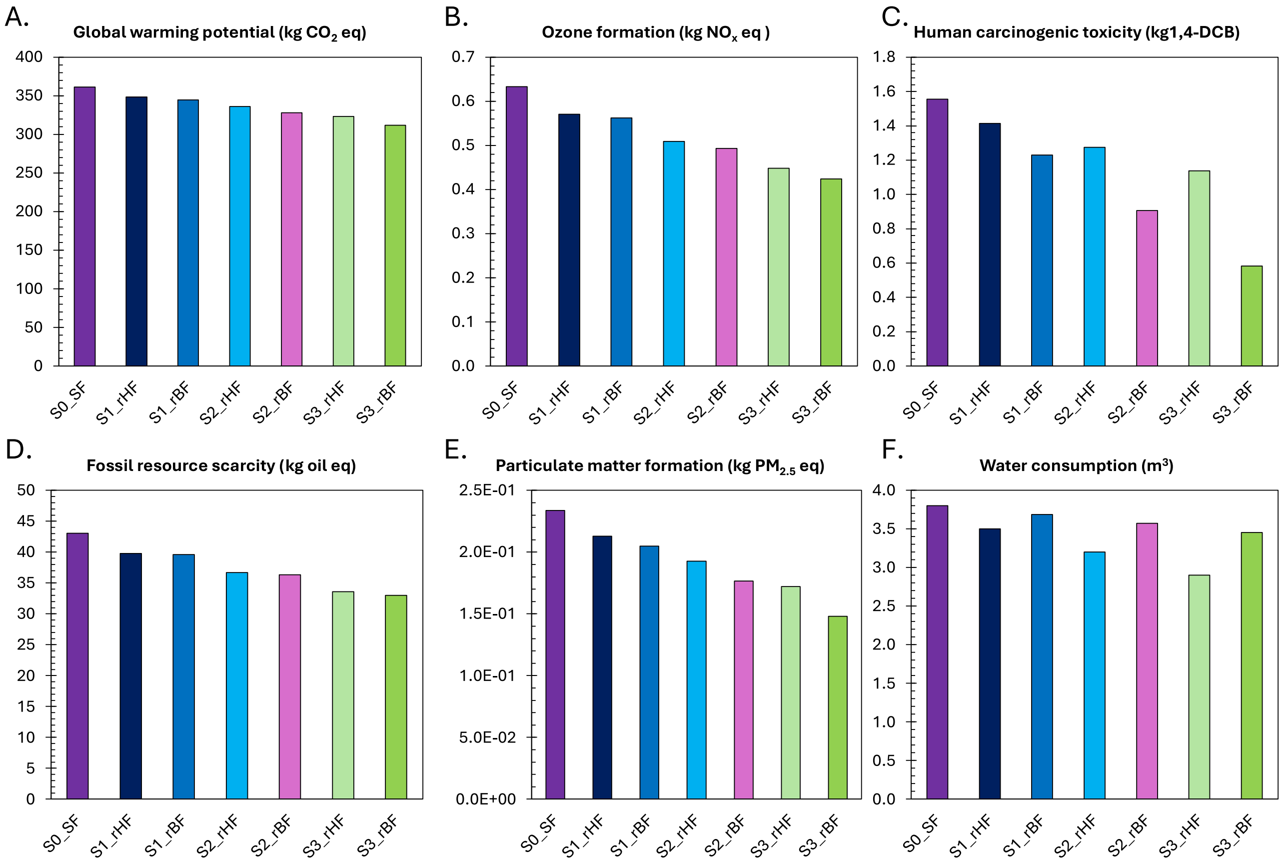

FIGURE 5
Environmental impacts of the reinforced concrete beam for Scenario 0 (S0), Scenario 1 (S1), Scenario 2 (S2), and Scenario 3 (S3): **(A)** Global warming potential (kg CO_2 eq), **(B)** Ozone formation (kg NO_x eq), **(C)** Human carcinogenic toxicity (kg 1,4-DCB eq), **(D)** Fossil resource scarcity (kg oil eq), **(E)** Fine particulate matter formation (kg $PM_{2.5}$ eq), and **(F)** Water consumption (m^3).

mitigate some of the indicators most affected by the construction sector. Furthermore, the reduction in HC (up to −62% with rBF) highlights benefits not only for climate mitigation but also for human health. Interestingly, the impacts of rHF and rBF differ across the impact categories. rHF shows particularly favorable results for LU indicator, in some cases even showing negative values due to the avoided impacts. This suggests that growing and recycling hemp could contribute to the restoration of ecosystem services, provided that agricultural practices remain sustainable. In contrast, rBF significantly increases the impact on LU.

Comparison with other studies reinforces these insights. For instance, the study of Ghali et al. (2023) reported that the GW values for 1 m^3 of concrete with 0.25% fibers ranging from 373 kg CO_2 eq (polypropylene) to 392 kg CO_2 eq (glass), 384 kg CO_2 eq (basalt), and 382 kg CO_2 eq (steel), highlighting the relatively small variations among conventional fibers. The research of Backes et al. (2023) indicated CC of 453–754 kg CO_2 eq for CRC double walls and 611–1,239 kg CO_2 eq for SRC double wall. Furthermore, Santos et al. (2022) showed promising results for natural fibers, with 6.32 kg CO_2 eq per m^2 of concrete composite containing 2% of sisal fiber and 5.89 kg CO_2 eq per m^2 of concrete composite containing 0.4% of sisal fiber. Finally, Sbahieh et al. (2023) reported a CC equal to 322 kg CO_2 eq for GFRP-reinforced beam, 401 kg CO_2 eq for CFRP-reinforced beam and 417 kg CO_2 eq for steel-reinforced beam. On balance, these results suggest that, although conventional fibers exhibit limited variations in environmental impacts, bio-based and recycled alternatives, particularly rBF, rHF, and sisal, offer significant opportunities to mitigate environmental impacts in the construction sector.

4.2 Limitations of the study

The limitations of this study are mainly due to the use of the LCA methodology. First, the analysis was based on literature data rather than primary data. Future research should therefore prioritize primary data collection to improve its representativeness and accuracy. It would be desirable for this data collection to be carried out in synergy with companies and research centers operating in the construction sector. Second, this work represents a preliminary assessment that requires experimental validation through laboratory tests, particularly to confirm the mechanical performance and durability of composites reinforced with bio-based fibers. Partial or total replacement of steel with recycled bio-based fibers is often not technically feasible due to the reduction in mechanical strength (Shelly et al., 2025); future research should therefore focus on identifying optimal fiber contents that improve composite performance without compromising structural reliability. Furthermore, this study only considered environmental aspects. To provide a comprehensive sustainability assessment, future research should integrate economic (Life Cycle Costing) and social (Social Life Cycle Assessment) dimensions within a Life Cycle Thinking (LCT) framework, according to the study of Purvis et al. (2019).

4.3 Policy implications and future direction

In addition to methodological improvements, future directions for the construction sector should also focus on regulatory interventions by policymakers. This includes investments in research on innovative and sustainable materials and pilot projects that demonstrate the structural reliability and long-term performance of recycled bio-based fibers. For sectoral actors such as designers, contractors, and material suppliers, these results underscore the need to align design strategies, construction practices, and material choices with evolving policy agendas that promote sustainability, resilience, and circularity throughout the built environment. Regulatory frameworks should be updated to integrate recycled natural fibers into building codes and certification systems, ensuring their safe and widespread application. Furthermore, fostering collaboration between university and industry could create knowledge-sharing platforms that reduce uncertainty and amplify practical solutions. By combining technological innovation with supportive policy frameworks, the construction sector can move toward a more resource-efficient future.

5 Conclusions

This research aims to evaluate the environmental benefits of replacing traditional reinforcing steel with rHF and rBF at different replacement rates using LCA methodology. The results demonstrate that even low replacement rates can lead to significant reductions in environmental impact, particularly in terms of GW, FR, and HC. In the most favorable scenario, a 30% replacement with rBF resulted in a 14% reduction in GW emissions, passing from 362 kg CO_2 eq to 312 kg CO_2 eq, while rHF showed additional benefits in terms of LU indicator. However, the results also highlight increased impacts, particularly regarding LU for rBF, where a significant increase in impacts was observed. On balance, the study demonstrates that incorporating recycled bio-based fibers into building materials can improve circularity and contribute to the sustainability of the sector. Future work should include experimental validation of the mechanical performance of fiber-reinforced concrete and extend the analysis to encompass economic and social dimensions, providing a more comprehensive sustainability assessment. Future progress in the construction sector will depend on the integration of regulatory support, technological innovation, and cross-sector collaboration to promote the safe and widespread adoption of recycled and bio-based materials. Aligning industry practices with sustainability policies can facilitate the transition toward a more resilient and resource-efficient built environment. This study offers new insights into the environmental performance of recycled bio-based fibers by evaluating different replacement rates of steel through the LCA, highlighting their potential to enhance the sustainability of cement composites in structural applications.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

AB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. MS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2025.1716779/full#supplementary-material

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