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Environmental assessment of recycling carbon fiber reinforced composites: current challenges and future opportunities

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Abstract

The increasing application of carbon fiber reinforced polymer composites (CFRP) across different industries raises environmental concerns. It requires focusing on the end-of-life phase of the product/material. The environmental benefits of CFRP recycling over conventional ways of treatment are apparent. However, estimating the environmental impacts is followed up with various challenges. In this study, the aspects of environmental assessment of CFRP recycling and their respective challenges are examined. CFRP recycling methods such as mechanical treatment, pyrolysis, fluidized bed process, and solvolysis have been previously studied in the context of energy and environmental assessment under the Life-Cycle-Assessment (LCA) framework. This study focused on the identification of challenges associated with variability of applied methods used, comparability, scaling results, data, uncertainty, and resource-demanding process of LCA. Recommendations on overcoming the identified challenges are provided and discussed.

Introduction

Carbon Fiber Reinforced Polymers (CFRP) are a commonly used type of material among car and aircraft manufacturers.It contributes

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to 65% and 20% weight reduction respectively leading to a reduction in terms of fuel demand (Tapper *et al.*, 2020). The range of products made from CFRP is rapidly increasing, thus, increasing the amount of waste to be accumulated in landfill sites unless treated properly. According to Lefeuvre, Garnier, *et al.* (2017), nearly 500 thousand tons of scrap and end-of-life carbon fiber composite waste are projected to be accumulated from the aerospace industry alone by 2050. Polymer matrix composite materials have existed for a long time but there are no effective and global solutions for recycling this type of waste. Both scientists and industries are constantly attempting to improve the existing CFRP waste treatment methods, but not all are functioning at an industrial scale. Although landfilling and incineration are common practices in this context, recycling is becoming a more strategic way due to economic, environmental and legislative considerations (Lefeuvre, Yerro, *et al.*, 2017). At the same time, the production of virgin carbon fiber requires large financial and energy inputs making the recycled carbon fiber more attractive (Gopalraj and Kärki, 2020). However, unlike landfilling and incineration, the environmental impacts or benefits of existing CFRP recycling techniques still need to be quantified (Tapper *et al.*, 2020).

Although recycling is perceived to be environmentally advantageous, it also causes environmental damage through the collection, sorting, transportation and processing of the material (Craighill and Powell, 1996). Therefore, environmental and economic feasibility studies are needed for the evaluation of recycling processes. One of the main impact criteria considered in environmental impact assessment studies is the climate change (kg CO_2 equivalent). However, many other impact indicators make the environmental assessment inaccurate and challenging to apply to different scenarios (Guo and Murphy, 2012; Ylmén *et al.*, 2020). Therefore, this paper summarizes the common life cycle inventories (LCI) in different CFRP recycling techniques.

In the case of CFRP waste, there are few papers on environmental impact assessment with reliable and scalable results. The commonly used LCA method is still in the early stage of application for CFRP materials. This is mainly due to the shortage of data on CFRP recycling processes at an industrial scale. These and other issues hinder the advancement of sustainable recycling strategies, particularly in the context of understanding the supply chain for CFRP recycling. Therefore, this study aims to review the scientific literature on the environmental impact assessment of CFRP recycling techniques and analyse the related challenges to provide further directions for the assessment design of CFRP recycling processes and sustainable supply chain networks.

Methods

This paper used a narrative literature review method proposed by Mayer (2009). The review considers the recent environmental impact works related to recycling CFRPs. This study focuses on an overview of the intersection of "environmental assessment" and "recycling CFRPs in the context of the current situation and perspectives. The primary databases used are Scopus, Science Direct and Research gate. The publication date of papers included in the study is limited by the last 20 years. Also, only papers written in English with clear references were included in this work. The keywords for the search were "environmental impact", "environmental assessment", "LCA", "Life Cycle Assessment", "LCI", "environmental impact categories" combined with "recycling carbon fibers", "recycling CFRPs", "recovery of carbon fiber composites". Finally, all the relevant articles were selected after thoroughly reading the abstracts.

CFRP Waste Recycling Methods

Currently used CFRP waste recycling methods are mechanical, thermal and chemical. While mechanical recycling methods are based on mechanical treatment (shredding, milling and sieving), the most popular and mature thermal recycling method is pyrolysis. Solvolysis with fluid in supercritical conditions (such as water, alcohol, acetone) is a promising chemical recycling method too (Pimenta and Pinho, 2011). In this section, these methods will be discussed to analyse the inputs and outputs of the system that contribute to the damage in the context of environmental assessment.

Mechanical Recycling

Mechanical recycling is the cheapest but the least preferable way of recycling. This method implies waste size reduction to very small particles (10-50 mm) and using it as a filler material, for example for concrete reinforcement (Ogi *et al.*, 2005). Mechanical cutting, shredding, milling and sieving are done by the rotating equipment. In this process, the higher the output of the machine the less the energy demand per unit of recycled CF, thus, causing less environmental impact. Other than that, these machines can only process small size waste (e.g., 3 mm thickness), therefore, may require additional work such as dismantling and downsizing of composites. These processes might entail additional electrical energy and human health impact, therefore, need to be considered in the Life Cycle Inventory phase.

Pyrolysis

Thermal recycling method such as pyrolysis uses heat to decompose carbon fiber. It is widely adopted at an industrial scale due to its efficiency. The important role in pyrolysis recycling is played by the parameters of the process (temperature, pressure, heating rate etc.). Theyinfluence the mechanical properties of reclaimed fibers. This means that depending on the required application process optimization is needed which in turn will affect the energy demand (Meyer et al., 2009). Figure 1 Represents LCI for the pyrolysis process.

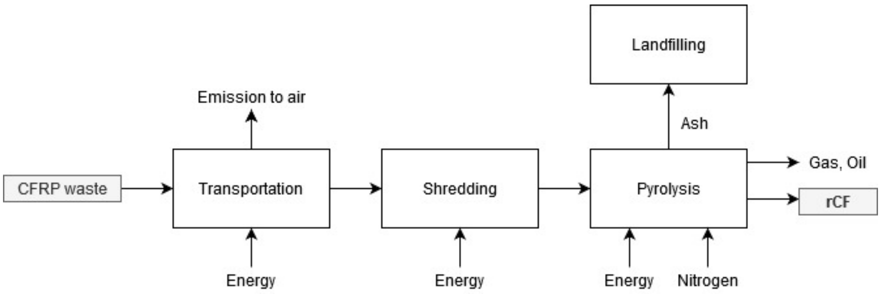

Figure 1. Lifecycle environmental impact of Pyrolysis Process

Fluidized bed process

Fluidized bed process (FBP) is the thermal process that uses silica sand to decompose the composite waste into the fibers and reinforcing material. During the process, a hot stream of air runs through a bed at a temperature >500 ^{0}C. After that fibers are discharged by a cyclone from the stream of the gas. The degraded components remain in the bed. The method has its advantages such as tolerance to contaminants and moderately preserved fiber characteristics, indicating a Technology Readiness Level (TRL) TRL of 6 at Nottingham University (Meng *et al*., 2020). The schematic representation of LCI of FBP is represented in Figure 2.

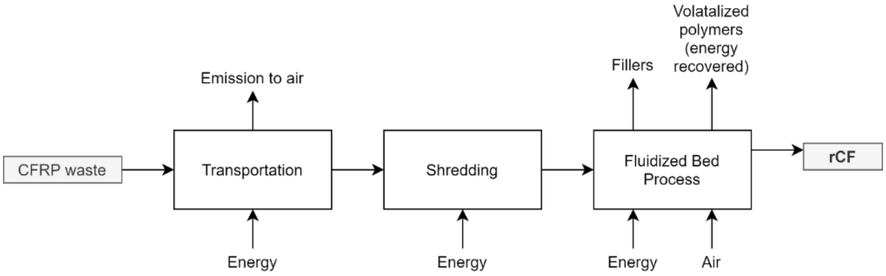

Figure 1. LCI of Fluidized Bed process.

Solvolysis

Chemical recycling process or solvolysis is utilized to decompose polymer matrix with the help of chemical components. Based on the solvent's state the method is subdivided as solvolysis with 1) lower temperatures and 2) supercritical fluids. During the process, the waste is shredded initially to increase the surface of interaction with the chemical and then dissolved using solvents (Figure 3). The range of used chemicals is wide starting from supercritical water and ending with solvents such as ethanol, acetone, and methanol (Krauklis *et al.*, 2021). The method is not still applied at the industry scale, though the results were validated at the laboratory level (Rybicka *et al.*, 2016).

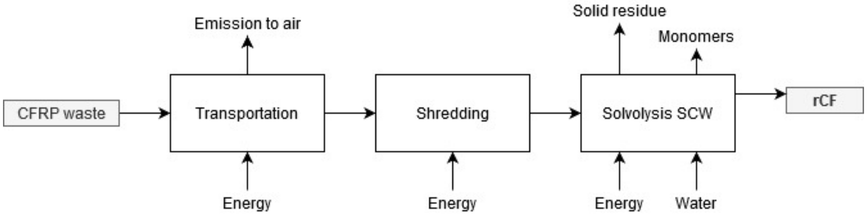

Figure 2. LCI of Solvolysis process

Life Cycle Assessment

LCA is one of the widely applied methods for the environmental assessment of a product. This method is ISO 14000 standardized and is conducted following the established procedures (Petrakli *et al.*, 2020). LCA assessment is performed in several steps. These steps include identifying the aim and defining the system of the LCA, quantifying the input and output flow of the system, evaluating the life cycle impact, and classifying their impact categories to the environment and improving assessment (Craighill and Powell, 1996). Throughout the lifecycle of a product, different process stages require a different number of resources and have varying levels of impact on the environment. As a part of the LCA study, the assessor needs to delineate the system boundaries and scope of the study. After that, inventory analysis is carried out on emissions and waste generated during the process. Then their environmental impact is quantified in terms of ozone depletion, eco- and human toxicity and so on (Petrakli *et al.*, 2020). Depending on the chosen scope, LCA analysis can cover the whole life cycle of a system or only a part of it (da Silva *et al*, 2021). "Gate to Gate" LCA covers partial LCA which considers only a single process. In our work, Gate to Gate indicated studies are those which covered only the recycling process itself. "Cradle to Grave" is a standard full-cycle LCA which covers all production phases, use, and disposal phase. "Cradle to Cradle" or closed LCA is a type of "Cradle to Grave" LCA, but it also includes the recycling process. This whole lifecycle assessment allows relevant stakeholders to manage the product and drive its production and disposal in a more sustainable way.

Life Cycle Inventory

The lifecycle inventory (LCI) analysis stage is an important and challenging step in the LCA process. It is challenging because it requires appropriate data which usually tends to be limited in the early-stage development of a process or a product. Inventory refers to all direct and indirect environmental impacts of a process such as inputs (raw stock material, energy, etc.) and outputs (emissions, waste, etc.) (Mansor *et al.*, 2019). It is also possible to include social considerations such as health and safety, risks as well as human health impact. Depending on the chosen set of inputs/outputs during the LCI, the accuracy and validity of the LCA results will vary. Moreover, the inventory data (e.g. energy, material, emission etc.) is aggregated to quantify the specific environmental concerns for example, global warming and resource depletion. There are far more examples of environmental impact categories. However,no standard method or criteria exists for selecting the “right” impact category. The decision is mostly dependent on the studied sector, scope and authors’ judgement (Reyes *et al.*, 2020).

Another important deliberation is the availability of several impact categories to quantify one environmental concern.For example, global warming indicators could be a global warming potential (GWP, kg CO2 eq.), the climate change impact (kg CO2 eq.), greenhouse gas emissions (kg CO2 eq.), CO2 emission (kg CO2 eq.) and others. According to general observations, the recycling CFRP sector tends to evaluate GWP as a function of energy required to recycle by one of the aforementioned methods. There are several works published that quantify and compare the energy consumption of CFRP recycling techniques. However, they use different functional units, and experimental setups and make different assumptions. Therefore, the data usually varies from one study to another. The indicative energy consumption by methods is shown in Table 1.

Table 1. Energy Consumption Levels by different CFRP recycling methods

Recycling Method	Reported Energy consumption (MJ/kg)	References
Mechanical recycling	2.03 (10 kg/h)	(Howarth *et al.*, 2014)
Pyrolysis	2.8	(Song *et al.*, 2009)
	30	(Witik *et al.*, 2013)
Solvolysis	63-91	(Shibata and Nakagawa, 2014)
	19	(Keith and Leeke, 2016)

In addition, sometimes one impact category can be measured with different units which also confuses relevant stakeholders (Tapper *et al.*, 2020). For example, acidification can be expressed as kg SO2 eq. or m^2 UES (area of an unprotected ecosystem) or as the number of extinct species per year. The list of commonly used impact categories and their units are presented in Table 2.

Table 2. List of impact categories for LCI analysis of CFRP material.

Name	Abbreviation	Units	Comment	Source
Global Warming Potential (Climate change)	GWP	kgCO2eq/kg	If the process emits gas, it will have GWP, which compares the energy absorbed by 1 ton of gas over time with the emissions of 1 ton of CO2.	(Vallero, 2019)
Greenhouse Gas Emissions	GHG	kgCO2eq/kg	The most widely used environmental impact assessment category.	(Tapper et al., 2020)
Cumulative Energy Demand	CED	MJ/kg	The energy required to make the product, process or service.	(Bachmann et al., 2017)
Energy Intensity	EI	MJ/kg	Equivalent to cumulative energy demand (CED) corresponding to primary energy.	(Bachmann et al., 2017)
Ozone Layer Depletion	OLD	kg CFC-11 eq	The function of the emission of ozone depleting gas.	(Bałdowska-Witos et al., 2021)
Human toxicity (cancer causing and non-cancer effect)	HTP	CTUh	The function of the number of toxic releases to humans in water, air and soil media.	(Imbeault-Tétreault et al., 2013)
Acidification Potential	AP	Kg SO2- eq	The function of soil acidity due to sulfates, nitrates and phosphates (NOX, NH3, and SO2) in the atmosphere.	(Geisler et al., 2005)
Eutrophication Potential	EP	kg N-Eq	Nutrient enrichment of marine ecosystem.	(Thiel et al., 2013)
Ecotoxicity (freshwater, marine, terrestrial)	ET	kg O3-Eq	The function of exposure level to released toxic substances to the environment.	(Frischknecht et al., 2005)
Resource Depletion (water, natural resources)	RD	m3 water/oil eq	Depletion of non-renewable natural resources.	(Ciroth et al., 2004)
Photochemical oxidation	POCP	kg Sb eq	Also known as summer smog, the air pollution resulted from the reaction of emissions with sunlight.	(Frischknecht et al., 2005)

According to Craighill and Powell (1996), the environmental impact assessment is three-step process: classification, characterisation and evaluation. First, the data or inventory needs to be classified into the environmental issue (e.g. global warming), the scale of the impact (e.g. local, global), and impact media (e.g. air). Second, characterization refers to quantifying the impact of the inventory to determine environmental issues. Some of the terms to quantify such contributions can be GWP and Ozone Depletion Potential (ODP). Similarly, recycling CF from CFRP entails unique environmental impacts which are summarised in Figure 4. These are the main impact categories that are widely reported in the literature (Bulle *et al.*, 2019).

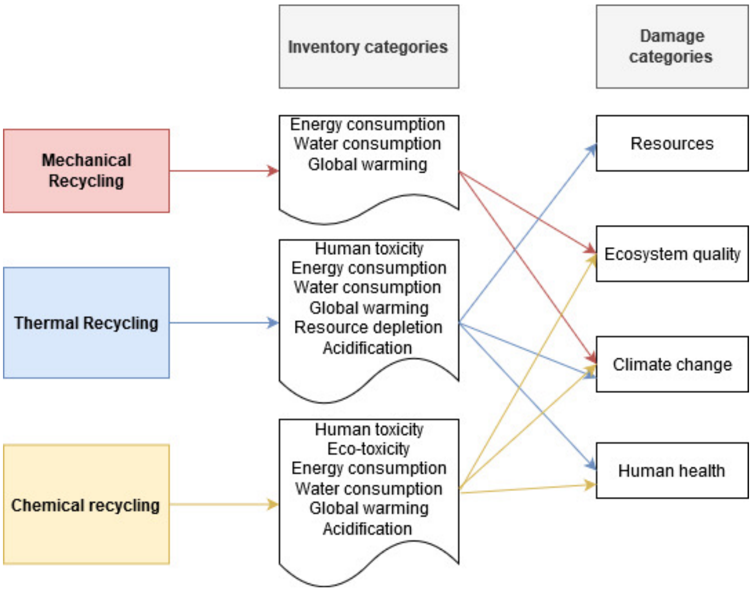

Figure 4. Environmental Inventory and damage categories of CFRP recycling methods.

Although LCA is a very useful tool, users should be aware of its sources of uncertainty which might lead to different outcomes (Ylmén *et al.*, 2020). For example, as was discussed before, some steps of the analysis require personal judgement (determining system boundary, analyzing the recycling process, choosing quantifiable impact categories etc.). This and other challenges in the environmental analysis of CF recycling will be discussed in the next sections.

Environmental Assessment of CFRP recycling: current status

The works related to the environmental assessment of CFRP recycling methods are listed in Table 2. Most of the authors compared different recycling options according to their global warming potential, acidification and ecotoxicity potential. Also, as data plays a crucial role in the LCA analysis, most of the authors used databases of well-known platforms such as Simapro, Ecoinvent and Gabi. The works presented in Table 3 are grouped according to the recycling methods included.

Reference	**Year**	**Approach Used**	**Recycling process**	**Main impact categories**	**Database**	**Comments/ Main findings**
(Pillain et al., 2017)	2017	Review of indicators	n/a	GWP, El, AP, OLD, HTP	n/a	The authors state that the most relevant indicators for the CFRP recycling sector are GWP , human toxicity, and acidification.
(Markatos *et al.*, 2021)	2021	MCDM	Pyrolysis, FBP, Microwave pyrolysis, Solvolysis SCW	End-of-Life index	n/a	The authors proposed End-Of-Life Index to support decisions in choosing a recycling process. The index includes the quality, cost, and environmental aspects of recycling methods.
(Tapper *et al.*, 2020)	2020	Review	n/a	n/a	n/a	The authors proposed an LCA framework for composite recycling applicability review, including all phases. The authors state that the use phase is the greatest potential for CFRP in terms of emissions savings. Authors believe that different LCA databases affect negatively cross comparison between different study outputs.
(Bachmann *et al.*, 2017)	2017	Review	n/a	n/a	n/a	The authors provided an extensive LCA review of composites use in aviation including biobased fibers, biobased thermoset resins, and recycled CFRPs; Also, LCA studies in pyrolysis usage for CFRP recycling were briefly discussed.
(Witik et al., 2011)	2011	Manufacture, use, end-of-life	Mechanical	Climate change, HTP, ET, RD	Ecoinvent, IDEMAT	Currently, automotive manufacturers are concerned only about reducing emissions

					LCI database, literature	during the useful life and increasing the recovery rate of end-of-life waste. Authors suggest that these two requirements are not enough to decide on an environmentally friendly strategy for transportation. Instead, the whole lifecycle is needed to be considered.
(Howarth et al., 2014)	2014	Gate-to-gate(End-Of-Life)	Mechanical	EI	Experiment	The energy demand for mechanical recycling was estimated: the energy intensity for the milling process was defined to be between 0.27-2.03 MJ/kg
(Li et al., 2016)	2016	Gate to gate (End-of_life)	Mechanical	GWP, EI	Ecoinvent	The environmental impacts of landfilling, incineration and mechanical recycling were assessed. Mechanically recycled CFRP may offer great GHG reductions if used instead of virgin glass fiber (-378 CO2 eq./t.), though the costs of recycling are an obstacle to prompting the method to a larger scale.
(Akbar and Liew, 2020)	2020	Gate-to-gate(End-Of-Life)	Mechanical	GWP, EI	Simpro 9.0.0	The authors provided environmental considerations of rCF coprocessing in cement kilns, which showed a positive trend. 1% of added rCF replacing 10% of cement with silica fume allowed to reduce GWP impact by 14%.
(Meng *et al.*, 2017)	2017	Gate-to-gate	Fluidized bed process	GWP, EI	Gabi, Ecoinvent, Experiment	The authors evaluated the lifecycle environmental impact of FBP recycling followed by manufacturing from rCF using the wet papermaking process. Results demonstrate that rCF energy demand and GHG emissions can be reduced by 32-50% and 33-51% respectively

(Meng *et al.*, 2020)	2020	Gate-to-Gate	Fluidized bed process	GWP, EI	Gabi, Ecoinvent, GREET	The work assesses the environmental impact of rCF utilization for aviation applications using the FBP recycling. The phases start with a collection of rCF, manufacturing components, and use phase. The environmental impact reductions are between 4 and 31% compared to virgin glass fiber productions
(Khalil, 2018)	2018	Gate-to-Gate (end-of-life)	Pyrolysis vs Solvolysis SCW	AP, ET, EP, GWP, HTP (non-carcinogenics, carcinogenics), ODP, smog	Gabi	ODP is the most responsive impact category to variations in the energy inputs of grinding. The ET is the least sensitive category to variations in the grinding energy.
(Dauguet et al., 2015)	2015	Gate-to-Gate (end-of-life)	Solvolysis (supercritical Fluid)	GWP, RD, HTP, OLD, AP, ET	Ecoinvent 3.0	The realignment and the cleaning rCF have a small environmental impact, and supercritical water solvolysis and remanufacturing have a substantial impact. Electricity and natural gas account for more than 33% of the impact.
(Prinçaud et al., 2014)	2014	Cradle-cradle (without Use phase)	Solvolysis SCW		Experimental data.Simapro, Ecoinvent, recipe Midpoint (H) method	Using recovered carbon reinforcement by aqueous solvolysis results in an 80% gain for all impact categories compared to landfilling. .
(La Rosa et al., 2016)	2016	Production and recycling of the (CF) (gate-to-gate)	Chemical treatment	CED, GWP, AP, OLD, HTP, ET, POCP	Simapro 8.01 ,Ecoinvent v3, laboratory data	Recycling is environmentally beneficial because recovered fibers could be used instead of virgin fibers for different applications. The avoided energy consumption for vCF production is the main influencing positive factor in the environmental assessment of

						chemical treatment for CFRP. Laboratory data were used in the study, but plant data is planned to be integrated into the LCA study.
(He et al., 2021)	2021	Cradle-to-gate and use phase	Pyrolysis	Primary Energy Demand (PED),, GWP	Gabi, GREET model and literature studies	The environmental benefits vary from country to country and for different fiber mass content in recycled carbon fiber. 13% and 34% decrease in GWP can be achieved with a 40% recovery rate in cradle-to-gate and use phases respectively. In Europe, the positive effect on GWP is larger than in the United States.
(Witik et al., 2013)	2013	End-of-life recycling	Pyrolysis	RD, GWP, HTP, ET	Simapro	This study is one of the pioneers in LCA analysis for recycling CFRPs. Results indicated that when rCF is used instead of virgin CF, the recycling via pyrolysis has less impact by 78, 84, and 82 % on climate change, resource, and ecosystem quality compared to landfilling.
(Lee et al., 2010)	2010	Gate-To-Gate (End-Of-Life)	Acid, pyrolysis in oxygen and nitrogen, organic solvents, supercritical process	Energy Foot Print, GHG Footprint	Simapro 7.0.0. And Ecoinvent	The overall footprint (Energy +GHG) is 5 times larger for pyrolysis compared to acids. The overall potential of recycling with acid was shown by the authors.
(Shuaib and Mativenga, 2017)	2017	Gate-to-gate (Only recycling)	Mechanical, High Voltage Fragmentation (HVF), Solvolysis	Energy footprint	Ecoinvent 3, European Life Cycle Database	Experiment and LCA were conducted by the authors. HVF has the highest Energy Demand (60 MJ per kg) in comparison with chemical (12.3 MJ/kg) and mechanical (0.37 MJ/kg)

(Meng *et al.*, 2018)	2018	Gate-to-gate	Mechanical, pyrolysis, fluidized bed, and chemical recycling process)	GWP, EI	Gabi and Ecoinvent	Four recycling methods were compared to landfilling option in terms of environmental impact. According to the authors, all recycling methods propose GWP reductions from -19 to -27 CO2eq and energy reductions from 395 to 520 MJ per 1 kg. The study notes that the net PED and GHG impact categories are more affected by replacing vCF, which are 10-20 times more effective than the recycling process itself.
(Vo Dong *et al.*, 2018)	2018	Gate-to-Gate (end-of-life recycling)	Mechanical, Pyrolysis, Microwave, Supercritical water	GWP	Ecoinvent v 2.2	The authors considered the difference of GWP impact between substituted virgin fiber and process impact. All recycling methods have beneficial GWP impacts from recycling, though grinding showed only minor improvements.
(Ghos*h et al.*, 2021)	2021	Gate-to-gate (recycling content approach)	Pyrolysis (assumed)	GHG, EI	Ecoinvent, GREET,	The main focus on the analysis of the production of subframes from recycled CFs. According to the authors, CFRP subframe may reduce GHG emissions in combination with increasing lifecycle distance compared to the conventional subframe
(Petrakl*i et al.*, 2020)	2020	Cradle to cradle	Landfilling, Incineration, Pyrolysis	GWP, OLD, HTP, etc.	Ecoinvent, Experimental data	LCA analysis was conducted with the experiment of prototypes such as sailing boats and handbrake levers. According to the authors, pyrolysis allows up to 40% impact savings because of recovered material.

From Table 3, it is clear that numerous research attempts have been made to discover the environmental impacts of recycling CFRPs. Most studies rely on LCA/LCI databases and follow similar procedures. However, the studies tend to be different in terms of considered recycling methods, lifecycle phases included in the investigation, assessed impact indicators, and databases used. Also, the studies mainly considered energy impact and GWP in terms of assessed impact categories. The research interest in determining the environmental aspects of recycling CFRPs is robust and notable work has already been done in this field. All the recycling methods mentioned in this study were examined to some extent to see if the positive environmental implications compared to traditional disposal ways are observed. Despite numerous research efforts that have been highlighted in this review, there are still other challenges associated with the effective and accurate estimation of environmental impacts of recycling CFRPs. These challenges are tightly tied with the research gaps which were formulated based on the conducted literature review. The following subsections provide information on challenges related to this field.

a. Variability of methodologies

Although ISO 14044 documentation stipulates specific standards for the LCA assessment, there is still a great variability within an inventory (LCI) and impact analysis (LCIA) (Kousemaker *et al.*, 2021). First, the modelling approach may vary as some modellers can use the attributional LCA method. In attributional LCA the functional units or phases of the product are attributed according to average retrospective data within a specific period. Conversely, consequential LCA is conducted to determine the change in the environment due to the effects of inputs and outputs of the product(Kousemaker *et al.*, 2021).

Overall, LCA methodologies have evolved significantly in the last 30 years and have different classification and characterization methods. For instance, the midpoint level indicators might vary from method to method. Some of the methodologies might include completely different indicators compared to the others. (Bekker *et al.*, 2016).

b. Comparability - functional and system boundaries, oversimplification

It is critical to determine the functional and system boundaries in the assessment as it directly influences the final interpretation of the assessment results. Ambiguous or unclear definitions of the functions and processes in the recycling chain (not mentioning the usage of accompanied products during the recycling process and other similar omissions) may result in an inaccurate estimation of the final impact. It may seem that comparing recycling methods in terms of an environmental impact is sufficient to examine only the primary processes, however, it may jeopardize the purpose of the environmental assessment (Hetherington *et al.*, 2014). The recycling processes differ in terms of functions (some of them are multifunctional), and the byproducts they produce. It is a challenging task to split the environmental impact within multifunctional recycling methods (Heidrich and Tiwary, 2013). For instance, the fluidized bed and pyrolysis process results in byproducts that can be transformed into energy, whereas mechanical recycling does not recover energy (Pickering, 2006).

The mentioned challenges in terms of comparability methods are accompanied by the challenge related to the LCA methodology itself. For example, an oversimplification, during which the model limitations and simplify cations result in significant influence on the outputs (da Silva *et al.*, 2021). The oversimplification challenge is highly tied to small companies which struggle to implement the LCAs due to the lack of amplitude (Heidrich and Tiwary, 2013).

c. Scaling the results

Not all recycling processes have reached the readiness level to be exploited at an industrial scale. Only pyrolysis and mechanical grinding for recycling CFRPs have shown Technology Readiness Levels (TRLs) of 8 and 6.5 respectively. Whereas solvolysis and fluidized bed processes are still at the validation phase in the laboratory environment (Rybicka et al., 2016). This indicates that these methods do not consider the complexity of the industrial scale equipment, management, and additional investment (Hetherington *et al.,* 2014).

Hence, scaling the results by using common practices or just by normalization may not result in accurate results for processes that are still at the laboratory scale.

d. Data related challenges

Data for LCI/LCA approach is systematically summarized and publicly available in Ecoinvent and Simapro for various materials and processes (Ecoinvent, 2021; Simapro, 2021). However, those databases do not contain specific information for processes related to composite manufacturing, recycling and disposal. For instance, Vo Dong *et al.* (2018) extract data for a landfilling process from Simapro v7.3 and Ecoinvent 2.2 for mixed polymer plastics instead of composites, as there is no specific data on the environmental effects of composites landfilling. Other parameters of a model for LCI in the studies are also accompanied by the great extent of impreciseness, e.g., energy consumption levels of recycling processes. In the analysis done by Witik *et al.* (2013), the authors examined the product manufacturing phase which is assumed to be using 162 MJ for electricity and 191 MJ of heat from gas. On the other hand, the manufacturing of virgin carbon fibers varies between 183 to 286 MJ per kg (Giorgini *et al.,* 2020). This all demonstrate that the data used in models are not accurate with uncertainty factors embedded in input parameters. Thus, missing datasets for specific processes is a challenge to some extent that has to be overcome by conducting experiments and investing time (Hetherington *et al.,* 2014). In addition, other circumstances negatively affect the reliability of data such as the quality of data in terms of the geographical source, consistency, the compatibility of data from different sources, reasonable assumptions and reproducibility (Heidrich and Tiwary, 2013).

e. Uncertainty

Any LCA study will have results affected by a degree of uncertainty. During the assessment, all the factors will influence the accuracy of results, for example how model data is arranged and which scope is selected (Heinzle *et al.*, 1998). In fact, most of the studies considered in this work agree with the uncertainty of the LCA method to a certain degree. The difference in methodologies, the discrepancy between lab test results vs implementation of an industrial project, and data quality in combination create a snowball effect. This causes the level of uncertainty of a study to be too high to be used for decision making. Given that the LCA analysis for new emerging recycling methods is conducted for further decision making, determining and leveraging the uncertainty of conducted studies is essential (Hetherington *et al.*, 2014). Figure 5 demonstrates the level of uncertainty and technology readiness level relationship. Composites recycling technologies (CRT) on the technology readiness (TRL) scale is adapted from Rybicka et al., 2016. The more data is available to conduct LCA, the more accurate results will be obtained during the assessment.

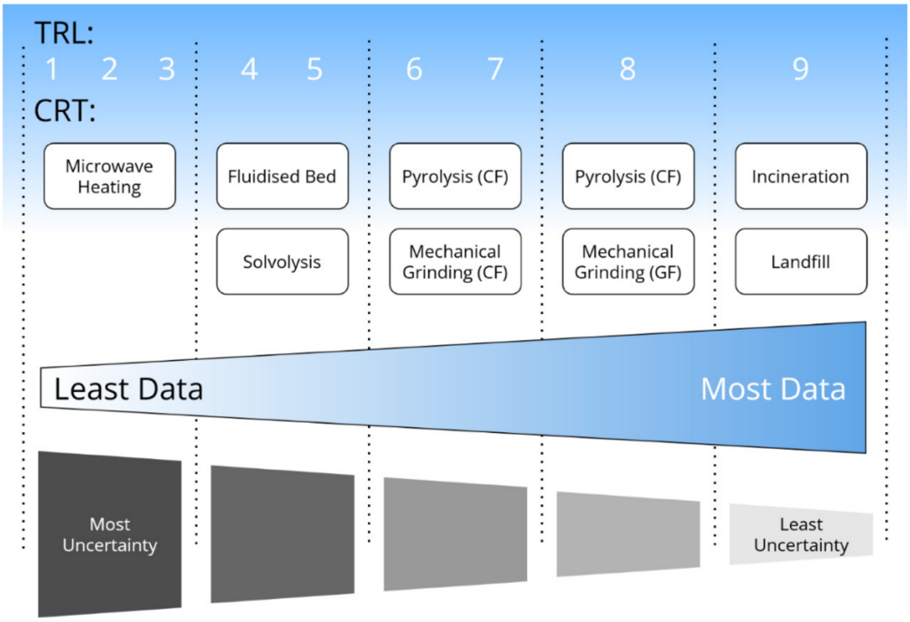

Figure 5. Uncertainty level representation with respect to TRL of the CFC recycling process

f. Resource demanding assessment.

Although there is no minimum threshold for assessing product sustainability (Heidrich and Tiwary, 2013), the LCA methodology allows approximating the environmental impact of supply chain operations by analyzing the data. However, environmental assessment is a time and resource-consuming activity for the industry. It requires expertise, knowledge and financial support as well as adequate environmental data to conduct an LCA study (Heidrich and Tiwary, 2013). Moreover, the information and data need to be updated accordingly, especially for products with a long lifecycle due to economic and environmental conditions changing over time (Kousemaker *et al.,* 2021).

Conclusions and future directions

The processes for recycling CFRPs such as mechanical recycling, pyrolysis, fluidized bed process, and solvolysis result in different qualities of recovered fibers and vary in terms of costs and environmental impacts. This work provided a brief overview of studies that covered the theme of environmental assessment aspects of recycling CFRPs. At present, this field has several studies that mainly investigated CFRP recycling in the context of LCA frameworks. Several works were published assessing the environmental challenges including different lifecycle phases for different methods. This study has identified the main challenges such as the variability of methodologies, comparability, scaling results, data, and uncertainty, resource demandsThe further developments in the environmental assessment of CFRP recycling can be fulfilled through the following future directions:

- A combined methodology should be used with a preliminary agreement with the studies considered in this research. Standardization of the LCA framework for CFRPs within the industries (automotive, and aerospace) will help to unite and compare statements from different authors.

- Promoting data availability for CFRP in current databases could be a critical action to bring potential benefits to various stakeholders instantly. However, no accurate data on CFRP manufacturing and recycling is present in databases. The quality of data and availability are the key factors which define the reliability of results. Therefore, it is highly recommended to improve current databases with specific composite materials data.
- LCA studies convey a lot more information as they include the use phase. Some industries benefit from weight savings (for instance, in the automotive industry), therefore consume less fuel in the use phase..
- The collaboration between researchers and recycling industry-related stakeholders will increase the reliability of conducted studies. Because simplyscaling the laboratory output does not provide reliable data. The LCA studies conducted within the laboratories using existing databases could be integrated into plant-level studies to demonstrate real-time cases.

Design informed thinking should be promoted. The LCA proves that the positive environmental effects during the production and use phases could be achieved ifthe design of a product is known beforehand. Though composite material components are usually produced with specific shapes and parameters, it is always possible to incorporate into the design features. This would further allow reuse/remanufacturing of the component in less demanding applications. The opportunities for secondary applications of recycled CFRP shall be rigorously researched to reduce landfilling impacts and avoid an intensive increase in manufacturing rates of virgin CFRPs. This statement is especially critical that the effect of replacing virgin carbon fiber has the dominating positive environmental effect due to avoided energy consumption.

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