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Environmental assessment of a spinning process for the production of ring-spun hybrid yarns from recycled carbon fiber: A cradle-to-gate approach

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ABSTRACT

The study of sustainable remanufacturing processes using recycled carbon fiber to enhance its applicability in high-performance materials is a key research direction. To this end, their environmental performance should be assessed. Here, an attributional life cycle assessment combined with environmental life cycle costing is performed for an innovative spinning process recently developed for the production of ring-spun hybrid yarns suitable for manufacturing reinforcements for good-quality polymer composites. Results indicate that the process cumulatively affects approximately 65.4% of the total environmental impact regarding climate change, use of fossils, and use of minerals and metals. The preparing and carding phase predominantly contributes to nearly all environmental impact categories. Greenhouse gas emissions from the process were quantified as 10.5 kg-CO_2 eq/kg, significantly below those produced by virgin carbon fiber manufacturing (24-31 kg-CO_2 eq/kg). Overall, considering the potential landfilling or incineration of waste used as input, the process brings environmental benefits ranging from 56% to 76%. A sensitivity analysis indicates that replacing manufacturing scraps with recycled carbon fiber from pyrolysis represents the input change with the highest environmental impacts, while thermoplastic fiber use does not significantly alter environmental performance. The study demonstrates that using recycled carbon fiber from manufacturing scraps is preferable to using recycled carbon fiber from pyrolysis when life-cycle impact is considered. The choice between polyamide and polyester should rely on the specific impact category to be addressed and the desired mechanical properties to be achieved in the final composite.

1. Introduction

Carbon fiber-reinforced plastic (CFRP) composites consist of two distinct phases: an oriented reinforcement composed of carbon fibers (CFs) and a polymer matrix. These materials are gaining momentum in industrial applications concerning, among others, transportation (i.e., automotive and aircraft), construction, and luxury sport equipment owing to their strength, durability, corrosion resistance, and low weight (Gouveia et al., 2022; Hadigheh et al., 2021; Hermansson et al., 2019; Li et al., 2023; Liu et al., 2017). The yearly worldwide manufacture of CFRPs is estimated to be approximately 65,000 tons, and the demand for CF is expected to rise 2.5-fold to reach 161,000 tons by 2025 (Nistratov et al., 2022). As a result, the amount of both pre- and post-consumer waste generated from these materials has also significantly increased (Gouveia et al., 2022; Hadigheh et al., 2021). It is anticipated that the volume of this waste will grow to 20 kt per year by 2025 (Rademacker, 2018). Despite the attention now paid to sustainability, landfilling and incineration continue to be the most commonly used options for managing CFRP waste, as it is usually difficult to recycle due to its heterogeneous nature (Krauklis et al., 2021). These behaviors have negative long-term impacts on the environment (Pakdel et al., 2020).

Various methods, which can be classified into four groups (Longana et al., 2021), are available to manage such waste. (i) Primary recycling encompasses methods directly reusing waste with limited or no processing. This is generally the case with pre-consumer waste. (ii) Secondary recycling involves at least one process for reclaiming the fibers. In this case, the remanufactured product usually has properties similar to those of the virgin material. (iii) Tertiary recycling refers to methods that involve thermal or chemical degradation of the matrix to recover

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Nomenclature

CE	Circular economy
CF	Carbon fiber
CFs	Carbon fibers
CFRP	Carbon fiber-reinforced plastic
CFRPs	Carbon fiber-reinforced plastics
CV	Coefficient of variation
eLCC	Environmental life cycle costing
ELU	Environmental load unit
EPS	Environmental priority strategy
GHG	Greenhouse gas
ISP4rCF	Innovative spinning process for recycled carbon fiber
LCA	Life cycle assessment
rCF	Recycled carbon fiber
rCFs	Recycled carbon fibers
SD	Standard deviation
SEM	Standard error of mean
vCF	Virgin carbon fiber

the fiber. (iv) Quaternary recycling comprises methods for recovering energy from matrix decomposition, such as incineration or disposal in landfills. Unfortunately, these reclaiming technologies enable the recovery of recycled CF (rCF) in "fluffy" form (Longana et al., 2021). Thus, the final products obtained using rCF usually have low mechanical properties since they are characterized by random fiber orientation, production damage, and limited fiber amount (Abdkader et al., 2022; Hengstermann et al., 2016). To improve the properties of recycled CFRPs, increasing fiber alignment and volume fraction is necessary (Longana et al., 2016, 2021; Tapper et al., 2020). This has spurred research and development of remanufacturing processes (Colombo et al., 2022; Hadigheh et al., 2021; Longana et al., 2021; Pakdel et al., 2020). More generally, interest in recycling CF scraps and reusing them for the production of high-value application products has been steadily increasing, with the volume of high-value waste sent to landfills diminishing (Diaz et al., 2021). This interest has gained momentum, partly propelled by regulations such as 2000/53/EC and heightened consciousness regarding the need to prolong the utility of these fibers within the circular economy (CE) framework (Girtan et al., 2021; Pakdel et al., 2021). Fresh insights into new remanufacturing technologies can bolster the contribution of rCF to novel value-added applications (Longana et al., 2021).

According to recent literature, when selecting a new technology, it is fundamental to consider both engineering performance and environmental aspects. Hence, to align with CE principles, appropriate methodologies such as life cycle assessment (LCA) should be adopted to assess the environmental performance of the developed processes (Velenturf and Purnell, 2021). The environmental evaluation of remanufacturing technologies for composites has often been overlooked due to a lack of accurate data (Longana et al., 2021). Nevertheless, preliminary analysis using data from laboratory-scale processes can be conducted to validate and optimize their sustainability at the industrial level as well as to direct policy initiatives (Adelfio et al., 2023).

Based on the above, this paper assesses the environmental performance of a technically feasible CF remanufacturing process. It thus addresses two research questions:

RQ1: What is the environmental performance of ISP4rCF?
RQ2: How does the environmental performance of the process change as the inputs vary?

To answer these questions and bridge the existing gap, we performed an attributional LCA combined with an environmental life-cycle costing (eLCC), using a cradle-to-gate approach, of a CF remanufacturing technology known as ISP4rCF. This process was recently proposed for the production of ring-spun hybrid yarns from rCF (Colombo et al., 2023a). First, we conducted an LCA analysis of a ring-spun hybrid yarn composed of 70% rCF and 30% polyamide with a number of draw frame doubling equal to 5, as, according to Colombo et al. (2023b), this is the blending ratio allowing for the production of unidirectional thermosetting CFRPs with the best mechanical properties (i.e., tensile strength and Young's modulus). Then, to increase the robustness of the results and address RQ2, we conducted a sensitivity analysis. Finally, to provide a monetary value of the impacts analyzed in the LCA, we implemented an eLCC considering the same functional unit, system boundaries, and assumptions. In summary, the key contribution of this study is its investigation of the actual environmental benefits of a laboratory-scale remanufacturing process (the ISP4rCF) to foster CE in the composite materials industry.

The remainder of the paper is organized as follows. Section 2 reviews what has been done so far at a technical level and in terms of LCA analysis for the development of spinning processes for handling rCF and highlights the novelty and contribution of this work. The methods and tools adopted throughout the study for the environmental assessment are presented in Section 3. The results and their discussion are thoroughly reported in Section 4. Section 5 concludes the paper.

2. Literature review

2.1. The importance of the spinning process

Over recent years, researchers have focused on the spinning process as a way to improve the mechanical properties of CFRPs produced with rCF. This is because yarns, which are generated through spinning, exhibit high fiber orientation, high volume content, and good compactness, making them suitable for the production of oriented reinforcements with rCF (Abdkader et al., 2022; Hasan et al., 2018). At present, hybrid yarns consisting of rCFs are predominantly manufactured using friction spinning technology (Hasan et al., 2018), roving frame (Hengstermann et al., 2016, 2017), and wrap spinning (Akonda et al., 2012; Goergen et al., 2020). However, recent work by Colombo et al. (2023a)Colombo et al. (2023) demonstrated at the laboratory level the significant potential of ring-spinning technology for producing good-quality hybrid yarns made up of rCFs from manufacturing scraps. The study revealed that a good balance between the CF residual quantity and tensile strength of the produced hybrid yarns can be achieved with a weight ratio ranging from 50% to 70% of rCFs. Additionally, irrespective of the type of virgin thermoplastic fiber used, the best mechanical and thermal properties were observed in ring-spun hybrid yarns composed of 70% rCF and a draw frame doubling number of 5. Due to their high fiber orientation and volume fraction, these yarns have the potential to be exploited for the production of CFRPs for structural components.

2.2. Life cycle assessment for CF reclaiming and remanufacturing technologies

LCA analysis is a valuable tool for analyzing sustainable production options (Buyle et al., 2013). It has been widely exploited for environmental assessment of the production of different types of composites, including concrete composites (e.g., Onyelowe et al., 2022a, 2022b) and thermosetting composites (e.g., Pillain et al., 2019; Vo Dong et al., 2018), using both virgin and waste raw material. The focus of this section is on the LCA of the latter type of composites, since in the current study the environmental assessment of ISP4rCF was conducted from an upcycling perspective. In fact, the process aims to produce ring-spun hybrid yarns with aligned rCF to be used as reinforcements for good-quality CFRPs.

LCA applications primarily investigate the environmental impact of CF reclaiming technologies, such as pyrolysis, fluidized bed, and solvolysis (Longana et al., 2021; Pakdel et al., 2020), through a comparative approach (He et al., 2020). This involves comparing two or more reclaiming technologies with each other or with landfill and incineration alternatives, which are still the most common treatment options for end-of-life CFRPs (Krauklis et al., 2021). For instance, Pillain et al. (2019) performed an LCA to compare end-of-life scenarios, such as disposal in landfill and incineration, with pyrolysis, supercritical solvolysis, and high-voltage fragmentation. They found that reclamation is environmentally advantageous as it avoids the production of virgin products, which is energy-intensive. Obviously, the quality of the fibers recovered from the reclaiming processes and the technology readiness level affect the outcomes. Gopalraj et al. (2021) studied the environmental impacts of a thermal recycling process previously developed to recycle and remanufacture CFRPs. Then, they compared the results with those obtained with traditional waste management routes such as landfill, incineration with energy recovery, etc. Overall, they found that thermal recycling technology has lower environmental impacts.

Vo Dong et al. (2018) compared end-of-life scenarios with reclaiming technologies, namely grinding, pyrolysis, microwave, and supercritical water, and discovered that landfilling is the cheapest option but has potentially significant global warming impacts. On the other hand, reclaiming technologies that enable the recovery of good-quality fibers greatly reduce global warming potential impacts, but they require higher capital investments. Li et al. (2016) conducted a life-cycle study of mechanical recycling for automotive waste compared to conventional treatments. Their findings highlighted that the benefits of reclamation depend on factors such as the displacement of vCF by rCF and the recycling rate, which help balance the energy-intensive reclaiming process. La Rosa et al. (2021), instead, assessed the environmental performance of leveraging solvolysis to recycle thermosetting CFRPs and then investigated the properties of the injection-molded composites produced using the rCF. They found that the recycling process avoids some impacts on the environment, especially compared to the landfill disposal scenario. Meng et al. (2017) evaluated the life-cycle environmental impacts of fluidized bed technology and the use of rCF for the production through compression molding or injection molding of composites suitable for automotive applications. Their findings proved the environmental feasibility of the CFRP recycled materials. In a subsequent study, Meng et al. (2018) analyzed the financial feasibility of both reclamation and remanufacturing of rCF. They discovered that, in comparison to virgin CF (vCF) composites and even to steel and aluminum, composite materials made of rCF, particularly aligned rCF composites, offer significant cost savings. More recently, Kawajiri and Kobayashi (2022) assessed the environmental impacts of two CFRP recycling techniques, namely pyrolysis and solvolysis. The outcomes proved that both reclaiming technologies can reduce environmental impacts compared with the production of vCF. Concurrently, they evaluated the tensile strength of the obtained rCF. In this respect, He et al. (2020) found that to increase both the quality of recycled CFRP and the energy efficiency of the cradle-to-gate stages, meticulous selection of the pre-processing steps and remanufacturing technology is necessary.

As is evident from the above studies, the environmental performance of developed remanufacturing technologies has generally been overlooked in the scientific literature. Among others technologies enabling the realignment of rCF, only the HiPerDif technology first proposed at the University of Bristol (Yu et al., 2014) has been evaluated from an environmental viewpoint. Through their investigation, Fitzgerald et al. (2022) demonstrated that electrical energy consumption is responsible for most of the greenhouse gas (GHG) emissions of the process and that water consumption strongly impacts ecosystem quality damage. No comparisons with other remanufacturing or recovery technologies were proposed in their study. Overall, LCA analyses of CF remanufacturing technologies that take advantage of spinning technology, such as those by Akonda et al. (2014), Hasan et al. (2018), and Hengstermann et al. (2016), have been neglected in favor of studies focused on improving the technical performance of finished products.

2.3. Novelty and contribution

This study contributes to knowledge of the link between CE and composite materials. Overall, the main novelty lies in the fact that, to the best of the authors' knowledge, the study is the first application of the LCA method to evaluate a CF remanufacturing process leveraging a spinning technology. Additionally, we conducted a dominance analysis to determine the inputs and process stages with the most substantial environmental impacts. Further, a sensitivity analysis allowed us to understand how the environmental performance of the process at hand changes as inputs vary. Obviously, this article also makes a practical contribution. The clean and sustainable nature of ISP4rCF at the laboratory level is demonstrated. Notably, its use circumvents the energy-intensive process for manufacturing vCF. Once transposed to an industrial scale, ISP4rCF can be leveraged by companies to improve their sustainability. Finally, the obtained results are useful to policymakers. Regulators can incentivize the adoption of specific inputs to feed remanufacturing technologies and encourage the use of particular reclamation methods to align with sustainable development goals.

3. Material and methods

The LCA methodology (ISO 14040 series) is widely accepted as one of the most useful tools for quantitatively assessing the sustainability of technologies, critically discussing the choices to implement in eco-design, and evaluating the environmental performance of newly developed technologies and production processes (Hauschild et al., 2018). For these reasons, it was adopted to determine the environmental impacts of ISP4rCF, which has been identified as a promising technology for aligning rCF and potentially obtaining CFRPs for structural applications.

LCA can be conducted through two types of analyses: So-called attributional LCA is aimed at explaining the relevant inflows to and outflows from the life cycle, while its subsystems and consequential LCA are aimed at describing how the flows could vary in response to the decisions made (Finnveden and Potting, 2014). In the present study, an attributional LCA approach was used, where the life-cycle modeling assumes linear and stationary technology and environmental models, following the *ceteris paribus* assumption. Particularly, the modeling only considers what the system under consideration directly modifies (JRC, 2010).

The LCA process is divided into four stages according to ISO 14040 and ISO 14044: goal and scope definition, inventory analysis, impact assessment, and interpretation.

3.1. Goal and scope definition

By identifying material and energy consumption hotspots, emissions to the environment, and waste produced at each stage of the process, this LCA seeks to evaluate the environmental impacts connected with the proposed ISP4rCF for the manufacturing of ring-spun hybrid yarns. Additionally, a sensitivity analysis, which measures the variance in environmental outcomes as a result of changes in pertinent inputs, was conducted to assess the robustness of the findings.

The raw materials used were rCFs from manufacturing scraps. The choice fell on this type of input since it represents approximately 40% of all waste generated (Pakdel et al., 2021). Specifically, rCF from dry fabrics (unidirectional or weaving) that had been mechanically processed by the provider to untangle weft and warp threads or unidirectional wefts was utilized. The finished product was a ring-spun hybrid yarn composed of 70% rCF and 30% polyamide 6 with the number of draw frame doublings equal to 5. This ring-spun hybrid yarn was chosen because it allows for the production of unidirectional thermosetting CFRPs with the best mechanical properties in terms of tensile strength and Young's modulus (Colombo et al., 2023b). This base scenario is denoted as 'baseline.'

Fig. 1 illustrates the system boundaries of the study, which were

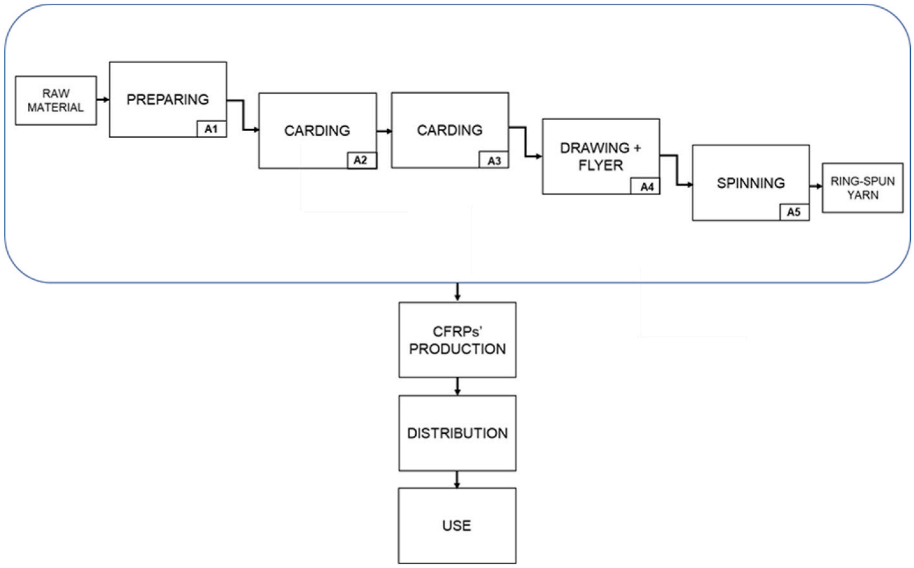

Fig. 1. System boundaries of the study.

defined using a cradle-to-gate approach. In other words, the study refers only to a specific phase in the life cycle of the ring-spun hybrid yarn. All processes—from the extraction of the raw materials to the production of the hybrid yarns—were considered, while the production, distribution, use, and disposal phases of CFRPs were excluded. Lastly, the functional unit was set to 25 g of material, equivalent to approximately 360 m of ring-spun hybrid yarns, which represents the amount of fibers actually used for their manufacturing at the laboratory level (Colombo et al., 2021, 2023a).

3.2. Life-cycle inventory analysis and key assumptions

The life-cycle inventory enables the quantification of flows into and out of the system boundaries; thus, it is recognized as the most crucial procedure for assessing life-cycle impact. These flows involve the use of resources, such as raw materials and energy, as well as releases into the air, water, and soil related to the system. In this step, a report listing the substances consumed and released into the environment and the amount of energy used was drawn up by mapping the production process following the IDEF0 methodology (Fig. 2). This methodology is a versatile modeling technique that accurately identifies the inputs, outputs, controls, and mechanisms of the process activities (Bevilacqua et al., 2015).

For this investigation, the raw materials necessary for the production of ring-spun hybrid yarns were rCFs and polyamide 6 fibers. Table 1 displays the main materials, resources, energy consumption, and waste produced in the process.

According to ISO 14040, primary data for the process, which includes all material and energy flows, were gathered in the laboratory facility. Secondary data were extrapolated from the international database Ecoinvent v.3.6 (Wernet et al., 2016), which is a thorough and reliable database encompassing consistent and transparent life-cycle inventory data and methods commonly used in LCA research (Frischknecht and Rebitzer, 2005; Scrucca et al., 2020; Siracusa et al., 2014) and in other areas (e.g., Khalil, 2017). These secondary data include information on the extraction of resources and the production of raw materials and energies within the geographical boundaries of Italy. In the Ecoinvent database, the 'market for' option was selected. For energy, the 'electricity mix/IT U' option was selected. According to the database, this mix comprises 67% energy from fossil fuels (i.e., hard coal, oil, and natural gas) and 18% from renewable sources (i.e., solar, wind, and hydro). Notably, Italy is energy dependent on neighboring countries, with about 14% of energy being imported. For this share, the electricity mix of the countries from which energy is imported, namely Austria, Switzerland, France, and Slovenia, was considered.

At this point, it is worth noting that the waste generated during the Preparing (A1) + Carding (A2), Carding (A3), and Spinning (A5) stages was considered to have no environmental impact and was not included in the LCA analysis. This is a reasonable assumption because the waste from the Preparing (A1) + Carding (A2) and Carding (A3) stages could potentially be used to make molded compounds instead of being disposed of in landfills. Moreover, such a choice is aligned with existing studies where pre-consumer waste available for reuse options was not considered in the analysis (e.g., Cook et al., 2022). On the other hand, the waste from Spinning (A5) consists of a very small amount of powder (about 0.04% of the entire material) that is scattered into the environment, and, as a result, it can reasonably be neglected. SimaPro[1] v. 9.3.0.3 was used to model the LCA study.

3.3. Life-cycle impact assessment

Several methods can be adopted to carry out a life-cycle impact assessment. In this study, the EF method 3.0 normalization and weighting set – impact assessment method of the Environmental Footprint initiative (Fazio et al., 2018) proposed by the European Commission was adopted. It comprises 16 main impact categories, namely climate change; ozone depletion; human toxicity cancer; human toxicity non-cancer; particulate matter disease incidence ionizing radiation; photochemical ozone formation; acidification; eutrophication terrestrial; eutrophication freshwater; eutrophication marine; ecotoxicity freshwater; land use; water use; resource use – minerals and metals; and resource use –fossils. In accordance with Famiglietti et al. (2021), it was decided to retain all the impact categories to preserve the information that the European Commission had defined.

3.4. Environmental life-cycle costing method

An eLCC, which is an LCA-based costing technique using the same functional unit, system boundaries, and scope (Hunkeler et al., 2008), was performed to provide a general idea of the monetary values associated with different impacts outlined in the LCA analysis. A steady-state

[1] https://simapro.com/.

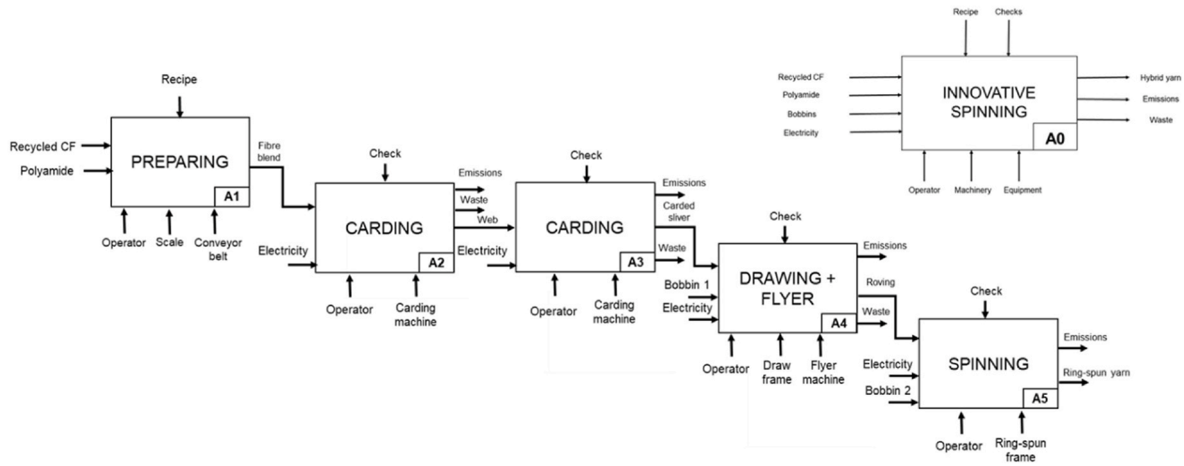

Fig. 2. IDEF0 of the innovative spinning process.

Table 1
Life cycle inventory data.

Phase	Flow	Quantity
Preparing (A1)	Recycled carbon fiber	17.5 g
	Polyamide	7.5 g
Carding (A2)	Electricity	0.15 kWh
	Waste fiber	1.8 g
Carding (A3)	Electricity	0.09 kWh
	Waste fiber	0.8 g
Drawing + Flyer (A4)	Electricity	0.06 kWh
	Waste fiber	0.5 g
Spinning (A5)	Electricity	0.18 kWh

modeling approach, which assumes that all technologies remain constant across time without taking any temporal factors into account, was used. The environmental product strategies (EPS) approach (Steen, 1999) was chosen to estimate the external costs of a good, a process, or a service in accordance with the willingness to pay to restore a degraded safeguard entity to a set reference point (Afrane and Ntiamoah, 2012). This monetary quantity is known as an environmental load unit (ELU), which is equal to one euro in cost.

For the effect evaluation, the EPS 2015 dx approach (Bengt, 2015) was applied. According to the described state of the environment in 2015, its outcomes are assessed based on the average OECD resident's willingness to pay to prevent environmental damage. The technique also evaluates the impacts of emissions and resource use that have a major negative influence on any of the following areas of protection: ecosystem services, access to water, biodiversity, building technology, human health, and abiotic resources.

4. Results and discussion

This section presents the dominance analysis used to quantify the potential environmental effects of the ISP4rCF. Furthermore, both a sensitivity analysis and an uncertainty analysis were performed to assess the impact of input data uncertainty on the results, as well as the robustness of our assumptions and modeling approaches (Andrianandraina et al., 2015).

4.1. Dominance analysis

Investigating the life-cycle stages and/or the inputs with the highest environmental impact was the main goal of the dominance analysis (Baumann and Tillman, 2004). The outcomes of characterization, normalization, and weighting for each impact category for ISP4rCF are reported in Table 2. Although the last two elements are optional for an LCA analysis, they are usually used to facilitate understanding of the results (Famiglietti et al., 2021).

Considering weighted impacts, we estimated that 65.4% of the overall environmental impact of the innovative spinning process was attributable to three impact categories: climate change, resource use – fossils, and resource use – minerals and metals. Each of the remaining categories accounts for less than 10% of the total impact. The categories of human toxicity, ecotoxicity freshwater, and climate change were further broken down into subcategories. Fossil, biogenic, and land use and land-use change contributions were classified into climate change

Table 2
Impact assessment findings for functional unit.

Impact category	Unit	Characterization	Unit	Normalization	Unit	Weighting	%
Climate change	kg CO_2 eq	2.64E-01	–	3.26E-05	µPt	6.86E+00	31.31%
Ozone depletion	kg CFC11 eq	2.57E-08	–	4.79E-07	µPt	3.02E-02	0.14%
Ionizing radiation	kBq U-235 eq	2.57E-02	–	6.09E-06	µPt	3.05E-01	1.39%
Photochemical ozone formation	kg NMVOC eq	6.39E-04	–	1.57E-05	µPt	7.52E-01	3.43%
Particulate matter	disease inc.	6.87E-09	–	1.15E-05	µPt	1.03E+00	4.72%
Human toxicity, non-cancer	CTUh	2.02E-09	–	8.81E-06	µPt	1.62E-01	0.74%
Human toxicity, cancer	CTUh	7.64E-11	–	4.52E-06	µPt	9.63E-02	0.44%
Acidification	mol H+ eq	1.19E-03	–	2.14E-05	µPt	1.32E+00	6.05%
Eutrophication, freshwater	kg P eq	4.96E-05	–	3.08E-05	µPt	8.64E-01	3.94%
Eutrophication, marine	kg N eq	1.99E-04	–	1.02E-05	µPt	3.01E-01	1.37%
Eutrophication, terrestrial	mol N eq	2.13E-03	–	1.20E-05	µPt	4.46E-01	2.04%
Ecotoxicity, freshwater	CTUe	2.36E+00	–	5.54E-05	µPt	1.06E+00	4.85%
Land use	Pt	9.24E-01	–	1.13E-06	µPt	8.95E-02	0.41%
Water use	m^3 depriv.	1.49E-01	–	1.30E-05	µPt	1.11E+00	5.05%
Resource use, fossils	MJ	3.69E+00	–	5.68E-05	µPt	4.72E+00	21.55%
Resource use, minerals and metals	kg Sb eq	2.32E-06	–	3.65E-05	µPt	2.76E+00	12.58%

categories. Organic, inorganic, and metal were classified into human toxicity non-cancer, human toxicity cancer, and ecotoxicity freshwater. The findings of our characterization for these impact subcategories are reported in Table 3. As the one most affected by the process, the climate change category needed to be further investigated. The use of fossil fuels is the main cause of high impacts on climate change. Considering the electricity mix used for the analysis, this outcome can be traced back to the fact that ISP4rCF as well as the energy-intensive process for vCF production are mostly fed using traditional energy sources. In any event, environmental performance on climate change is expected to significantly improve in coming years when Italy fully implements the Integrated National Energy and Climate Plan, aimed at curbing GHG emissions by 2030 through the promotion of renewable energy sources. Under this scenario, the carbon intensity of energy production is anticipated to reduce by 50% (Carvalho et al., 2022).

Overall, ISP4rCF generates 10.5 kg CO_2 eq/kg. This value is significantly below the GHG emissions from producing vCF which, according to the literature, vary between 24 and 31 kg CO_2 eq/kg (Kawajiri and Kobayashi, 2022; Tapper et al., 2020). Hence, the environmental benefit of leveraging ISP4rCF to produce yarn to substitute vCF for CFRPs destined for structural applications is between 56% and 66%. This clearly suggests the potentialities of ISP4rCF as a cleaner and more sustainable production process with the potential of fostering CE principles in CFRP industry. It is also worth noting that the actual environmental benefit of using ISP4rCF instead of using vCF is much higher considering that the manufacturing scraps used as input for ISP4rCF would likely have been incinerated or disposed of in landfills. This would have generated further GHG emissions in the order of 0.09–4.6 kg CO_2 eq/kg. Also considering these emissions, then, ISP4rCF allows for a reduction in emissions ranging between 56% and 76%.

At this point, an uncertainty analysis using the Monte Carlo method available in a specific calculation module included in the SimaPro v. 9.3.0.3 software was performed to assess how input variability affects final results. The Monte Carlo method considers each input parameter as a stochastic variable with a lognormal probability distribution, according to the Ecoinvent database. The number of executions was set at 1000 with a 95% confidence interval to obtain convergence for both mean and variance values (Raynolds et al., 1999). The characterization results are shown in Table 4. Overall, barring a few specific categories, the level of uncertainty is fairly low.

Fig. 3 displays the distribution graph derived from the uncertainty analysis for the category of climate change, which, after normalization, has the highest influence (31.3%) and is the most commonly studied. The obtained values confirm that, with also considering the uncertainty associated with the inputs, the GHG emissions produced (between 8.6 and 13.1 kg CO_2 eq/kg) are significantly below those produced by the manufacturing of vCF, thus confirming the benefits of the proposed remanufacturing process.

The breakdown of the different impacts for the various phases of the innovative spinning process is represented in Fig. 4, and the specific values are summarized in Table 5. The Preparing (A1) + Carding (A2) phase contributes the most to nearly all the environmental impact categories, with values ranging from 36.5% for human toxicity – cancer to 61.9% for particulate matter. When it is not the most impactful, it is replaced by the Spinning (A5) phase, with values equal to 37.4% for ionizing radiation, 37.3% for ozone depletion and land use, 36.7% for ecotoxicity – freshwater, and 36.3% for eutrophication – freshwater. In the case of human toxicity – non-cancer, the phases share the same percentage (35.2%). The same applies to the weighting results. Overall, the Preparing (A1) + Carding (A2) phase generally has higher impact percentages than the Spinning (A5) phase. Indeed, for about 73% of the impacted categories, the impact percentage exceeds 45%, while in the case of the Spinning (A5) phase, the percentages are around 37%. Furthermore, the Drawing + Flyer (A4) phase has the lowest impact for all categories under consideration, responsible on average for approximately 10.5% of the impact. Finally, the Carding (A3) phase impacts the different categories with values ranging from 10.5% to 19.0%.

As mentioned earlier, the phase responsible for the majority of the impact categories is Preparing (A1) + Carding (A2); therefore, it merited additional study. In particular, an investigation of the effects of the various inputs in contributing to the impact on each category would be worthwhile. Fig. 5 presents the findings of this analysis. Overall, no impact category is heavily dependent on the use of recovered CF from manufacturing scrap. In fact, rCF accounts for at most about 1% of the overall impact. By contrast, the use of polyamide fiber has a significant impact on approximately half of the impact categories, ranging from 55.8% (climate change) to 72.6% (particulate matter). Similarly, electricity, which has the highest values, varies from 98.3% for ionizing radiation to 53.0% for resource use – minerals and metals. These two main inputs equally affect the acidification and resource use – fossils categories.

Moreover, it is worth analyzing the impact of the waste produced during the Drawing + Flyer (A4) phase on each impact category, as it is the only type usually not directly reused. To this end, we carried out a thorough investigation, whose results are shown in Table 6. The produced waste contributes to eutrophication – marine with its highest value (3.84%), followed by climate change with 2.34%, particulate matter with 2.06%, and human toxicity – cancer with 1.98%. On all other categories analyzed, it has an impact of less than 1%. The lowest value (i.e., 0.03%) is attributed to the categories ionizing radiation and resource use – minerals and metals.

Table 3
Characterization results for functional unit considering only climate change, human toxicity, and ecotoxicity – freshwater.

Impact category	Units	Total
Climate change - Fossil	kg CO_2 eq	2.61E-01
Climate change - Biogenic	kg CO_2 eq	2.70E-03
Climate change - Land use and LU change	kg CO_2 eq	3.34E-05
Human toxicity, non-cancer - organics	CTUh	9.89E-11
Human toxicity, non-cancer - inorganics	CTUh	3.46E-10
Human toxicity, non-cancer - metals	CTUh	1.62E-09
Human toxicity, cancer - organics	CTUh	2.45E-11
Human toxicity, cancer - inorganics	CTUh	0
Human toxicity, cancer - metals	CTUh	5.19E-11
Ecotoxicity, freshwater - organics	CTUe	2.05E-02
Ecotoxicity, freshwater - inorganics	CTUe	2.07E-01
Ecotoxicity, freshwater - metals	CTUe	2.14E+00

4.2. Sensitivity analysis

To compare the environmental performance of ISP4rCF under different input material scenarios, we conducted a sensitivity analysis. Specifically, we performed two analyses by changing the raw materials used (Andrianandraina et al., 2015). In the first scenario, Scenario 1, polyamide 6 fiber is replaced with polyester fiber. In the second scenario, rCF from manufacturing scraps used to manufacture a hybrid blend is replaced with rCF from pyrolysis.

These inputs were chosen for a variety of reasons. First, polyamide 6 fiber significantly influences numerous impact categories (see Section 4.1). At the same time, studies have shown that polyester may be effectively used to produce ring-spun hybrid yarns (Colombo et al.,

Table 4
Outcomes of uncertainty analysis using Monte Carlo method (SD: standard deviation; CV: coefficient of variation; SEM: standard error of mean).

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.5%	SEM
Acidification	mol H+ eq	1.19E-03	1.18E-03	1.32E-04	1.11E+01	9.74E-04	1.48E-03	4.19E-06
Climate change	kg CO_2 eq	2.64E-01	2.60E-01	2.90E-02	1.10E+01	2.15E-01	3.31E-01	9.18E-04
Ecotoxicity, freshwater	CTUe	2.38E+00	2.28E+00	6.75E-01	2.84E+01	1.41E+00	3.97E+00	2.13E-02
Eutrophication, freshwater	kg P eq	4.97E-05	4.30E-05	2.85E-05	5.73E+01	1.88E-05	1.32E-04	9.01E-07
Eutrophication, marine	kg N eq	1.99E-04	1.96E-04	2.37E-05	1.19E+01	1.61E-04	2.50E-04	7.48E-07
Eutrophication, terrestrial	mol N eq	2.12E-03	2.10E-03	2.57E-04	1.21E+01	1.72E-03	2.67E-03	8.13E-06
Human toxicity, cancer	CTUh	7.84E-11	7.68E-11	5.98E-11	7.62E+01	−3.65E-11	2.03E-10	1.89E-12
Human toxicity, non-cancer	CTUh	2.17E-09	2.19E-09	6.92E-09	3.20E+02	−1.23E-08	1.59E-08	2.19E-10
Ionizing radiation	kBq U-235 eq	2.64E-02	1.75E-02	2.66E-02	1.01E+02	7.91E-03	9.91E-02	8.41E-04
Land use	Pt	9.29E-01	9.09E-01	1.70E-01	1.83E+01	6.43E-01	1.31E+00	5.37E-03
Ozone depletion	kg CFC11 eq	2.59E-08	2.47E-08	7.00E-09	2.70E+01	1.56E-08	4.27E-08	2.21E-10
Particulate matter	disease inc.	6.89E-09	6.81E-09	6.13E-10	8.89E+00	5.91E-09	8.20E-09	1.94E-11
Photochemical ozone formation	kg NMVOC eq	6.39E-04	6.30E-04	7.05E-05	1.10E+01	5.27E-04	7.92E-04	2.23E-06
Resource use, fossils	MJ	3.72E+00	3.67E+00	5.41E-01	1.45E+01	2.82E+00	4.90E+00	1.71E-02
Resource use, minerals and metals	kg Sb eq	2.34E-06	2.29E-06	4.09E-07	1.75E+01	1.72E-06	3.33E-06	1.29E-08
Water use	m^3 depriv.	1.10E-01	1.20E+00	1.21E+01	1.10E+04	−2.75E+01	1.94E+01	3.84E-01

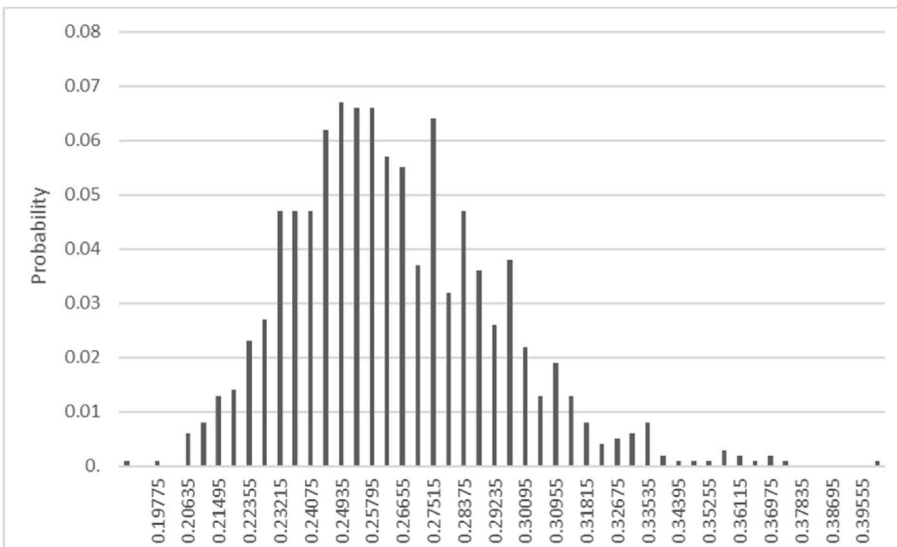

Fig. 3. Distribution of the climate change impact category for characterization results.

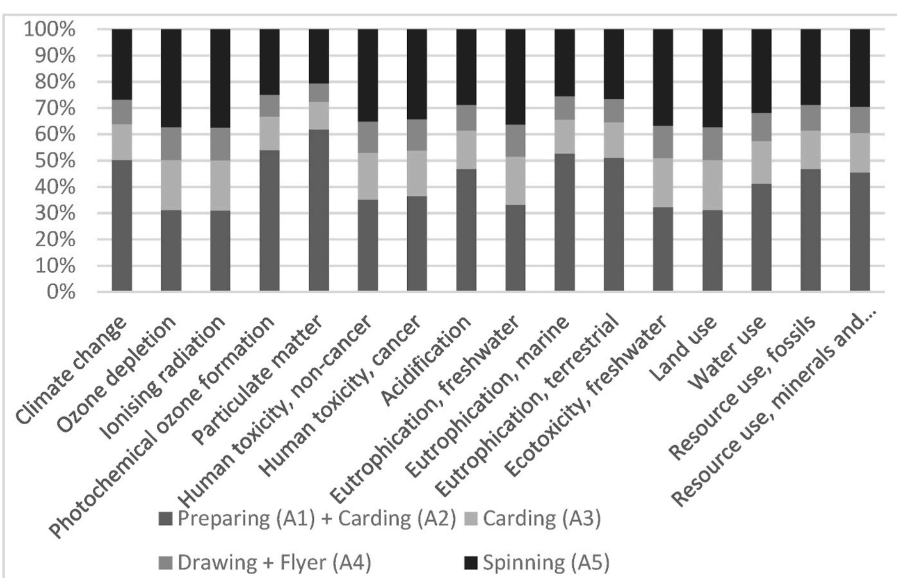

Fig. 4. Contributions of the various phases of the innovative spinning process to each impact category.

Table 5
Characterization results for functional unit related to each phase of the innovative spinning process.

Impact category	Unit	Total	Preparing (A1) + Carding (A2)	Carding (A3)	Drawing + Flyer (A4)	Spinning (A5)
Climate change	kg CO_2 eq	2.64E-01	1.32E-01	3.60E-02	2.44E-02	7.09E-02
Ozone depletion	kg CFC11 eq	2.57E-08	8.01E-09	4.87E-09	3.22E-09	9.58E-09
Ionizing radiation	kBq U-235 eq	2.57E-02	7.97E-03	4.88E-03	3.23E-03	9.61E-03
Photochemical ozone formation	kg NMVOC eq	6.39E-04	3.45E-04	8.09E-05	5.37E-05	1.59E-04
Particulate matter	disease inc.	6.87E-09	4.25E-09	7.18E-10	4.85E-10	1.41E-09
Human toxicity, non-cancer	CTUh	2.02E-09	7.11E-10	3.61E-10	2.41E-10	7.10E-10
Human toxicity, cancer	CTUh	7.64E-11	2.79E-11	1.33E-11	9.00E-12	2.62E-11
Acidification	mol H+ eq	1.19E-03	5.55E-04	1.74E-04	1.15E-04	3.43E-04
Eutrophication, freshwater	kg P eq	4.96E-05	1.64E-05	9.13E-06	6.04E-06	1.80E-05
Eutrophication, marine	kg N eq	1.99E-04	1.05E-04	2.57E-05	1.77E-05	5.06E-05
Eutrophication, terrestrial	mol N eq	2.13E-03	1.08E-03	2.86E-04	1.90E-04	5.64E-04
Ecotoxicity, freshwater	CTUe	2.36E+00	7.63E-01	4.40E-01	2.93E-01	8.66E-01
Land use	Pt	9.24E-01	2.88E-01	1.75E-01	1.16E-01	3.45E-01
Water use	m^3 depriv.	1.49E-01	6.15E-02	2.42E-02	1.60E-02	4.76E-02
Resource use, fossils	MJ	3.69E+00	1.73E+00	5.41E-01	3.58E-01	1.07E+00
Resource use, minerals and metals	kg Sb eq	2.32E-06	1.06E-06	3.49E-07	2.31E-07	6.87E-07

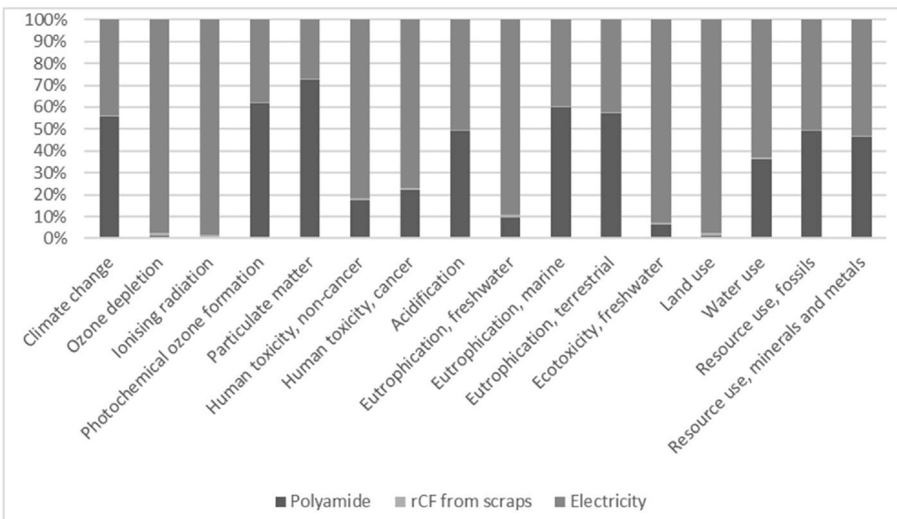

Fig. 5. Details on the share of inputs of Preparing (A1) + Carding (A2) phase for each impact category.

Table 6
Impact of flows concerning Drawing + Flyer (A4) phase to each impact category.

Protection Area	Electricity	Waste
Climate change	97.66%	2.34%
Ozone depletion	99.90%	0.10%
Ionizing radiation	99.97%	0.03%
Photochemical ozone formation	99.54%	0.46%
Particulate matter	97.94%	2.06%
Human toxicity, non-cancer	99.01%	0.99%
Human toxicity, cancer	98.02%	1.98%
Acidification	99.83%	0.17%
Eutrophication, freshwater	99.96%	0.04%
Eutrophication, marine	96.16%	3.84%
Eutrophication, terrestrial	99.53%	0.47%
Ecotoxicity, freshwater	99.43%	0.57%
Land use	99.78%	0.22%
Water use	99.82%	0.18%
Resource use, fossils	99.93%	0.07%
Resource use, minerals and metals	99.97%	0.03%

2021, 2023a). Second, CF recycled through pyrolysis represents another significant source of waste. In fact, pyrolysis enables the recovery of CFs from end-of-life CFRPs (Zhang et al., 2020). Additionally, this scenario may be practically tested in the near future since pyrolysis is the only reclaiming process currently exploited at the industrial level.

A comparison between Baseline, Scenario 1, and Scenario 2 can be made by examining the values reported in Table 7. Processes' environmental performances in the Baseline and Scenario 1 are very similar considering each impact category in terms of both magnitude and normalized total values. However, for some impact categories, such as particulate matter and marine eutrophication, Scenario 1 reports impact reductions, ranging between −4.4% and −24.0%, but also significant increases, such as in the ozone depletion category (+451.5%). The use of polyester fiber results in a reduction of 15.9% in climate change, one of the most targeted categories. Overall, it can be argued that the environmental benefits of using one thermoplastic fiber over another are dependent on the specific impact category under consideration. As such, from a sustainability perspective, our findings could support policymakers in deciding which input material to prioritize based on the total environmental performance achieved or the environmental category whose impact needs to be reduced, but without forgetting the technical-mechanical properties to be achieved in the final CFRP.

As expected, Scenario 2 has the worst effects on the environment. It exhibits considerable increases in impact values across all categories compared to the Baseline and Scenario 1. This finding may be attributable to rCF from pyrolysis and to its energy-intensive production process (i.e., thermal recycling via pyrolysis), since the contribution of effects from stages A3, A4, and A5 of the innovative spinning process

Table 7
Results of LCA analyses - comparison between scenarios (functional unit: 25 g of material).

Impact category	Unit	Baseline	Scenario 1	Scenario 2
Climate change	kg CO_2 eq	2.64E-01	2.22E-01	6.55E+00
Ozone depletion	kg CFC11 eq	2.57E-08	1.42E-07	7.41E-07
Ionizing radiation	kBq U-235 eq	2.57E-02	2.78E-02	1.78E+00
Photochemical ozone formation	kg NMVOC eq	6.39E-04	5.67E-04	1.10E-02
Particulate matter	disease inc.	6.87E-09	5.22E-09	6.96E-08
Human toxicity, non-cancer	CTUh	2.02E-09	2.26E-09	3.48E-08
Human toxicity, cancer	CTUh	7.64E-11	8.85E-11	1.42E-09
Acidification	mol H+ eq	1.19E-03	1.05E-03	2.05E-02
Eutrophication, freshwater	kg P eq	4.96E-05	5.62E-05	3.01E-03
Eutrophication, marine	kg N eq	1.99E-04	1.66E-04	3.73E-03
Eutrophication, terrestrial	mol N eq	2.13E-03	1.78E-03	3.47E-02
Ecotoxicity, freshwater	CTUe	2.36E+00	2.85E+00	4.20E+01
Land use	Pt	9.24E-01	9.93E-01	1.18E+01
Water use	m^3 depriv.	1.49E-01	1.43E-01	3.49E+01
Resource use, fossils	MJ	3.69E+00	3.49E+00	1.14E+02
Resource use, minerals and metals	kg Sb eq	2.32E-06	2.12E-06	1.00E-05
Normalized total	–	3.17E-04	3.14E-04	1.05E-02

remains unchanged in all scenarios. Fig. 6 shows that of all the impact categories considered, the contribution related to rCF from pyrolysis is the most significant. Although it is the most impactful, this scenario cannot be overlooked as it enables targeting a huge portion of waste, namely end-of-life CFRPs. Therefore, regulators should jointly consider this aspect and the high technology readiness level (equal to 8: Krauklis et al., 2021; Nistratov et al., 2022) of pyrolysis when making decisions on the CF-reclaiming technologies to incentivize.

To summarize, the findings of this comparative analysis could support policymakers in making preliminary reasoned decisions about CFs waste management and deciding which scenario to favor so as to provide long-term benefits to society as a whole, as required by the sustainable development goals (Duc Nguyen et al., 2022; Koley, 2022). The setting up of pilot plants for ISP4rCF will be crucial to generate reliable data, thus improving the confidence of regulators in this cleaner and more sustainable production method (Duc Nguyen et al., 2022).

4.2.1. *Environmental life-cycle costing*

The results of the eLCC analysis for damage assessment are presented in Table 8. Overall, the Baseline exhibits an environmental cost of 0.215 ELU per 1 functional unit. Specific values indicate that emissions and resource use for ISP4rCF have a major negative impact on abiotic resources (81.9%) and human health (17.6%). Indeed, these areas of protection account for 99.4% of the whole value. This means that the average European citizen's willingness to pay is directed toward restoring these two categories to an established reference point. Comparatively, in line with the outcomes of the LCA analysis, Scenario 2 is the worst solution in terms of environmental costs, whereas the Baseline option is the most favorable. The Baseline total value is extremely close to the characteristic value of Scenario 1 (0.236 ELU), confirming the numerous similarities between Scenario 1 and Baseline. Additionally, it should be noted that, also for Scenario 1 and Scenario 2, the human health and abiotic resource categories contribute the most to the overall value of environmental costs, with respective shares of 14.7% and 84.5% in Scenario 1 and 45.9% and 52.8% in Scenario 2.

Table 8
Results of eLCC analysis - comparison between scenarios.

Protection Area	Unit	Baseline	Scenario 1	Scenario 2
Ecosystem services	ELU	1.02E-03	8.52E-04	2.54E-02
Access to water	ELU	6.19E-05	5.19E-05	1.56E-03
Biodiversity	ELU	3.32E-06	2.80E-06	8.16E-05
Building technology	ELU	8.80E-06	7.30E-06	2.29E-04
Human health	ELU	3.78E-02	3.47E-02	9.97E-01
Abiotic resources	ELU	1.76E-01	2.00E-01	1.15E+00
Total	ELU	2.15E-01	2.36E-01	2.17E+00

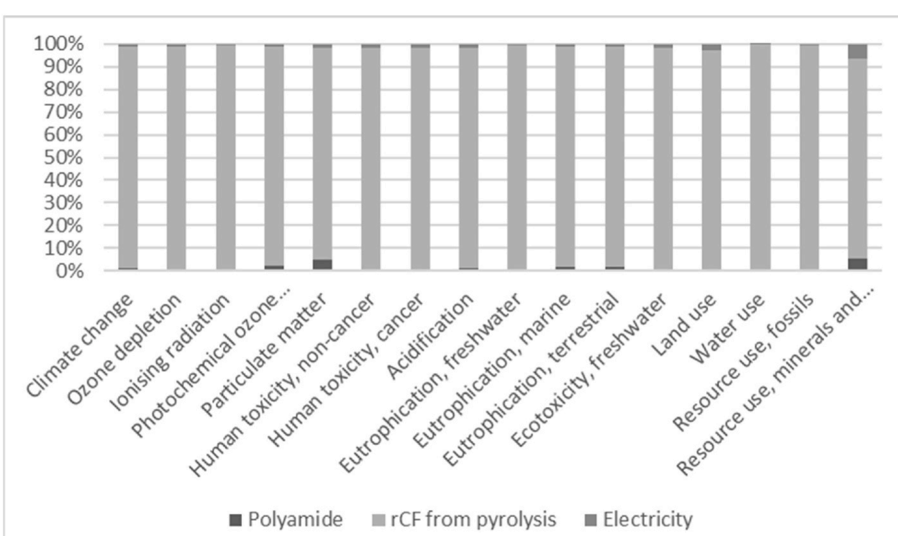

Fig. 6. Details on the share of inputs of Preparing (A1) + Carding (A2) phase for each impact category - Scenario 2.

5. Conclusion

This paper investigated the environmental performance of ISP4rCF, a recently developed remanufacturing process for handling rCFs and enabling the production of CFRPs for structural applications. A combined attributional LCA and eLCC analysis was conducted using a cradle-to-gate approach. This study responds to explicit requests in the scientific literature to consider both engineering performance and environmental aspects when selecting a CF remanufacturing technology to bring the composite materials industry closer to circularity.

The results of the dominance analysis highlighted that the majority of ISP4rCF impacts (65.4%) concern the climate change, resource use fossils, and resource use – minerals and metals impact categories. Furthermore, with values between 31.2% and 61.9%, the Preparing (A1) + Carding (A2) phase is the major contributor to nearly all environmental impact categories. The second-most impactful phase is Spinning (A5), which ranges from 36.3% for eutrophication – freshwater to 37.4% for ionizing radiation. Overall, GHG emissions from the process amount to 10.5 kg-CO_2 eq/kg, significantly below those produced by vCF manufacturing (24-31 kg-CO_2 eq/kg) even when considering the uncertainty associated with inputs. This results in an improvement of environmental performance in producing the reinforcement to be used in manufacturing CFRPs for structural applications ranging between 56% and 66%. However, this positive impact increases to a maximum value of 76% when considering that ISP4rCF avoids landfilling and incineration while also enabling the recovery of rCF and promoting CE. These considerations allow for the assertion that ISP4rCF is cleaner and more sustainable than currently existing solutions. Moreover, the sensitivity analysis revealed that Scenario 2 (i.e., use of rCF from pyrolysis instead of manufacturing scraps) is worst in terms of both environmental performance and externalities, while Baseline and Scenario 1 (i.e., use of virgin polyester instead of polyamide as virgin thermoplastic fiber) show similar environmental impacts. However, as regards the climate change impact category, the environmental performance of ISP4rCF can be improved by replacing polyamide 6 fiber with polyester. Indeed, a reduction of approximately 16% in the carbon footprint can be achieved against an increase in environmental costs of 3%. Overall, the use of rCF from manufacturing scraps is preferable to the use of rCF from pyrolysis in terms of life-cycle impacts. Additionally, as the Baseline and Scenario 1 are characterized by comparable environmental impacts and their technical feasibility has been already tested, the choice between polyamide 6 or polyester fiber should rely on the technical properties to be achieved in the final CFRP composite.

This paper makes both theoretical and practical contributions. As regards the former, a well-established methodology (i.e., LCA) was applied for the first time to analyze a remanufacturing technology for rCF. The results demonstrate that incremental innovation with an existing technology (in this case, the yarn spinning) can foster the development of environmentally friendly processes. Regarding the latter, this work demonstrates the clean and sustainable nature of ISP4rCF at the laboratory level. Hence, it is foreseen that this process could be transposed to an industrial scale to be exploited in the near future. Concurrently, ISP4rCF is a promising technology from a policy perspective. In fact, beyond the limited environmental burden generated and the ease of transposition to an industrial level due to the diffusion of ring-spinning technology, it ensures the flexibility to handle either rCF from pyrolysis or manufacturing scraps. This will allow for the possibility of reducing the amount of end-of-life waste destined for landfills as well as the amount of manufacturing scraps that are currently used, in the best option, for low-value applications. Taking a cross-sectional perspective, this analysis confirms that the use of LCA is a valuable eco-design tool (Civancik-Uslu et al., 2019). For instance, LCA allowed us to compare the environmental performance of the process when fed with different inputs. Through the analysis of various scenarios, policymakers can promote the use of specific input materials or prioritize particular technologies that save the environment while providing long-term social and economic benefits to society as a whole (Koley, 2022).

This study has limitations. First, the findings are drawn from the application of ISP4rCF at the laboratory level. Thus, certain conclusions might not be directly applicable in an industrial setting. Certainly, scaling up the process to a pilot plant is a key direction for future research.

Second, the energy used for the production of both ring-spun hybrid yarns and rCF from pyrolysis was modeled based on specific Ecoinvent datasets considering the average energy mix at the Italian level. Accordingly, the results accurately represent the specific geographical boundary but may undergo notable variations whether alternative regional contexts or boundaries are contemplated. At the same time, no thorough comparison of the obtained outcomes with other studies was conducted. The reasons for this are twofold. First, to the best of our knowledge, no other LCA studies on CF remanufacturing processes leveraging other spinning technologies have been conducted. Fitzgerald et al. (2022) proposed an LCA of the HiPerDif remanufacturing technology without, however, reporting a value for GHG emissions. Therefore, a direct comparison was not feasible. Second, comparing these results with the outcomes of LCA on reclaiming processes for CF could lead to biased considerations due to significant differences in modeling assumptions, system boundaries, and input material. Thus, performing an LCA analysis on existing processes leveraging wrap, roving frame, or friction spinning under the same inputs and outputs is a key priority in the near future (Akonda et al., 2012; Hasan et al., 2018; Hengstermann et al., 2016). This could provide insights into the most environmentally friendly CF remanufacturing technology among those currently developed at the laboratory level, thus supporting policymakers devising incentives to upscale the most promising remanufacturing processes.

Finally, in the current study, the LCA was conducted only on ISP4rCF since, considering the entire production chain for the manufacturing of recycled CFRPs, it is the process more closely resembling a well-established industrial process (i.e., yarn spinning). The weaving of reinforcement and the actual production of CFRPs were performed manually; therefore, they are not fully representative of procedures conducted in an industrial process. In this context, expanding the system boundary to encompass the whole production chain, particularly after industrialization of the process, would be interesting. In the first instance, conducting field-scale experiments and establishing ISP4rCF pilot plants may provide verified information that assesses feasibility, minimizes uncertainties, and boosts the trust of regulators toward this cleaner and more sustainable production mode (Duc Nguyen et al., 2022).

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CRediT authorship contribution statement

Beatrice Colombo: Conceptualization, Methodology, Investigation, Formal analysis, Software, Writing – original draft, Writing – review & editing. **Paolo Gaiardelli:** Conceptualization, Supervision. **Stefano Dotti:** Supervision. **Flavio Caretto:** Supervision.

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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