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Insights into environmental sustainability of microwave assisted chemical recycling of CFRP waste using life cycle assessment

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ABSTRACT

With the rapid development of fiber/matrix-based composites in the wind and aerospace industries, minimizing the environmental impact of composite waste has become a critical concern. This study compares pyrolysis and chemical recycling using nitric acid with the microwave assisted chemical recycling (MACR) process for carbon fiber reinforced polymer (CFRP) composite waste. The Life Cycle Assessment (LCA) tool in OpenLCA2.1® software evaluated three recycling scenarios, assuming recovered carbon fibers (RCFs) could be used for new composites. An inventory model was developed for virgin carbon fiber (VCF) production, CFRP manufacturing, and the three recycling processes, with environmental indicators identifying key variables. The results show that the MACR process has the lowest global warming potential (0.64 kg CO_2 eq.) and ozone depletion potential (0.46×10^{-8} kg CFC-11 eq.) compared to other methods. VCF production is energy-intensive, but if RCFs exhibit similar mechanical properties, they could replace VCFs in new composites. The MACR process also demonstrated higher Recycling System Credits (RSC), lower environmental impacts, and reduced energy consumption. Through comprehensive analysis of the results obtained in this study, the MACR process demonstrates significant benefits by reducing VCFs production burdens and pollution emissions, making it a promising solution for managing composite waste.

Introduction

Transitioning to a circular economy demands a fundamental departure from the linear “take-make-waste” model toward a comprehensive multi-life-cycle circular paradigm (Abagnato et al., 2024; Arena et al., 2023; Bisinella et al., 2024). This shift necessitates addressing design and material aspects in producing fiber reinforced polymer (FRP) composites to facilitate circularity (Hao et al., 2020; Krauklis et al., 2021; Hancox, 1996). Recycling is a cornerstone in this endeavor, aiming for “closed loop recycling,” where waste resources are restored to their near original state without compromising quality.

For years, FRP composite waste predominantly found its way into landfills. The recent EU Directive on Landfill of Waste (Directive 99/31/EC) marks a significant step towards reducing the disposal of FRP composite waste (Bishop, 2001). The wide-ranging applications of FRP composites, i.e., carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composites, spanning renewable energy, automobiles, construction, aeronautics, aerospace, sports, and defense, underscore their value in high-performance and lightweight endeavors (Duflou et al., 2012; Larsen, 2009). The global FRP composite market, valued at USD 95.89 billion in 2020, is projected to reach USD 160.54 billion by 2027, with CFRP and GFRP composites playing a significant role, particularly in lightweight applications (Meng et al., 2020; Thomas and Ccev, 2015). The 2021 report by the Global Wind Energy Council (GWEC) underscores the indispensability of attaining net-zero CO_2 emissions by 2050 to mitigate climate change, with wind energy playing a pivotal role (Wind and Council, 2021).

Mechanical, thermal, and chemical recycling approaches have emerged as potential solutions for FRP composite waste management. While mechanical recycling compromises fiber quality, thermal

Abbreviations: CFs, Carbon fibers; CFRP, Carbon fiber reinforced polymer; EIA, Environmental impact assessment tools; FRP, Fiber reinforced polymer; GFs, Glass fibers; GFRP, Glass fiber reinforced polymer; GHG, Greenhouse gases; GWP, Global warming potential; HTP, Human toxicity potential; LCA, Life cycle assessment; MACR, Microwav assisted chemical recycling; ODP, Ozone depletion potential; RCFs, Recovered/recycled carbon fibers; RFs, Recycled fibers; RSC, Recycling system credit; VARIMC, Vacuum assisted resin infusion microwave curing; VCFs, Virgin carbon fibers; VFs, Virgin fibers; WTs, Wind turbines.

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processes are high energy consumption and contribute to greenhouse gas emissions. Chemical recycling shows promise in recovering fibers with comparable properties to virgin fibers, yet operational costs remain challenging (Rani et al., 2021).

The life cycle analysis (LCA) is a globally standardized framework that comprehensively examines a product's environmental impact from production to disposal (Antelava et al., 2019; Dominguez Aldama et al., 2023). Several studies have focused on employing LCA as a decision-supporting tool for identifying the most suitable recycling processes based on environmental impact assessment (BASF, 2020; Deschamps et al., 2018; Foelster et al., 2016; La Rosa et al., 2018; Xiao et al., 2016). Lee et al. revealed higher energy consumption (6 times) and greenhouse gas (GHG) emissions (5 times) in pyrolysis compared to the acid method (Lee et al., 2010). Seeking to be more sustainable, Nunes et al. further explored the environmental impacts of recycling CFRP composite waste using steam thermolysis. This study highlighted the reduced environmental burden associated with recycling scenarios compared to non-recycling scenarios (Nunes et al., 2018). Similarly, La Rosa et al. investigated the environmental implications of recycling composite materials. The study focused on the effects of different treatments on the mechanical properties of recovered carbon fibers (RCFs) (La Rosa et al., 2021, 2018, 2016). In 2018, Khalil compared thermolysis and solvolysis as recycling methods for CFRP waste, emphasizing their energy efficiency, GHG emissions, and potential health risks (Khalil, 2018). Despite their benefits, both techniques pose environmental and health hazards, necessitating careful consideration.

Additionally, the economic feasibility of recycling processes plays a crucial role in their viability. The cost analysis of recycling is essential, as the process and the resulting recycled products should be more cost-effective than producing new materials. From an economic standpoint, life cycle cost (LCC) analysis is particularly relevant, as it evaluates the overall cost implications of the recycling process, including energy consumption and resource use.

Existing recycling methods consume high energy and have significant environmental impacts, emphasizing the need for sustainable alternatives. Microwave-assisted chemical recycling (MACR) offers a promising solution using eco-friendly chemicals and microwave heating to recover fibers (Rani et al., 2022). Microwave energy has gained attention in green and synthetic organic chemistry. Researchers use the MACR process to recover GFs/CFs from composite waste by breaking down the crosslinked epoxy matrix under microwave irradiation with chemical solvents like tartaric acid, acetic acid, supercritical water, nitric acid, and hydrogen peroxide. This process is environmentally friendly, sustainable, energy-efficient, and rapid. Despite its advantages, MACR faces challenges in industrial applications. Non-uniform microwave energy distribution can create hot spots, degrading recovered fiber properties. Since crosslinked composites are microwave-transparent, chemical solutions initiate microwave interactions, accelerating the reaction and breaking down the matrix (Jiang et al., 2015). Thermal decomposition generates volatile gases (CO_2, CO, hydrocarbons), requiring effective gas handling, purification, and emission control to prevent pressure buildup and environmental hazards. Addressing these challenges is crucial for the industrial-scale adoption of MACR technology.

This study aims to assess the environmental and economic benefits of the MACR process using LCA and LCC. This study aims to assess the environmental and economic impact of the MACR process for CFRP composite waste. LCA of MACR is not reported in the literature, representing a potential research gap. By conducting an LCA and LCC assessment, this study aims to compare the environmental and economic impacts of the MACR process with traditional recycling routes such as pyrolysis and chemical methods. Ultimately, this research endeavors to provide insights into recycling routes for composite wastes, prioritizing material recovery, and fostering a circular economy approach.

The LCA and life cycle cost methodology

The concept of LCA was first introduced by SETAC (Society of Environmental Toxicology and Chemistry) in 1993, emphasizing the analysis of a product or process "from cradle to grave" to encompass all stages, from raw material extraction to final disposal (SETAC, 1993). According to the ISO 14040 series (ISO 14040; ISO 14044), an LCA study consists of distinct phases: the definition of study objectives and scope, inventory analysis, impact assessment, and interpretation of the life cycle (Foelster et al., 2016).

Goal and scope

This research focuses on the assessment and comparison of environmental impacts and life cycle cost (LCC) of recycling processes. Three product systems were analyzed for recycling the CFRP composite waste: pyrolysis, chemical recycling using nitric acid, and MACR. The MACR process was used in the lab to recycle the CFRP composite waste. The functional unit is the amount of CFRP waste composite quantified in 1 kg. Transport, waste cutting, and scrapping processes were excluded from the study due to their consistent nature in various scenarios and focus on laboratory-scale analysis.

System boundaries and End-of-life (EoL) allocation

The open-loop and closed-loop cycles are crucial for assessing the environmental impact of a system or product. The choice of allocation at the end of life plays a key role in life cycle analysis. In an open-loop cycle, the end-of-life allocation involves disposal or repurposing into another product. For example, Composite 1 uses virgin carbon fiber(s) (VCFs) as shown in Fig. 1. After its end of life, it is either disposed of or used in another application but not returned to the same product. In a closed-loop cycle, Composite 1 is recycled to recover CFs, which are then used to produce Composite 2. Here, RCFs replace VCFs in a 1:1 substitution approach. Since Composite 2 contains recycled content, the cut-off approach is applied, meaning all the environmental benefits of recycling are allocated to Composite 2 rather than Composite 1 (Pradhan et al., 2019; Tapper et al., 2020).

This study focuses on recycling waste composite materials and recovering recycled fibers for further use. The cut-off approach (100:0 approach), as suggested by Pradhan et al. (2019), assigns the entire environmental impact (positive or negative) of the recycling process to the product (Composite 2) that uses recycled fibers without attributing any burden to Composite 1. If the material can be reused for a new product, the 1:1 substitution approach will be adopted (Bovea and Gallardo, 2015).

Scenario description: the performed LCA is cradle to grave approach with the assumption that the recycled fibers (RFs) can be reused further for the manufacturing of the composites as fibers have smooth surfaces and no epoxy residue was observed for the MACR process (Rani et al., 2022). The input into the system was the CFRP waste. On the output side, the RCFs are for reuse with degraded epoxy as waste and emissions. The percentage of RCFs will be the same as the weight fraction of the CFs in the CFRP composite. The RCFs can be brought back into the value chain as the mechanical properties of the RCFs are like the VCFs (La Rosa et al., 2021). The various scenarios are as follows:

Scenario 1: Modeling of the CF manufacturing and epoxy material as raw material for CFRP composite.

Scenario 2: Modeling of the pyrolysis process of the CFRP composite waste.

Scenario 3: Modeling of the chemical recycling process with nitric acid for CFRP composite waste.

Scenario 4: Modeling of the MACR processes for CFRP composite waste.

Test for mass and energy balance: the mass balance was obtained by using the weight of the input as CFRP composite waste (weight fraction of the fibers in the composite) and output as RFs weight, while the

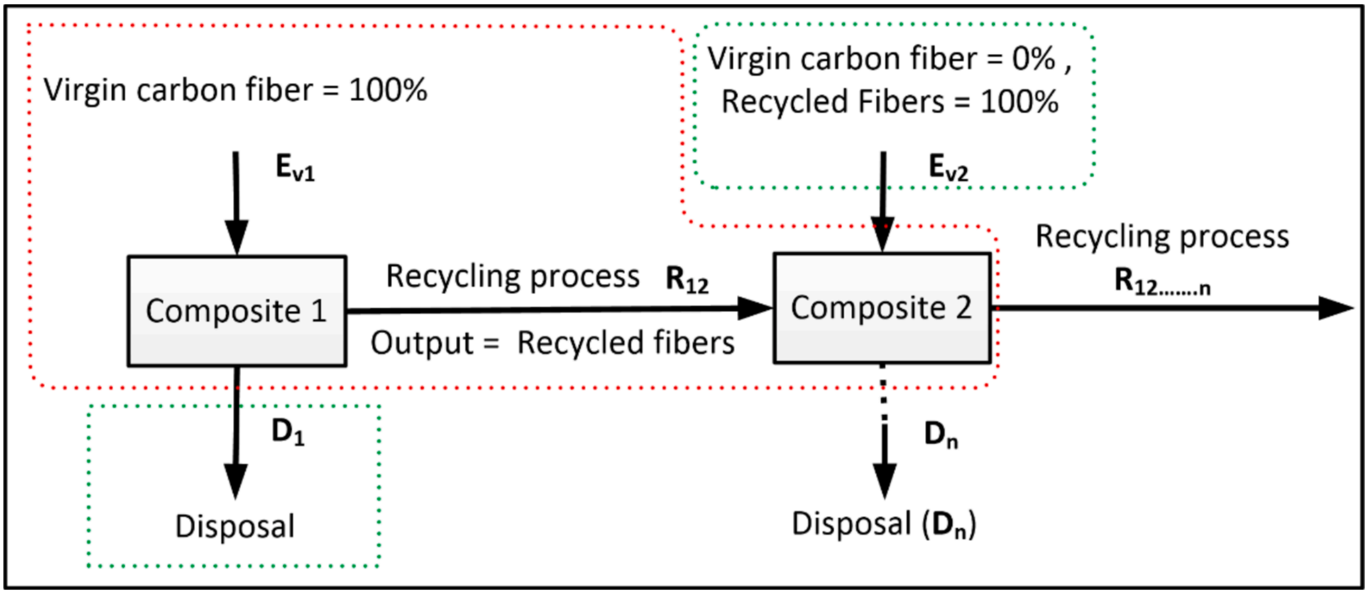

Fig. 1. Allocation of system boundaries for the open and closed loop cycles to assess the environmental impact.

consumption of electricity was determined by the power and time duration used for the recycling process.

Life cycle inventory (LCI) analysis

LCI (Life Cycle Inventory) is essential as it establishes the database for the analysis, detailing the input and output of selected scenarios in the LCA analysis. Data on raw materials, pyrolysis, and chemical recycling using nitric acid were obtained from literature databases and the commercial database Ecoinvent v3.8. The MACR data for LCA and LCC were collected from laboratory experiments. A detailed flow diagram was generated using LCA software to capture the necessary data for the database, outlining each process with comprehensive information.

Raw material (carbon fibers) and manufacturing of CFRP composite analysis

The data related to raw material (VCF and epoxy) production and consumables for CFRP manufacturing are listed in Table 1. VCFs are produced using polyacrylonitrile (PAN) as a precursor, which is obtained from the Ecoinvent 3.8 database and literature (La Rosa et al., 2021) along with electricity (Table 1). For the composite matrix, epoxy resin is used along with diethanolamine as a hardener. The flow graph of LCA for CFRP composite manufacturing is shown in Fig. 2, and the data from Table 1 is used in the LCA study.

CFRP composite as a composite waste

In this study, the CFRP composite waste material was taken from the left-out or cut-out samples from the lab. The CFRP composite waste with a density of 1.58 g/cm^3. The weight fraction of the fibers and epoxy of the unidirectional composite was 57.5 wt% and 42.5 wt%, respectively. To conduct the experiment, the initial step involves preparing a CFRP composite sample using the vacuum assisted resin infusion microwave curing (VARIMC) technique (Kumar et al., 2021; Rani et al., 2023; Sotoodeh, 2022). Epoxy resin and diethanolamine are utilized as the matrix. At the same time, consumables such as vacuum bags (made of Nylon 6,6), breathers, tacky tape (made of synthetic rubber), and aspiration tubes (made of PA 6,6) are employed during the VARIMC process. Additionally, electricity is required for the vacuum pump and oven. In the VARIMC procedure, fiber reinforcements are added to one side of a mold and covered with plastic bagging material to create an airtight seal. The resin is introduced into the structure via strategically positioned ports and feed lines called a 'manifold.' Channels designed within the structure aid in the wetting-out of fibers by facilitating the flow of resin through the reinforcements using vacuum assistance.

Table 1
The inventory required for manufacturing CFRP composites using the VARIMC process includes raw materials (carbon fiber and matrix material), consumables for the vacuum bagging arrangement, and electricity for composite curing.

S. No.	Process	Material		Amount	Unit
1.	Carbon Fibers production	Input	Polyacrylonitrile fibers (PAN)	22.72	kg
			Electricity, high voltage	10,428	MJ
		Output	Carbon fibers	22.72	kg
2	Composite-matrix production	Input	Diethanolamine (Hardener)	8.55	kg
			Epoxy resin, liquid	4.23	kg
		Output	Composite matrix	12.78	kg
3	Consumables requirement	Input	Nylon 66 granulate (PA 66) (Vacuum bags)	1.228	
			Polyethylene terephthalate (PET) granulate	2.579	kg
			Synthetic rubber (Tacky tape)	19.11	kg
			Polyamide 6.6 fibers (PA 6.6) (Aspiration tubes)	1.256	kg
		Output	Consumables	24.173	kg
4	Manufacturing of CFRP composite using VARIMC process	Input	Carbon fibers	22.72	kg
			Composite matrix	12.78	kg
			Consumables	24.173	kg
			Electricity	41.76	MJ
		Output	Composite panel	35.5	kg

Recycling process

Pyrolysis recycling process. It is a thermal recycling process. The flow graph for the LCA for the recycling of the CFRP composite using pyrolysis is shown in Fig. 3(a). The pyrolysis recycling process involves heating a composite material to decompose materials other than carbon fiber. In this process, the CFRP composite as a waste material is first put inside the furnace. Then, the CFRP composite waste sample is heated

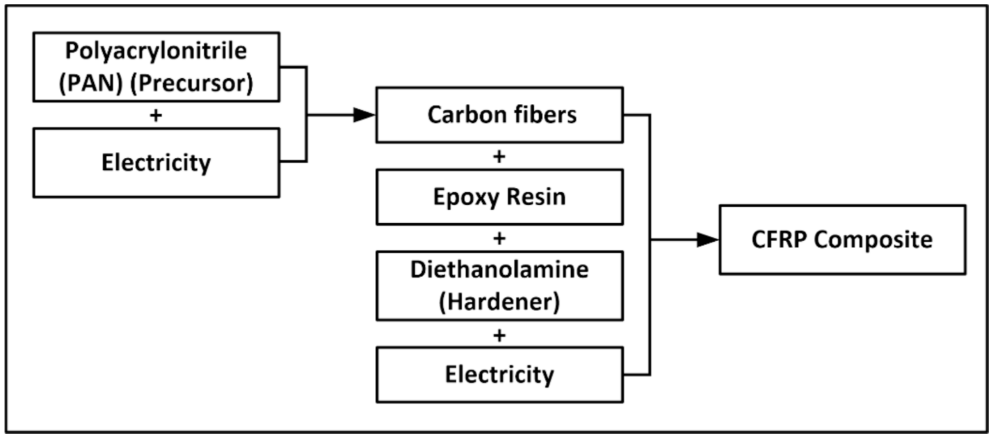

Fig. 2. The flow graph for the life cycle inventory of manufacturing the CFRP composite using the VARIMC process.

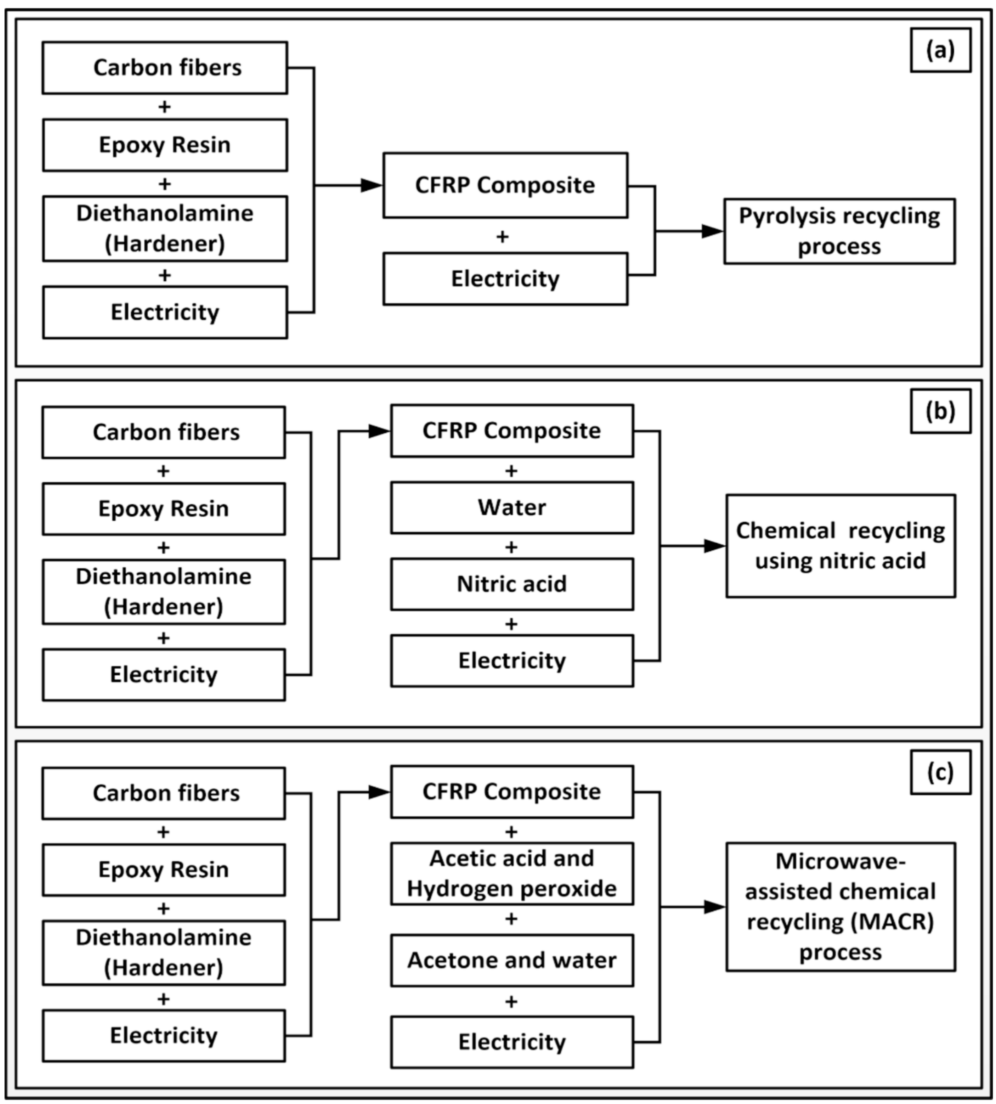

Fig. 3. The flow graph for the LCA for (a) Pyrolysis recycling process, (b) chemical recycling using nitric acid, and (c) MACR process of the CFRP composite.

from 400 °C to 1000 °C, depending on the composite waste type and the reinforcement material used. The by-product of this process is in liquid form, which means that tar and other heavy liquids can be taken in as oil and other products. Gas products, i.e., CO_2, H_2, CH_4, and other hydrocarbons with low calorific value (CV), could still be used as energy sources. This process is also called an independent recycling process because of these by-products. The process variables of the Pyrolysis process must be optimized to ensure economic and maximum recovery of solids, fuels, and chemical products (Rani et al., 2021). The decomposable product gets decomposed during the heating process, and only carbon fibers are left. The Pyrolysis process is performed without oxygen or with very little oxygen (Lee et al., 2010).

Chemical recycling using nitric acid. The utilization of nitric acid enables the recycling of both CFRP and GFRP. The process involves cutting the composite waste into small fragments and immersing them in heated nitric acid to decompose the waste and recover the CFs from the CFRP composite waste. The recovered material is then thoroughly washed and dried in air for 24 h. To recover CFs from the CFRP waste, the ratio used for composite waste and nitric acid solution for the experiment was 1 kg:1000 mL (Lee et al., 2010).

The CFRP composite waste prepreg was submerged to recover CFs. The matrix resin is broken down in heated nitric acid. First, the prepreg was cut into pieces. The procedure involved submerging the cut pieces into a glass tube containing nitric acid and placing the test tube in a bath of water at 60 °C for 30 min to recover the CFs. The next step involved adding a 10 % aqueous solution of sodium hydroxide to the prepreg and sonicating it in a 1 % aqueous solution of sodium sulfite at ambient temperature for 1 h. The carbon fiber recovered and was then air-dried for 24 h at 40 °C. The matrix resin was decomposed by submerging the prepreg in heated nitric acid (Hanaoka et al., 2022). The flow graph for the LCA for the recycling of the CFRP composite using chemicals with nitric acid is shown in Fig. 3(b).

Microwave-assisted chemical recycling (MACR). The MACR (microwave-assisted chemical recycling) process can recover CFs and glass fibers (GFs) from composite waste. Rani et al. suggested using a chemical solution composed of acetic acid (CH_3COOH) and hydrogen peroxide (H_2O_2) in a ratio of 50:50 with microwave heating (700 W) for 30 min duration to recover the GFs from the composite waste (Rani et al., 2022). For recycling the CFRP composite sample using the MACR process, a 1 kg CFRP composite is cut and employed in the recycling process to recover CFs, and the flow is shown in Fig. 3(c). A chemical solution is prepared using a ratio of 3000 mL of chemical solution to 1 kg of CFRP composite waste. The chemical solution comprises acetic acid and hydrogen peroxide, with 50 % hydrogen peroxide in acetic acid. Once the chemical solution is prepared, the sample is immersed. Subsequently, the immersed sample is subjected to microwave heating for 30 min, then cooling at room temperature. The decomposed epoxy resin and CFs are then separated, washed using acetone, and dried at 70 °C. Table 2 displays the inventory data for MACR, which is necessary to recycle 1 kg of CFRP composite waste using the MACR process to recover CFs. Microwave heating is then applied to the solution, which requires electricity, to enable the recycling of composite waste. Recycling of composite waste using the MACR process is done experimentally to recover CFs, as reported in the previous study (Rani et al., 2022). The decomposition rate of epoxy was more than 97 %. The mechanical properties of the RCFs were determined using the ASTM D3822M. The decomposition rate of epoxy exceeded 97 %. The RCFs showed smooth (defect-free) and clean surface morphology. The mechanical properties of the RCFs were determined using ASTM D3822M. The RCFs retained 98.3 % of the tensile strength, 94.1 % of Young's modulus, and 96.2 % of the strain-to-failure of the VCFs. Literature also reports similar retained mechanical properties for RCFs, with 92 % tensile strength and 94 % strain-to-failure compared to VCFs, and a decomposition efficiency exceeding 95 % (Zabihi et al., 2020).

Life cycle impact assessment (LCIA) method

All the inventory data described in the previous section (Section 3) were modeled using the OpenLCA 2.1® software tool (GreenDelta, Berlin, Germany) with the Ecoinvent 3.8 database for the LCI phase. Selecting impact categories is crucial for obtaining clear and relevant LCIA results. During the recycling phase, the environmental impacts caused by resource consumption and emissions are estimated by evaluating the materials generated. A variety of impact categories is considered when assessing environmental impacts. For this analysis, the LCIA methodology was applied, offering methods such as CML-IA baseline, ReCiPe endpoint, ReCiPe midpoint, and cumulative energy demand (CED) for impact assessment (Iswara et al., 2020; Nunes et al., 2018; Pradhan et al., 2019; Shahadahtul Afizah Asman et al., 2023). For this study, the CML-IA baseline method was used. It is a midpoint approach that links all stages of the life cycle inventory to the following impact categories: global warming potential (GWP) (GWP100a) (kg CO_2 eq.), human toxicity Potential (HTP) (kg 1,4-DB eq.), ozone layer depletion (ODP) (kg CFC-11 eq.), abiotic depletion (kg Sb eq.), abiotic depletion (fossil fuels) (MJ), acidification (kg SO_2 eq.), eutrophication (kg PO_4 − eq.), freshwater aquatic ecotoxicity (kg 1,4-DB eq.), marine aquatic ecotoxicity (kg 1,4-DB eq.), photochemical oxidation (kg C_2H_4 eq.), and terrestrial ecotoxicity (kg 1,4-DB eq.).

Results and discussion

Interpretation of results is the final phase of LCA. This section discusses the findings obtained from the LCI and LCIA phases. The impact evaluation will be discussed for each process, highlighting the impact of materials and energy for a clearer understanding.

LCIA: Raw material and manufacturing process

First, an analysis was performed to determine the influence of the VCFs production and CFRP manufacturing process. Fig. 4(a) shows all the potential stages that can contribute to the GWP. The GWP is a key consideration for the LCA analysis of VCFs production and CFRP

Table 2
Inventory data for chemical, pyrolysis, and MCAR recycling processes.

Recycling Process	Input raw material		Energy Input		Output material	
	Material (kg)	Quantity	Process CED (MJ)	Quantity	Material (kg)	Quantity
Chemical Recycling	Nitric acid	6.3	Electricity	23.08	Carbon fiber	0.6
	Water	1			2,4 Dinitrophenol (g) (degraded epoxy)	2.4
	Composite waste	1				
Pyrolysis	Composite waste	1	Electricity	43.2	Carbon fiber	0.32
					Sulfur dioxide (SO_2)	0.26
					Hydrogen cyanide (HCN)	0.13
					1-Butene, 2,3-dimethyl	0.13
					Other waste	0.186
MACR	Composite waste	1	Electricity	1.26	Carbon fiber	0.64
	Acetic acid (CH_3COOH)	1.5			Plastic and epoxy waste	0.36
	Hydrogen peroxide (H_2O_2)	1.5				
	Acetone	0.50				
	Water	1				

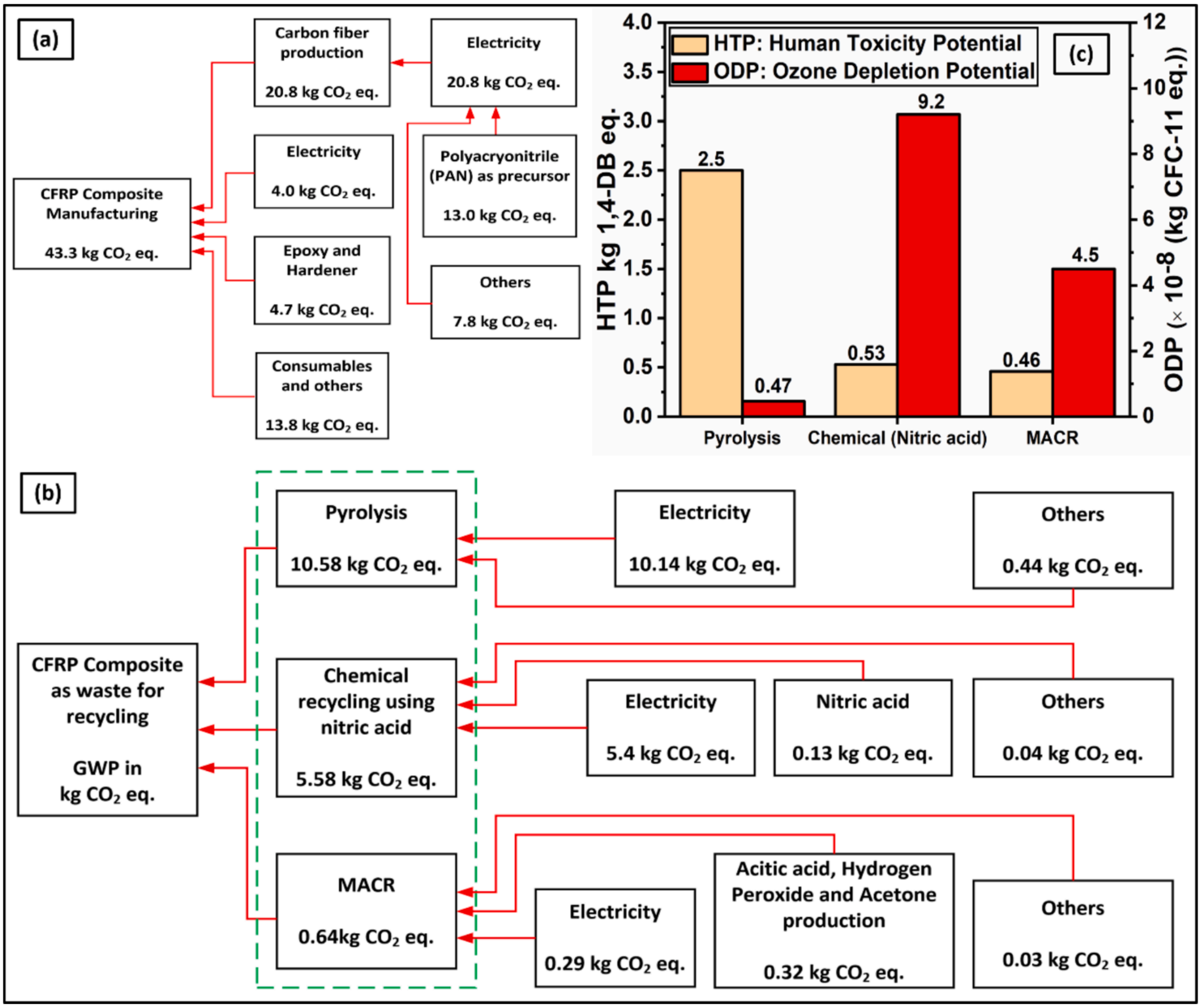

Fig. 4. Network graph showing the global warming potential (GWP) with unit kg CO_2 eq. of the (a) virgin carbon fiber production and CFRP composite manufacturing and (b) different recycling processes for CFRP composite waste. Scenario of the virgin carbon fiber production, manufacturing, and recycling of the CFRP composite in OpenLCA2.1®. Fig. 4 (c) Impact analysis of recycling process for Human toxicity potential, and ozone depletion potential.

composite manufacturing. Fig. 4(a) illustrates the LCA network of the VCFs and CFRP composite manufacturing process. Each unit process described in the boxes indicates the results of GWP as kg CO_2 eq.

The production of VCFs is the main GHG emission source. The largest GWP impact primarily was due to electricity usage, making it an energy-intensive process (Paulauskas et al., 2000; Rani et al., 2021). In this scenario, the main contributor to GWP is the production of VCFs alone. Similar results were reported in another study (Howarth et al., 2014). In contrast, the manufacturing of CFRP composite uses less electricity, using the VARIMC process, which incorporates microwave heating. Here, the use of microwave energy helps to reduce the GWP impact of the manufacturing process.

It is evident from Fig. 4 that the primary contributor to GWP impact in this system or scenario is electricity production. Electricity generation typically relies on fossil fuels, leading to carbon dioxide (CO_2) emissions. This combustion process accounts for approximately 40 % of the global carbon dioxide emissions, a significant contributor to global warming. Effective recycling processes are crucial to address the GWP impact and reduce the need for VCFs production. Millions of tons of CFRP composite waste end up in landfills or are incinerated, presenting environmental concerns. Efficient recycling processes can recover CFs from CFRP composite waste, minimizing the demand for new VCFs production. By implementing effective recycling methods, the industry can mitigate the impact of VCFs production on GWP and manage waste sustainably.

LCIA: Recycling process

The impact factors considered for recycling processes are GWP, HTP, and ODP. The impact of GWP for all recycling processes is shown in the network diagram (Fig. 4b.). From the Fig. 4b analysis, the maximum contribution in both the recycling process (pyrolysis and chemical recycling with nitric acid) is because of the emissions from electricity production or electrical power production required to recycle the waste generated from CFRP composite to recover the carbon fibers. The impact associated with the electricity production for the pyrolysis process (i.e., 10.14 kg CO_2 eq.) is almost 2 times more than the impact associated with the electricity production for chemical recycling process using nitric acid (i.e., 5.4 CO_2 eq.) as shown in Fig. 4b. The maximum impact is associated with the electricity production required to recover the CFs from the CFRP composite waste in all three processes (pyrolysis recycling process, chemical recycling process and MACR process). Compared to the remaining two processes, i.e., the pyrolysis recycling process and chemical recycling process using nitric acid, the impact associated with electricity production in the case of the MACR process is comparatively much less. The contribution of electricity production in the GWP for the MACR process (0.29 kg CO_2 eq.) is almost 36 times less than the contribution of electricity production in the global warming potential for pyrolysis recycling (i.e., 10.14 kg CO_2 eq.) process and almost 19 times less than the contribution of electricity production in GWP for chemical recycling process using nitric acid (i.e., 5.4 kg CO_2 eq.). Some impact categories were selected for the impact assessment phase for LCA analysis of recycling. Considering these impact categories, the results obtained are represented in the graphical form, as shown in Fig. 4c.

The HTP can be described as a measure that indicates the potential danger posed by a unit of chemical released into the environment. The harm caused by each hazardous chemical is evaluated based on its equivalence to 1,4-dichlorobenzene (DB) per kilogram of emission. Because of the limited oxygen and high heat, this process generates synthetic oils and gases, which come with ash, char, and air pollution. These are dangerous for our health and the environment. The ozone depletion potential (ODP) measures each compound's capacity to contribute to atmospheric ozone depletion.

Comparison of GWP for VCFs production, CFRP manufacturing, and all recycling processes by LCA analysis

Recycling allows the environmental burden to be avoided for GWP impact categories, as it avoids the consumption of VCFs at a substitution rate 1:1 of RCFs. The networking diagram (Fig. 5) shows the contribution of GWP impact categories for each process. The red line with the arrow shows the environmental impact of the process or product. The green line with the arrow shows the burden avoided by recycling systems or processes. Fig. 5 suggests that the largest GWP impact (20.8 kg CO_2 eq.) occurs during VCFs production due to the high energy-intensive process. All the recycling processes reduce the environmental burdens and encourage the reuse of RCFs in new composites. If recycling is adopted as the waste management strategy for CFRP composites. It can reduce the manufacturing demand for VCFs and promote the reuse of RCFs if the properties of the RCFs are similar to VCFs. Encouraging the use of RCFs in new composites will promote circular economy principles and sustainability while enhancing recycling credits due to the lower energy consumption to produce RCFs via recycling compared to VCFs production processes. If the output is nearly similar, we should prioritize energy and environmental conservation to achieve sustainability goals, which are primary objectives for every nation. While all recycling processes contribute to sustainability goals, the most sustainable recycling process, according to the analysis of LCA results, is MACR. The MACR process has a carbon footprint of 0.64 kg CO_2 eq., 16 times and 8 times lower than pyrolysis and chemical recycling, respectively. Impact assessment highlights that energy usage during pyrolysis and chemical recycling is a major contributor to environmental impacts. Using microwave energy during MACR can be attributed to lower carbon footprints or environmental impact.

The environmental burden associated with the recycling process and the equivalence system (CFRP manufacturing and VCFs production). The environmental burdens caused by recycling are less compared to non-recycling. The equivalence system in Fig. 6 (a) shows an environmental impact of 43.3 kg CO_2 eq. The environmental burdens for recycling systems are less compared to the equivalence system. The environmental burden is decreased by 75.5 %, 87 %, and 98.5 % for pyrolysis, chemical, and MACR process with respect to the equivalence system. This equivalence system involves the manufacturing of CFRP composite. After the EoL of the CFRP composite product, if no waste management is applied, there will be a loss of CFs and environmental

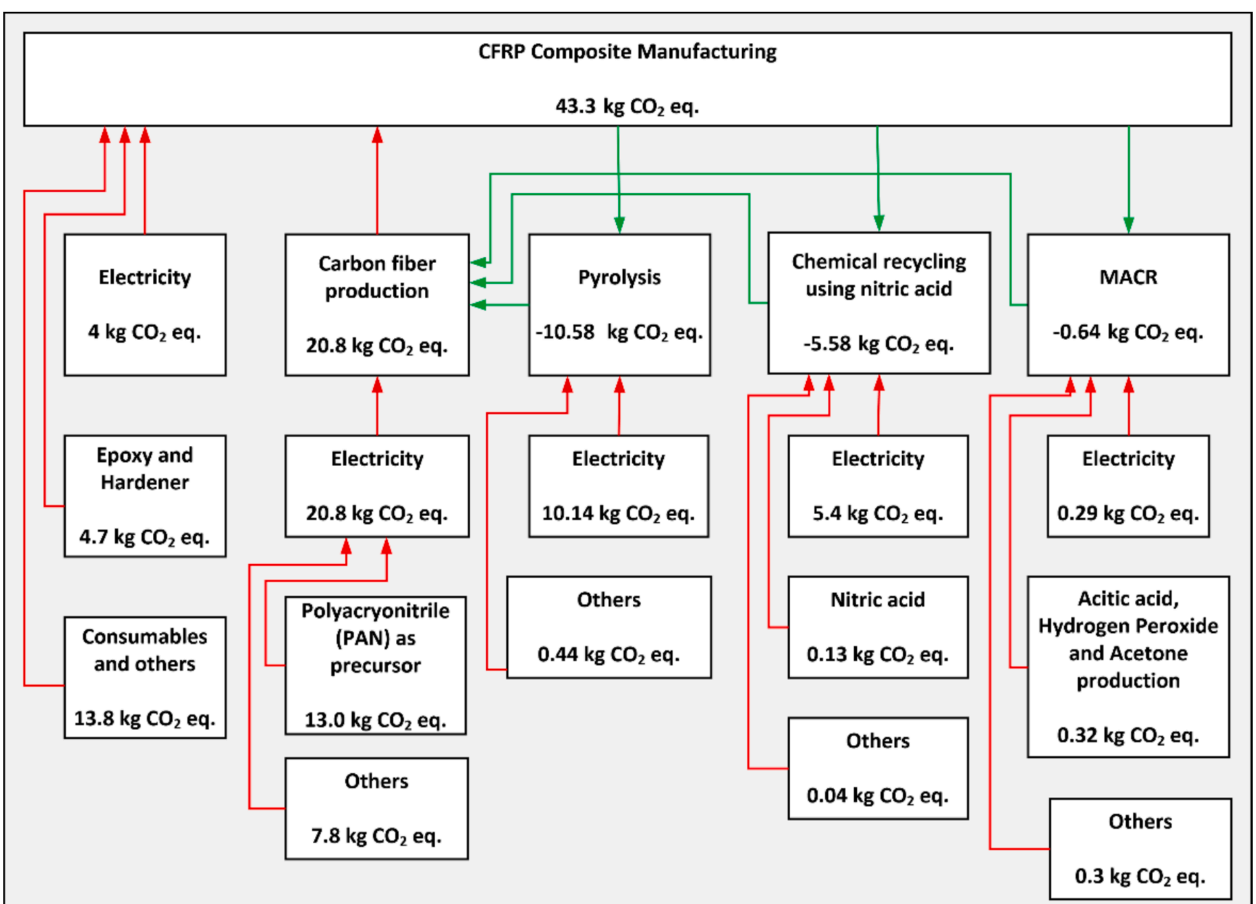

Fig. 5. Environmental burden analysis of pyrolysis, chemical recycling with nitric acid, and MACR process by LCA study.

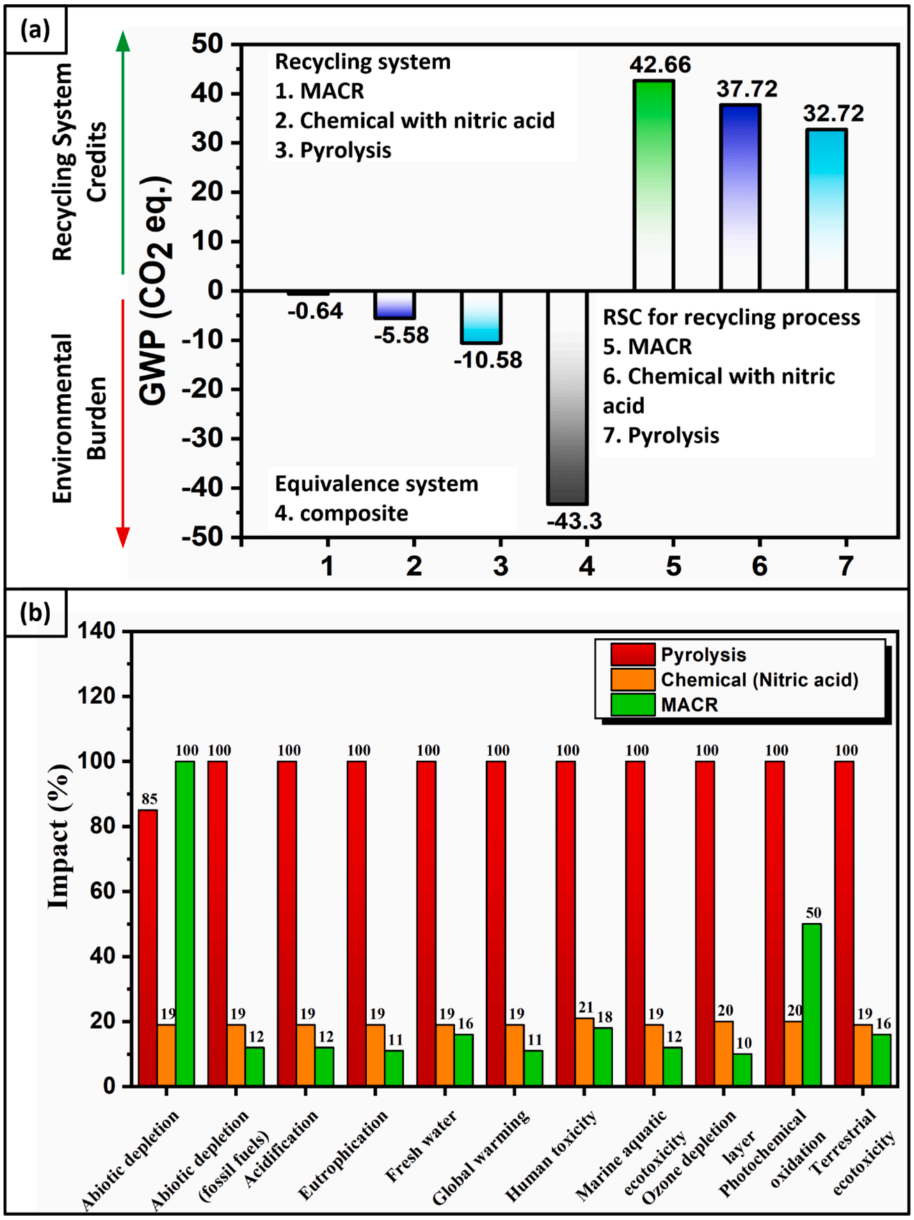

Fig. 6. (a) Environmental burden and recycling system credits analysis by LCA study. (b) Comparative percentage impact of pyrolysis, chemical recycling with nitric acid, and MACR recycling process using CML-IA baseline LCIA method.

burdens. Initially, the production and manufacturing of CFRP composite have already created environmental burdens, and additional burdens are also considered if CFRP waste is not recycled. This action leads to a continuous increase in the demand for VCFs to manufacture CFRP composites.

If the recycling system or process can recover fibers like VCFs, it will be considered a closed-loop cycle, where no material is wasted, and the demand for VCFs decreases. In a closed-loop cycle, recycling system credits (RSC) can be calculated using the following formula:

$$Recyclingsystemcredits = Equivalencesystemimpact - Recyclingsystemimpact$$

The recycling system credits have been calculated for all recycling systems and are depicted in Fig. 6(a). The MACR process exhibits high recycling credits, highlighting its sustainability and energy efficiency. Compared to MACR, the recycling system credits for chemical processes decreased by 3.68 % and for pyrolysis by 36.9 %. Higher recycling system credits indicate the feasibility of recovering CFs with reduced GHG emissions and enhanced energy efficiency, demonstrating the sustainability of the process amidst the growing energy crisis. This highlights the quest for energy-efficient, sustainable solutions in managing CFRP waste. If remanufacturing CFRP composites using RCFs as the reinforcing material is adopted, the carbon footprint from VCF manufacturing will carry over to the new CFRP composite. However, by replacing VCFs with RCFs at a 1:1 ratio, the environmental impact of the composite will be reduced by 20.8 kg CO_2 eq.

Fig. 6(b) illustrates the comparative percentage impact of all three recycling processes across various impact categories using the CML-IA baseline method. The comparison shows the highest environmental impacts associated with pyrolysis, while the MACR process is lower. Based on the LCA results, the MACR process is sustainable and has a low energy cost for recycling CFRP composite waste and recovering RCFs with minimum emissions.

The environmental profiles derived from the analysis of all recycling scenarios depicted in Fig. 6(b) closely resemble the impact of the Global Warming Potential (GWP). The results indicate that the MACR process has low impacts across most categories, except for abiotic depletion and photochemical oxidation, where chemical recycling with nitric acid performs best. The MACR scenario also excels in terms of energy efficiency and electricity usage during recovering RCFs from CFRP composite waste. The abiotic depletion of the MACR process is higher than that of other methods. This can be attributed to the production of acetic acid and hydrogen peroxide and the lack of chemical recovery after the recycling process, which contributes to resource depletion. In the case of pyrolysis, all impact categories are higher compared to chemical and MACR processes. These higher impacts are largely due to the materials used in constructing the pyrolysis reactor. Specifically, the use of copper and steel significantly increases environmental impacts, as their production is energy-intensive and relies on fossil fuels. Among the materials, copper and steel contribute the most to abiotic depletion, human toxicity, and eutrophication. Additionally, aluminum plays a major role in marine ecotoxicity. These impacts primarily occur during the production of these materials, further emphasizing the need for sustainable material choices in recycling technologies.

A significant environmental advantage offered by recycling systems or processes is the substitution of RCFs for VCFs. This substitution assumes RCFs possess similar properties to VCFs and involves a closed-loop system with a 1:1 substitution ratio, reducing the demand for new VCF production in composite applications. Unlike pyrolysis, which does not achieve a 1:1 substitution ratio as suggested in previous studies, the properties of RCFs determine their reusability. If RCFs do not match VCF properties, a substitution ratio of $1 < 1$ may be necessary, requiring more or a combination of RCFs and VCFs in varying percentages to meet targeted material properties for specific applications. Alternatively, RCFs can be reused in other applications, albeit in reduced quantities compared to their original use in CFRP composite products or applications.

The LCA results of this study showed that MACR used less energy (1.26 MJ/kg). The energy demand for MACR is lower compared to reported in the literature for pyrolysis, thermolysis, and microwave heating, as shown in Fig. 7. Nunes et al. reported that pyrolysis consumes 22.5 MJ/kg, meaning that MACR is approximately 17.8 times more energy-efficient (Nunes et al., 2018). Khalil reported an even higher energy demand of 71.64 MJ/kg for thermolysis, making MACR 56.8 times more energy-efficient (Khalil, 2018). In the steam thermolysis process, the outgoing gas, which is converted into CO_2 by combustion, causes little impact on global warming. Additionally, Lester et al. used microwave heating to recover the RCFs, which required about 7.96 times more energy than MACR. Using chemical solutions positively reduced energy demand during the MACR process (Lester et al., 2004).

The primary reason for the reduction in energy consumption is the low-temperature (183 ± 2 °C) operating conditions of MACR, which avoid the high thermal requirements of pyrolysis and thermolysis. Pyrolysis typically relies on high temperatures (400 °C to 800 °C) to break down the epoxy matrix. In contrast, thermolysis demands even higher

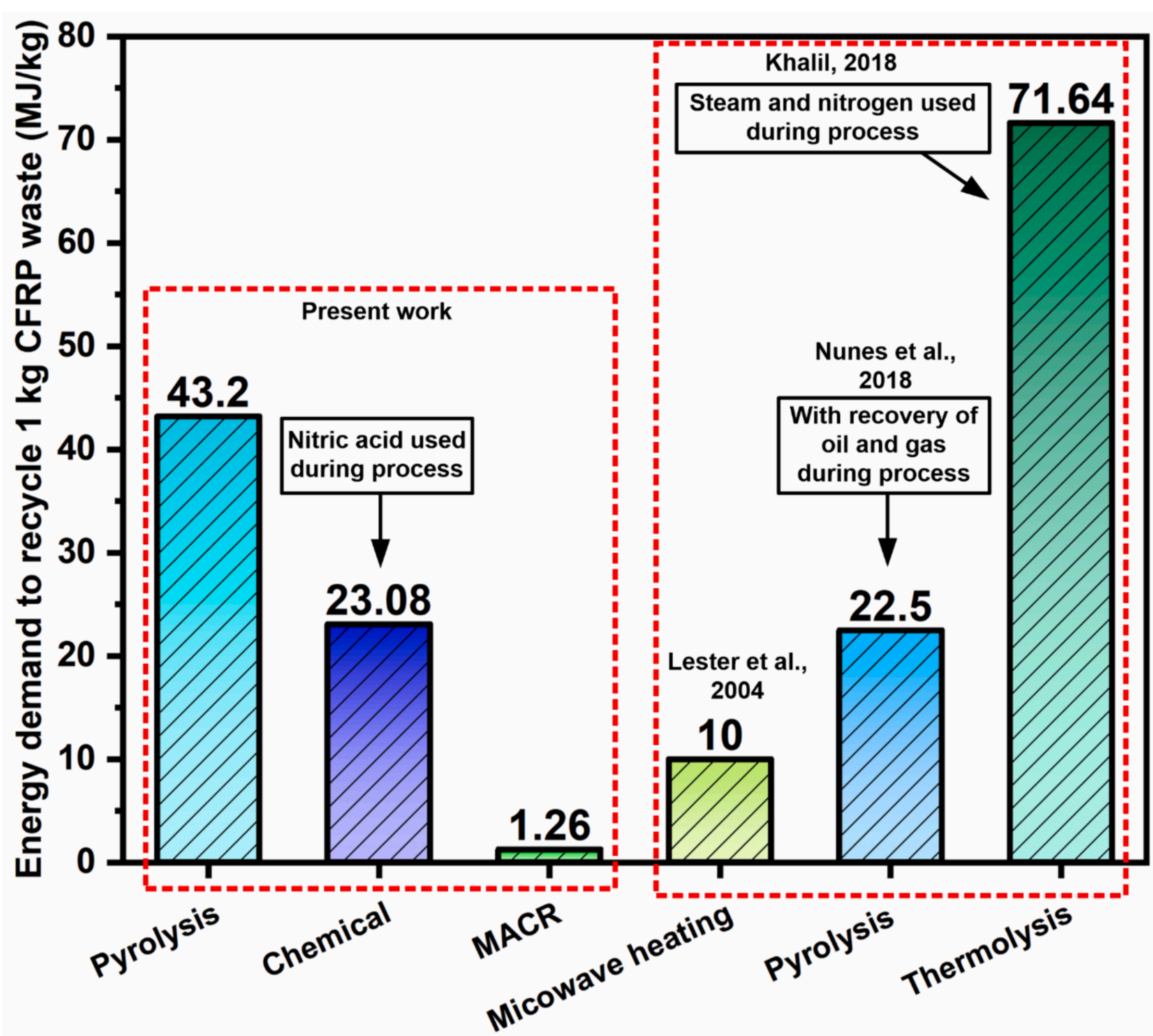

Fig. 7. Comparison of energy required during the different recycling processes to recover the RFCs from the 1 kg CFRP waste.

energy inputs due to the time needed to form the steam, particularly when steam or nitrogen is used. In contrast, MACR operates below 200 °C, significantly reducing the energy footprint.

Furthermore, study by Nunes et al. used the calorific value of recovered oil and gas in LCA results and reported less energy demand during pyrolysis. Using a chemical solution with microwave energy in MACR enables effective RCFs recovery with minimum energy input while maintaining fiber integrity, making it a more sustainable and practical alternative. Overall, these findings showed MACR as a promising recycling method in terms of energy efficiency, reducing the environmental impact with CFRP waste recycling.

Life cycle costing results and discussion

The energy, material, and labor costs were included in the LCC of the recycling processes. The transportation cost, shredding, cutting, raw material, manufacturing cost of CFRP, and set up cost for the recycling process have not been considered. The energy cost ₹ 10/kWh has been considered from the perspective of India based on the average energy price. The LCC data inventory related to the pyrolysis, chemical recycling with nitric acid, and MACR process is tabulated in Table 3 with the total cost for each recycling process.

For the recycling processes, the energy cost for the pyrolysis is high compared to the chemical and MACR processes, as shown in Fig. 8. The energy cost was determined based on the cumulative energy used during the recycling process. The materials cost in the MACR process is higher than in the pyrolysis and chemical recycling process. The main cost comes from the acetic acid and hydrogen peroxide. This part of the MACR process could be recovered as the RCFs surface is smooth and clean. The decomposition rate of epoxy is also higher for the MACR process than others. The labor cost in the pyrolysis and chemical recycling process is higher than that of the MACR process because of the total cycle time. In the MACR process, the cycle time is about 30 min, while pyrolysis and chemical recycling are about 7 h to 8 h.

Table 3
Life cycle inventory for material, labor, and energy for the recycling of the CFRP composite waste using pyrolysis, chemical recycling with nitric acid, and MACR process.

Input	Category	Cost	Unit	Pyrolysis	Chemical	MACR
Electricity	Energy	10	₹/kWh	119.67	63.9	3.49
Nitric Acid	Material	20	₹/kg	–	120.6	–
Water	Material	10	₹/litre	–	160	20
Acetic Acid	Material	70	₹/kg	–	–	210
Hydrogen Peroxide	Material	35	₹/kg	–	–	105
Worker	Labor	100	₹/hr	800	600	100
			Total	919.7	943.9	439.49

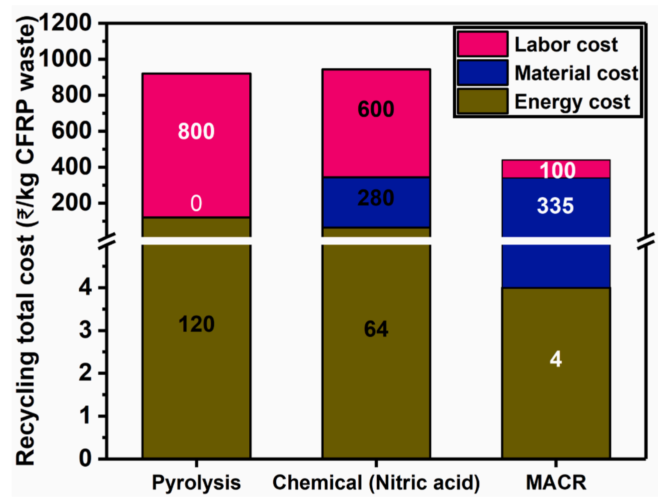

Fig. 8. Comparison of recycling process material, energy, and labor costs.

Feasibility of scale of the MACR process

The MACR process is currently at a laboratory scale and has not yet been widely implemented in industrial applications. Therefore, a comprehensive economic feasibility analysis, including large-scale production costs and commercialization, remains challenging due to limited real-world data. However, the current study has estimated the cost of recycling 1 kg of CFRP using MACR, pyrolysis, and chemical recycling. The results indicate that the energy cost of MACR is lower compared to pyrolysis and chemical recycling, as the process operates for a short cycle time, and that reduces energy input. This suggests that MACR could offer an economically viable alternative once scaled up. Since the feasibility of scaling the process is closely linked to its current lab-scale status, further research is required to explore its technical maturity, process optimization, and industrial scalability. Future studies should focus on conducting a detailed techno-economic analysis (TEA) to assess overall cost-effectiveness and practical implementation on a larger scale.

Conclusions

This study evaluated the production of VCFs, the manufacturing of CFRP composites, and the recycling of end-of-life CFRP composite waste using pyrolysis, chemical, and MACR processes. A comparative environmental impact and cost analysis (material, energy, and labor) was also conducted. The LCA results revealed that the MACR process is environmentally friendly and cost-effective. The cumulative energy demand for this process was 1.26 MJ/kg, with a GWP of 0.64 kg CO_2 eq. The energy cost for MACR was 16 times and 30 times lower than that of chemical and pyrolysis, respectively. MACR recycling helps reduce the environmental burdens associated with CFRP waste and VCF production. The MACR process demonstrated improved recycling system credits (42.66 kg CO_2 eq.), indicating energy savings and a decreased demand for VCF production. This research identifies MACR as the optimum recycling process among the options considered (pyrolysis, chemical, and microwave-assisted) for recovering CFs from CFRP composite waste.

Future research should focus on using RCFs in new composites to obtain more significant data at an industrial scale rather than being limited to laboratory studies. Additionally, an economic analysis considering the long-term performance of RCFs should be conducted to assess the feasibility of the MACR process compared to other methods. The long-term performance of RCFs, particularly in terms of fatigue resistance and environmental aging in different fluids based on the intended applications, should be investigated. This would provide deeper insights into the viability of RCFs as potential reinforcement in composites, contributing to a sustainable and economically circular approach.

CRediT authorship contribution statement

Ritesh Patre: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Manjeet Rani:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sunny Zafar:** Writing – review & editing, Supervision, Formal analysis.

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.

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References

Abagnato, S., Rigamonti, L., Grosso, M., 2024. Life cycle assessment applications to reuse, recycling and circular practices for textiles: a review. Waste Manage. 182, 74–90.
Antelava, A., Damilos, S., Hafeez, S., Manos, G., Al-Salem, S.M., Sharma, B.K., Kohli, K., Constantinou, A., 2019. Plastic solid waste (PSW) in the context of life cycle assessment (LCA) and Sustainable management. Environ. Manag. 64, 230–244.
Arena, U., Parrillo, F., Ardolino, F., 2023. An LCA answer to the mixed plastics waste dilemma: Energy recovery or chemical recycling? Waste Manag. 171, 662–675.
BASF, 2020. Life cycle assessment (LCA) for ChemCycling 14040.
Bishop, G., 2001. UK Polymer Composites Sector Foresight Study and Competitive Analysis. ISSN 1473 - 2734 NPL Rep. MATC 80 Natl. Phys. Lab. Teddington, Middlesex, UK, TW110LW 1–56.
Bisinella, V., Schmidt, S., Varling, A.S., Laner, D., Christensen, T.H., 2024. Waste LCA and the future. Waste Manage. 174, 53–75.
Bovea, M.D., Gallardo, A., 2015. Environmental assessment of alternative municipal solid waste management strategies. A Spanish Case Study. Waste Manage. 30, 2383–2395.
Deschamps, J., Simon, B., Tagnit-Hamou, A., Amor, B., 2018. Is open-loop recycling the lowest preference in a circular economy? Answering through LCA of glass powder in concrete. J. Clean. Prod. 185, 14–22.
Dominguez Aldama, D., Grassauer, F., Zhu, Y., Ardestani-Jaafari, A., Pelletier, N., 2023. Allocation methods in life cycle assessments (LCAs) of agri-food co-products and food waste valorization systems: Systematic review and recommendations. J. Clean. Prod. 421, 138488.
Duflou, J.R., Deng, Y., Van Acker, K., Dewulf, W., 2012. Do fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study. MRS Bull. 37, 374–382.
Foelster, A.S., Andrew, S., Kroeger, L., Bohr, P., Dettmer, T., Boehme, S., Herrmann, C., 2016. Electronics recycling as an energy efficiency measure - A Life Cycle Assessment (LCA) study on refrigerator recycling in Brazil. J. Clean. Prod. 129, 30–42.
Hanaoka, T., Ikematsu, H., Takahashi, S., Ito, N., Ijuin, N., Kawada, H., Arao, Y., Kubouchi, M., 2022. Recovery of carbon fiber from prepreg using nitric acid and evaluation of recycled CFRP. Compos. Part B Eng. 231.
Hancox, N.L., 1996. Engineering mechanics of composite materials. Mater. Des.
Hao, S., Kuah, A.T.H., Rudd, C.D., Wong, K.H., Lai, N.Y.G., Mao, J., Liu, X., 2020. A circular economy approach to green energy: Wind turbine, waste, and material recovery. Sci. Total Environ. 702, 135054.
Howarth, J., Mareddy, S.S.R., Mativenga, P.T., 2014. Energy intensity and environmental analysis of mechanical recycling of carbon fiber composite. J. Clean. Prod. 81, 46–50.
Iswara, A.P., Farahdiba, A.U., Nadhifatin, E.N., Pirade, F., Andhikaputra, G., Muflihah, I., Boedisantoso, R., 2020. A Comparative Study of Life Cycle Impact Assessment using Different Software Programs. IOP Conf. Ser. Earth Environ. Sci. 506.
Jiang, L., Ulven, C.A., Gutschmidt, D., Anderson, M., Balo, S., Lee, M., Vigness, J., 2015. Recycling carbon fiber composites using microwave irradiation: Reinforcement study of the recycled fiber in new composites. J. Appl. Polym. Sci. 132.
Khalil, Y.F., 2018. Comparative environmental and human health evaluations of thermolysis and solvolysis recycling technologies of carbon fiber reinforced polymer waste. Waste Manag. 76, 767–778.
Krauklis, A.E., Karl, C.W., Gagani, A.I., Jørgensen, J.K., 2021. Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. J. Compos. Sci. 5, 1–21.
Kumar, R., Rani, M., Zafar, S., 2021. Influence of stacking sequence on impact strength/hardness of CF/GF hybrid composites fabricated by VARIMC technique. Mater. Today Proc. 45, 4666–4670.
La Rosa, A.D., Banatao, D.R., Pastine, S.J., Latteri, A., Cicala, G., 2016. Recycling treatment of carbon fiber/epoxy composites: Materials recovery and characterization and environmental impacts through life cycle assessment. Compos. B Eng. 104, 17–25.
La Rosa, A.D., Blanco, I., Banatao, D.R., Pastine, S.J., Björklund, A., Cicala, G., 2018. Innovative chemical process for recycling thermosets cured with recyclamines® by converting bio-epoxy composites in reusable thermoplastic-an LCA study. Materials (Basel) 11.
La Rosa, A.D., Greco, S., Tosto, C., Cicala, G., 2021. LCA and LCC of a chemical recycling process of waste CF-thermoset composites for the production of novel CF-thermoplastic composites. Open loop and closed loop scenarios. J. Clean. Prod. 304, 127158.
Larsen, K., 2009. Recycling wind turbine blades. Renew. Energy Focus 9, 70–73.
Lee, C.K., Kim, Y.K., Pruitichaiwiboon, P., Kim, J.S., Lee, K.M., Ju, C.S., 2010. Assessing environmentally friendly recycling methods for composite bodies of railway rolling stock using life-cycle analysis. Transp. Res. Part D: Transp. Environ. 15, 197–203.
Meng, F., Cui, Y., Pickering, S., McKechnie, J., 2020. From aviation to aviation: Environmental and financial viability of closed-loop recycling of carbon fiber composite. Compos. B Eng. 200, 108362.
Nunes, A.O., Viana, L.R., Guineheuc, P.M., da Silva Moris, V.A., de Paiva, J.M.F., Barna, R., Soudais, Y., 2018. Life cycle assessment of a steam thermolysis process to recover carbon fibers from carbon fiber-reinforced polymer waste. Int. J. Life Cycle Assess. 23, 1825–1838.
Paulauskas, F.L., Bigelow, T.S., Yarborough, K.D., Meek, T.T., 2000. Manufacturing of carbon fibers using microwave-assisted plasma technology. SAE Tech. Pap.
Pradhan, S., Tiwari, B.R., Kumar, S., Barai, S.V., 2019. Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. J. Clean. Prod. 228, 679–691.
Rani, M., Carlone, P., Zafar, S., 2023. Analysis of mechanical performance and energy consumption of microwave cured GFRP composites: a low-energy footprint manufacturing process. CIRP J. Manuf. Sci. Technol. 42, 36–46.
Rani, M., Choudhary, P., Krishnan, V., Zafar, S., 2022. Development of sustainable microwave-based approach to recover glass fibers for wind turbine blades composite waste. Resour. Conserv. Recycl. 179, 106107.
Rani, M., Choudhary, P., Krishnan, V., Zafar, S., 2021. A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades. Compos. B Eng. 215, 108768.
SETAC, 1993, 1993. A CONCEPTUAL FRAMEWORK FOR LIFE-CYCLE IMPACT ASSESSMENT, 1993rd ed. Society of Environmental Toxicology and Chemistry, Sandestin, Florida USA.
Shahadahtul Afizah Asman, N., Raymond, M.B., Musa Mohamad, H., Bolong, N., 2023. Life cycle assessment of plastic waste into furniture using open LCA software. 2023. Trans. Sci. Technol. 10, 88–94.
Sotoodeh, K., 2022. Manufacturing Process. Pipeline Valve Technol. 42, 79–97.
Tapper, R.J., Longana, M.L., Norton, A., Potter, K.D., Hamerton, I., 2020. An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fiber reinforced polymers. Compos. B Eng. 184, 107665.
Thomas, C.R.P., Ccev, M.K., 2015. Composites Market Report 2015 challenges 1–44.
Wind, G., Council, E., 2021. GWEC | GLOBAL WIND REPORT 2021.
Xiao, R., Zhang, Y., Yuan, Z., 2016. Environmental impacts of reclamation and recycling processes of refrigerators using life cycle assessment (LCA) methods. J. Clean. Prod. 131, 52–59.
Zabihi, O., Ahmadi, M., Liu, C., Mahmoodi, R., Li, Q., Naebe, M., 2020. Development of a low cost and green microwave assisted approach towards the circular carbon fibre composites. Compos. B Eng. 184, 107750.