Sustainable Environmental Waste Management Strategies



Alok Prasad Das *Editor*

Bioconversion of Environmental Waste to Value Added Products

A Sustainable Approach

Springer

Sustainable Environmental Waste Management Strategies

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Alok Prasad Das, Department of Life Sciences, Rama Devi Women's University, Bhubaneswar, Odisha, India

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Editor
Alok Prasad Das
Department of Life Sciences
Rama Devi Women's University
Bhubaneswar, Odisha, India

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Recovery of Industrial Carbon Fiber Waste in Sustainable Green Transformation: Pros and Cons



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Abstract Carbon fiber has become an indispensable material for many industries with its high-performance properties and wide applications. It offers significant technical and economic advantages and is expected to become more widespread in the future. These materials, particularly carbon fiber-reinforced composites, are widely used in aerospace, automotive, sports equipment, and renewable energy sectors. Carbon fiber-reinforced composites combine carbon fibers with a polymer, metallic, ceramic, or carbon matrix to create composites that leverage the strengths of both the fibers and the matrix, resulting in superior mechanical properties and design flexibility. The recycling of carbon fiber materials is a critical aspect of their lifecycle, addressing environmental and economic concerns. Although recycling carbon fiber composites is challenging due to their durability and the strong bonding between fibers and matrices, advancements in recycling technologies are gradually making it more feasible. Effective recycling not only reduces waste but also conserves resources and lowers the environmental impact of producing new carbon fibers. Looking ahead, the future of carbon fiber materials appears promising. Compared to virgin carbon fibers, recycled carbon fibers retain many of their properties, providing an environmentally friendly and economical alternative, creating excellent usage potential. Ongoing research and development aim to reduce production costs and improve recycling methods, making these materials more accessible and sustainable. As these advancements continue, the adoption of carbon fiber composites is expected to expand, driving innovation and efficiency across multiple industries.

Keywords Recycling · Carbon fiber composites · Sustainability

N. Beköz Üllen (✉) · G. Karabulut Şevk
Department of Metallurgical and Materials Engineering, Faculty of Engineering, İstanbul University-Cerrahpaşa, Istanbul, Türkiye
e-mail: nbekoz@iuc.edu.tr

M. Akoğlu
VIMANSYS Digital Solutions and Smart Manufacturing, Bursa, Türkiye

İ. H. Kalkan · O. Otuz
Daimler Mercedes-Benz Turk, Istanbul, Türkiye

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1 Introduction

Carbon fiber (CF) is a material known for its high-strength and low-weight properties and found in thin strands where carbon atoms are tightly bonded to each other (De et al., 2024). It usually forms composite materials by being contained in a matrix (Ateeq et al., 2023). These composite materials are widely used in applications that require particularly high performance and durability. Although CFs are much lighter than steel, they can have the same or higher strength (Ahmad et al., 2020). Because of its low density, it is ideal for applications requiring weight reduction. CFs have high resistance to bending and tensile forces. It is resistant to many chemicals and environmental influences (Jang et al., 2022). It is used in the construction of aircraft and space vehicles, performance cars, and racing cars due to its lightness and high strength, increasing fuel efficiency and performance (Das et al., 2019; Muhammad et al., 2021; Seydibeyoğlu et al., 2020; Sreejith & Rajeev, 2021). Due to its strength and lightness, it is preferred in items such as bicycles, tennis rackets, golf clubs, and ski equipment (Lina & Zhen, 2012; Zhang, 2013). They are preferred in bridges, buildings, and other structural elements due to their durability and long life (Carolin, 2003; Hegde et al., 2019; Tuakta & Whittle, 2005). CF has become an indispensable material for many industries with its high-performance properties and wide applications (Lin et al., 2024; Ye et al., 2024). It offers significant technical and economic advantages and is expected to become more widespread in the future. Historically important developments of CF from the past to the present are shown in Fig. 1. Although it is known that the first studies on CF were made by Sir Joseph Wilson Swan in 1860, its first commercial use was performed in 1958 by American chemist Dr. Roger Bacon. While working at Union Carbide, Bacon conducted a series of experiments to produce graphite fibers. In these experiments, it was observed that the fibers obtained by heating polymers at high temperatures had a structure similar to graphite crystals (Peijs et al., 2022). Later, as a reflection of the developing technology, the CF market has gradually increased over the years with the developments in CF production processes and products. Nowadays, due to the increasing amount of CF products, the product cost has been reduced considerably and the competition in the market has increased considerably. With the replacement of traditional materials, their increasing use brings with it many environmental problems. In addition to the use of petroleum-based raw materials, CF transformation has come to the fore in recent years due to the increasing amount of carbon emissions and the increasing prevalence of concepts such as sustainable living and circular economy.

CFs are mainly used in composite materials as a dopant material. CF-reinforced composite materials are advanced engineering materials created by embedding CFs in polymer, metallic, ceramic, and carbon matrices (Hu et al., 2024; Newcomb, 2016; Park, 2018). Polymer matrix CF composites are favored in the automotive and aerospace industries for their lightweight and flexibility (Alshammari et al., 2021; Zhang et al., 2023). However, metallic matrix composites provide high-temperature

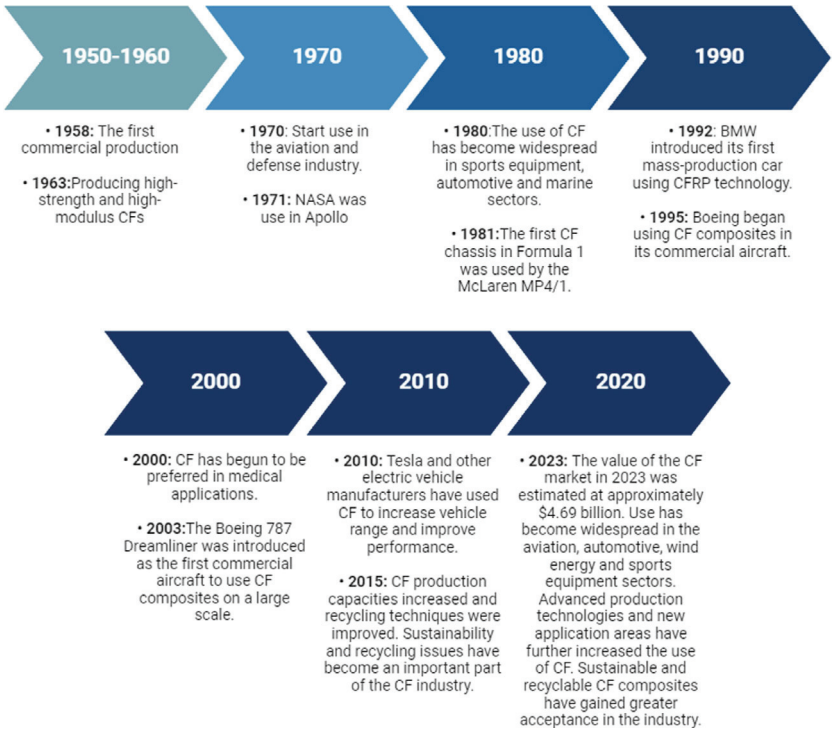

Fig. 1 Historical development of CF technology

resistance and strength, making them suitable for aerospace and defense applications (Shirvanimoghaddam et al., 2017). Ceramic matrix CF composites offer exceptional thermal and chemical resistance, which is valuable in rocket engines and thermal protection systems (Dhanasekar et al., 2022; Tang & Hu, 2017). On the other hand, carbon matrix composites deliver outstanding thermal conductivity and corrosion resistance, making them ideal for high-performance electronics and energy storage systems (Chawla, 2019; Chung, 2016). By combining CFs with various matrix materials, these composites offer unique advantages in their respective fields, providing high-performance solutions tailored to specific engineering challenges (Koumoulos et al., 2019; Sayam et al., 2022). CF holds significant strategic importance as a material due to its exceptional strength-to-weight ratio (Ahmad et al., 2020), high stiffness, and corrosion resistance (Ahmad et al., 2020). These properties make it indispensable in aerospace (Barile & Casavola, 2019; Tang & Hu, 2017), defense (Kacan & Elaldi, 2020), automotive (Ahmad et al., 2020), and renewable energy industries (Demski et al., 2024). Its ability to reduce weight while maintaining structural integrity enhances fuel efficiency and performance, which is crucial for both economic and environmental sustainability (Ahmad et al., 2020; Barile & Casavola, 2019; Tang & Hu, 2017). Furthermore, the use of CF in advanced military equipment

and infrastructure ensures superior durability and protection, underscoring its critical role in national security and technological advancement (Kacan & Elaldi, 2020).

Nowadays, the need for recycling emerges for this material, which has an increasingly widespread usage network. Recycling CF materials involves recovering and reprocessing CFs from used composites to create new, high-quality products. Recycling not only reduces waste and conserves natural resources but also lowers the environmental impact of producing new CFs. Due to the synthetic structure of most composite materials, the environmental impact during the production phase is more energy intensive and difficult to destroy or recycle. Therefore, it is not possible to fully adopt the concept of circular economy (CE) in the compound economy. Especially in recent years, the automotive industry based on environmental problems and sustainable materials has been carrying out studies on the conversion of vCF to rCF in order to deal with waste resulting from production processes and end-of-life (EoL) products. While the aerospace market is one of the main segments predicting higher CF demand by 2027, with the advent of electric cars, the use of CF in the automotive industry has emerged as the material of choice over lighter materials, replacing steel. Therefore, as the demand for CF in the transportation sector will increase significantly in the future, various studies are being carried out to develop greener solutions. Considering disadvantages such as strong dependence on fossil fuels and large CF waste, there is increasing interest in the use of alternative environmentally friendly biocomposite materials. In general, the term biocomposite refers to: natural fiber-reinforced petroleum derived from non-biodegradable polymers, biopolymers reinforced with natural fibers, and synthetic fibers (carbon, glass, etc.) reinforced with biopolymers. One of the biggest projects carried out in this context is the Horizon Europe (HORIZON-CL4–2022-RESILIENCE-01-11) project called advanced lightweight materials FOR Energy-efficient STructures (FOREST), in which the chapter authors are also involved. The FOREST project aims to produce biocomposites with bio-based polymers and additives and rCFs by combining renewable and recycling resources to maximize the sustainability of the products. The FOREST project aims to transform promising technologies by promoting overcoming economic, environmental, and social challenges. International projects of this type are a great chance to reduce dependence on fossil resources and reduce CF waste. Additional advantages such as recyclability, lightweight structure, and special functionality for safety and cost-effectiveness are predicted to make FOREST biocomposites an alternative to traditional composites (*Advanced Lightweight Materials for Energy Efficient Structures (RIA)*, n.d.). Such approaches and minimizing the difficulties and legal obstacles in recycling are seen as the key elements that will achieve groundbreaking success in CF recycling concepts. Although challenging due to the durability and complexity of CF composites, advancements in recycling technologies are making it increasingly feasible, promoting a circular economy and contributing to sustainable development in industries like aerospace, automotive, and construction. This chapter presents the pros and cons of sustainable green transformation in using rCFs in the development of lightweight and durable parts to close

the CF loop in the industry. Detailed information about CF materials is summarized, as well as information on current CF recycling technologies.

2 Carbon-Fiber Reinforced Composites

2.1 Polymer Matrix Composites

CF-reinforced polymer composites (CFRPCs) are advanced materials that combine CFs with a polymer matrix to create lightweight and high-strength structures (Bag et al., 2024; Liu et al., 2020; Mahato & Moharana, 2024; Oladele et al., 2023; Tusher et al., 2024). The polymer matrix, typically made from resins like epoxy, polyester, or vinyl ester, serves to bind the CFs together, transferring loads and protecting the fibers from environmental damage (Chen et al., 2022; Mahato & Moharana, 2024; Tusher et al., 2024). The resulting composite material retains the advantageous properties of CFs, such as high tensile strength, low weight, and excellent fatigue resistance, while gaining additional benefits from the polymer matrix, such as ease of manufacturing and flexibility (Khan et al., 2024; Mahboubizadeh et al., 2024; Oladele et al., 2023).

Several methods are used to manufacture CFRPCs, each suited to different applications and production scales:

- Resin Transfer Molding (RTM): In RTM, CF preforms are placed into a mold, and resin is injected to fill the mold and impregnate the fibers. This method is ideal for producing complex shapes and large structures with high fiber volume fractions (Sozer et al., 2012). Different types of RTM were used producing CFRPC such as vacuum-assisted RTM (Bodaghi et al., 2020), high-pressure RTM (Sarker et al., 2024), ultrasound-assisted RTM (Xu et al., 2024).
- Filament Winding: This process involves winding continuous CF strands coated with resin around a mandrel to create hollow, cylindrical components such as pipes and pressure vessels. Filament winding offers high precision and excellent control over fiber orientation (Azeem et al., 2022; Ma et al., 2015).
- Pultrusion: In pultrusion, continuous CFs are pulled through a resin bath and then through a heated die to form long, straight profiles. This method is efficient for producing structural elements like beams and rods with consistent cross-sections (Hong et al., 2017; Minchenkov et al., 2021; Wiedmer & Manolesos, 2006).

CFRPCs are significantly lighter than traditional materials like metals, which leads to improved fuel efficiency and performance in transportation applications (Kumar SHArma et al., 2022). The polymer matrix protects CFs from moisture and chemicals, ensuring long-term durability and reducing maintenance costs (Koumoulos et al., 2019; Kumar SHArma et al., 2022). CFRPCs can be molded into complex shapes and tailored to specific performance requirements, allowing for innovative designs and applications (Mitschang & Hildebrandt, 2012; Tian et al., 2022). CFRPCs are extensively used across various industries due to their superior mechanical properties

and design flexibility (Tian et al., 2024). In the aerospace industry, they are used for aircraft structures, such as fuselages, wings, and tail sections, where weight reduction is critical for improving fuel efficiency and performance (Barile & Casavola, 2019). The automotive industry uses CFRPCs in high-performance and electric vehicles to reduce weight, enhance safety, and improve overall efficiency (Mitschang & Hildebrandt, 2012). Additionally, in sports equipment, CFRPCs are favored for their high strength-to-weight ratio, making them ideal for bicycles, tennis rackets, and golf clubs (Oladele et al., 2023).

Despite their benefits, CFRPCs face challenges, including high production costs and difficulties in recycling (Ateeq, 2023). The cost of raw CFs and the specialized manufacturing processes required can make CFRPCs expensive compared to conventional materials (Aldosari et al., 2024). Additionally, recycling CFRPCs is complex due to the strong bond between the CFs and the polymer matrix (Ateeq, 2023). However, ongoing research and development are focused on addressing these challenges. Innovations in manufacturing techniques aim to reduce costs and improve production efficiency, while advancements in recycling technologies seek to develop effective methods for reclaiming and reusing CFs. As these developments progress, the adoption of CFRPCs is expected to expand, further enhancing their role in various high-performance applications and contributing to a more sustainable future.

2.2 Metal Matrix Composites

Metal matrix CF composites (MMCFCs) are advanced materials that combine CFs with a metal matrix, such as aluminum, magnesium, or titanium (Aldosari et al., 2024; Khanna et al., 2021; Mileiko, 2022). These composites are designed to leverage the high strength and stiffness of CFs while benefiting from the metal matrix's excellent thermal and electrical conductivity, as well as its resistance to high temperatures (Shirvanimoghaddam et al., 2017). The synergy between CFs and metal matrices results in materials that offer superior mechanical properties and performance in demanding environments (Sayam et al., 2022).

Several techniques are used to manufacture MMCFCs, each with its own advantages and applications:

- Powder Metallurgy: This process involves mixing metal powders with CFs and then compressing the mixture into a desired shape. The compacted material is then sintered at high temperatures to bond the metal matrix and CFs together. This method is suitable for producing complex shapes and components with uniform fiber distribution (Mahaviradhan et al., 2021; Neubauer et al., 2010).
- Liquid Metal Infiltration: In this technique, a preform made of CFs is placed in a mold, and molten metal is then infiltrated into the preform, filling the spaces between the fibers. This method is ideal for creating composites with high fiber volume fractions and excellent bonding between the fibers and the matrix (Blucher, 1992; Sree Manu et al., 2016).

- Squeeze Casting: Similar to liquid metal infiltration, squeeze casting involves infiltrating molten metal into a fiber preform under high pressure. This process ensures good fiber wetting and minimal porosity, resulting in high-quality composites with superior mechanical properties (Alhashmy & Nganbe, 2015; SHA et al., 2021).

MMCFCs are used in a variety of high-performance applications due to their exceptional properties (Sayam et al., 2022; Shirvanimoghaddam et al., 2017). These composites are utilized in aircraft and spacecraft components, such as structural elements, engine parts, and heat shields, where weight reduction and high-temperature performance are critical (Alam et al., 2022; Hussain & Immanuel, 2022). MMCFCs are employed in high-performance and racing vehicles to reduce weight, enhance strength, and improve fuel efficiency. They are used in engine components, drive shafts, and brake systems (Macke et al., 2013; Singh et al., 2021). The high strength-to-weight ratio and thermal stability of MMCFCs make them suitable for use in armor, weaponry, and other defense-related applications (Mehara et al., 2021; Siengchin, 2023). MMCFCs are also used in various industrial applications, including heat exchangers, cutting tools, and electronic packaging, where their thermal conductivity and mechanical properties provide significant advantages (Miracle, 2005; Perumal et al., 2020; Shirvanimoghaddam et al., 2017).

Despite their benefits, MMCFCs face several challenges. The production processes can be complex and expensive, and achieving uniform fiber distribution and strong bonding between the fibers and the matrix can be difficult (Shirvanimoghaddam et al., 2017). Additionally, the recycling of MMCFCs is challenging due to the strong bond between the CFs and the metal matrix (Nishida, 2013). However, ongoing research and development are focused on overcoming these challenges. Innovations in manufacturing techniques aim to reduce costs and improve the quality and consistency of MMCFCs. Advances in recycling technologies are also being explored to address environmental concerns and promote sustainability.

2.3 Ceramic Matrix Composites

CF-reinforced ceramic matrix composites (CFRCMCs) are advanced materials that integrate CFs within a ceramic matrix, such as silicon carbide (SiC) (W. Wang et al., 2024), alumina (Al_2O_3) (Cao et al., 2018), or zirconia (ZrO_2) (Bach et al., 2020; Zhao et al., 2011). These composites are engineered to capitalize on the high-temperature stability, wear resistance, and hardness of ceramics, while the CFs provide enhanced toughness, thermal shock resistance, and mechanical strength (De Omena Pina et al., 2007; Tang & Hu, 2017). The combination results in materials that can withstand extreme environments, making them ideal for high-performance applications (Duan et al., 2021).

The production of CFRCMCs involves sophisticated techniques to ensure proper integration and bonding between the CFs and the ceramic matrix:

- Chemical Vapor Infiltration (CVI): In this process, CF preforms are exposed to a gas-phase ceramic precursor, which infiltrates the preform and deposits the ceramic matrix within and around the fibers. CVI produces high-quality composites with excellent fiber-matrix bonding and minimal porosity (Monteleone et al., 2020; Niu et al., 2023).
- Polymer Impregnation and Pyrolysis (PIP): This method involves impregnating CF preforms with a polymer that converts to a ceramic upon heating. The impregnated preform is then pyrolyzed at high temperatures, transforming the polymer into a ceramic matrix. PIP is useful for producing complex shapes and large components (Servadei et al., 2023; Stalin et al., 2020).
- Hot Pressing and Sintering: CFs and ceramic powders are mixed and then compacted under high pressure and temperature. This process ensures good fiber dispersion and strong bonding within the ceramic matrix. It is suitable for creating dense, high-strength composites (Liu et al., 2022; Liu et al., 2022).

CFRCMCs are particularly valued in applications that demand high-temperature performance and durability (Zhu & Wang, 2023). CFRCMCs are used in aircraft and spacecraft components, such as turbine blades, heat shields, and combustion liners, where they provide exceptional thermal resistance and structural integrity under extreme conditions (De Omena Pina et al., 2007; Uyanna & Najafi, 2020). These composites are employed in missile components, armor, and other defense-related applications that require materials to withstand high temperatures and mechanical stresses (Bilisik et al., 2023). In the energy sector, CFRCMCs are used in gas turbines, nuclear reactors, and other high-temperature environments where their thermal stability and resistance to oxidation and corrosion are critical (Rueschhoff et al., 2020). CFRCMCs are also applied in industrial settings, including cutting tools, wear-resistant coatings, and high-temperature furnace components, benefiting from their hardness and durability.

While CFRCMCs offer numerous advantages, they also present certain challenges. The manufacturing processes can be complex and costly, requiring precise control to achieve the desired material properties. Additionally, ensuring uniform fiber distribution and strong bonding within the ceramic matrix can be challenging. The inherent brittleness of ceramics, despite the toughening effect of CFs, remains a consideration in some applications (Chung, 2016; Niu et al., 2023). Future prospects for CFRCMCs are promising, with ongoing research focused on improving manufacturing techniques, reducing costs, and enhancing material performance. Advances in nanotechnology and material science are expected to lead to even stronger and more durable composites. As these innovations continue, the use of CFRCMCs is likely to expand, driving further advancements in aerospace, defense, energy, and industrial applications.

3 The Role of Carbon Fiber in Strategic Materials

Strategic materials are crucial for the development and maintenance of a country's infrastructure, defense, and economic stability. CF, with its unique properties, has emerged as a vital component in various strategic applications. This section explores the role of CF in strategic materials, highlighting its importance, applications, and impact on various industries. When examined from a strategic perspective, CFs provide technological, economic, and environmental advantages. However, it is a material that is still under development and needs to be improved. CFs provide superior performance characteristics that are crucial for advanced technological applications (Yang et al., 2020). Although initially expensive, the long-term benefits of durability, reduced maintenance, and improved efficiency justify the investment (Maiti et al., 2022). Contributes to sustainability through weight reduction, leading to lower fuel consumption and reduced emissions in transportation applications (Ahmad et al., 2020). As a result of its prominent features, CFRCs are used in the construction of aircraft fuselages, wings, and other structural components, reducing weight and improving fuel efficiency (Agarwal et al., 2024; Muhammad et al., 2021). They are used in satellite components and space exploration vehicles, where weight reduction is critical for mission success (Wei et al., 2022). Applied in the production of lightweight and durable military gear, including helmets, body armor, and vehicle armor, enhancing mobility and protection (Kacan & Elaldi, 2020). CF is used in sports cars and racing vehicles to improve speed, handling, and fuel efficiency (Ahmad et al., 2020; Li et al., 2020). Helps reduce the weight of electric vehicles, extending battery life and range. CF-reinforced blades are longer and more efficient, capturing more wind energy and improving overall performance (Teng et al., 2023). Used in advanced battery technologies and hydrogen storage tanks due to its high strength and low weight (Benitez et al., 2021). CFRP is used to strengthen concrete structures, providing higher durability and resistance to environmental stressors. CFRP is used in the repair and reinforcement of aging bridges, buildings, and pipelines, extending their service life and enhancing safety (Hussain & Immanuel, 2022; Rashed Labanieh et al., 2022). CF is used in prosthetics, surgical instruments, and imaging equipment due to its biocompatibility and strength. Lightweight and strong CF components are used in orthopedic implants and braces (Chua et al., 2021; Kaufman & Bernhardt, 2021). However, the high production cost of CF remains a significant barrier to its widespread adoption. Requires specialized manufacturing processes and expertise. The recycling of CF composites is challenging and needs further development to improve sustainability. Ongoing research aims to reduce production costs and improve the properties of CF composites. With technological advancements, CF is expected to penetrate more industries and applications. Developing efficient recycling methods will enhance the environmental benefits of CF. CF, one of the strategic materials, is used in many areas on an industrial scale. Figure 2 gives the market forecast of CF-based composites in terms of application. Economic indicators and market dynamics show that composite material will grow much faster and the dominant materials are CFs, glass fibers in the reinforcement segment, and polyester resin

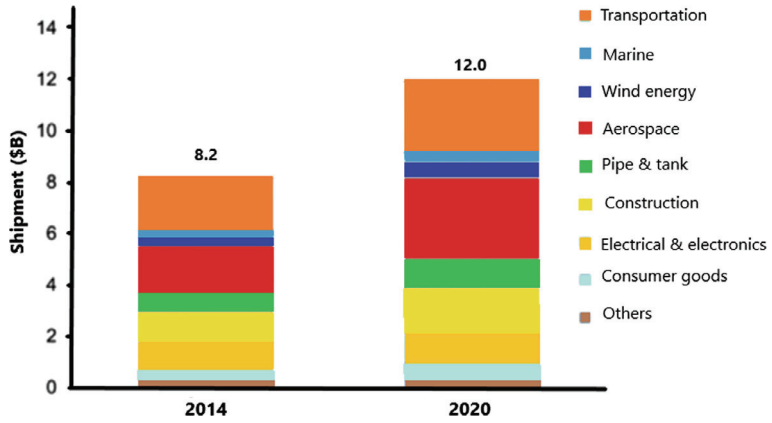

Fig. 2 Market forecast of CF-based composites in terms of application

in the resin segment. The CF-based composite material market, especially in the aviation, transportation, construction, wind energy, and electrical-electronics sectors, is expected to reach 18 billion dollars by 2030, with a compound annual growth rate of 6.6% (Erden & Ho, 2017; Naqvi et al., 2018). The FOREST project aims to lay the foundation for the wider use of biocomposite materials in the transport industry (bus, aviation, and automotive) with cost-effective sustainable solutions based on lightweight, bio-based, and recycled CF composite materials. The project also aims to develop CF, which is among the strategic materials, as a new, multifunctional, fully recycled product as a competitive alternative to traditional composites.

A significant growth in CF use was observed worldwide in 2023. Thanks to its low weight-to-high strength ratio and durability, CF finds wide use in the automotive, aerospace, defense, wind energy, sports, and construction sectors. The value of the CF market in 2023 is estimated at approximately $4.69 billion and is expected to reach $5.13 billion in 2024. It is predicted that the market will reach 7.16 billion dollars by 2028. The market's compound annual growth rate (CAGR) is estimated at 9.4% (*Carbon Fiber Global Market Report 2024—Research and Markets*, n.d.; *Carbon Fiber Market Analysis—US, China, Germany, Russia, Japan—Size and Forecast 2024-2028*, n.d.). The sector where CF is used most intensively is aviation and defense. In 2022, this sector accounted for 60.8% of the CF market. Major aircraft manufacturers such as Boeing and Airbus use this material to reduce the weight of aircraft and increase fuel efficiency by using CF. CF also plays an important role in the automotive industry. Thanks to its lightness and high strength, it is widely used in high-performance vehicles, including electric vehicles. An 8.5% increase in automobile production was recorded in South Korea in 2022, which increased the demand for CF. CFRCs are widely used in the production of wind turbines. Especially in North America and Western Europe, wind energy investments are increasing the demand for CF. Wind energy investments are increasing rapidly in countries such as India and Brazil. CF is also widely used in sports equipment. This

sector benefits from the advantages of CF in sports equipment that requires high performance and durability. Europe, which is the leader in the CF market with a 31.6% share in 2022, maintains this position with the influence of major players in the aerospace and defense sector (Airbus, MBDA). In addition, the low-weight and high-performance-oriented production approach of giants in the automotive industry such as Volkswagen, Mercedes, and Ferrari increases the demand for CF in the region. Asia-Pacific countries such as China, India, South Korea, and Vietnam are increasing the demand for CF with increasing commercial aviation activities and automotive production. There are many important brands in the CF market trying to gain competitive advantage by investing in advanced technology. Among these, companies such as Toray Industries, Teijin Limited, Mitsubishi Chemical Corporation, SGL Carbon, and Hexcel Corporation stand out.

4 Industrial Carbon Fiber Waste

CF is widely used in many sectors and can be in different forms as waste. Figure 3 shows the increase rates in global CF demand over the years. The increase in global CF demand also affects the amount of CF waste on an industrial scale. According to a report by Composites World, approximately 30% of CF production ends up as waste (Isa et al., 2022; Khurshid et al., 2019). These include cut-offs, scrap pieces, and damaged or defective products that cannot be reused in the production process (Koumoulos et al., 2019). These are small pieces of CF that result from the cutting and shaping of CFRCs. They are typically irregular in size and shape and are often not reusable in further production processes (Feraboli et al., 2011). Parts that are produced with defects or do not meet quality control standards are classified as scrap. These pieces are considered waste as they do not maintain the structural integrity required for their intended applications. Products that have reached the end of their useful life or are damaged beyond repair fall into this category. These items were originally manufactured for specific uses but are no longer functional and are classified as recyclable waste.

Currently, the management of CF waste is crucial for both environmental sustainability and economic efficiency (Pakdel et al., 2021). However, the recycling and management of CF waste are more complex and costly compared to traditional materials (Vo Dong et al., 2018). Various approaches have been adopted in the industry for managing CF waste (Ateeq, 2023). One of the most common practices is sending CF waste to landfills or incinerating it (Bianchi et al., 2021). While these methods are relatively low-cost, they are not environmentally sustainable. Incineration of CF releases harmful gases and results in the loss of valuable materials, whereas landfilling provides only a limited solution. Recycling CF waste is increasingly preferred to enhance material efficiency and reduce environmental impact. The recycling process involves various physical and chemical treatments to make CF waste reusable (Naqvi et al., 2018; Zhang et al., 2020). Mechanical methods (cutting, grinding), thermal methods (pyrolysis), and chemical methods (solvent use) are employed to recover

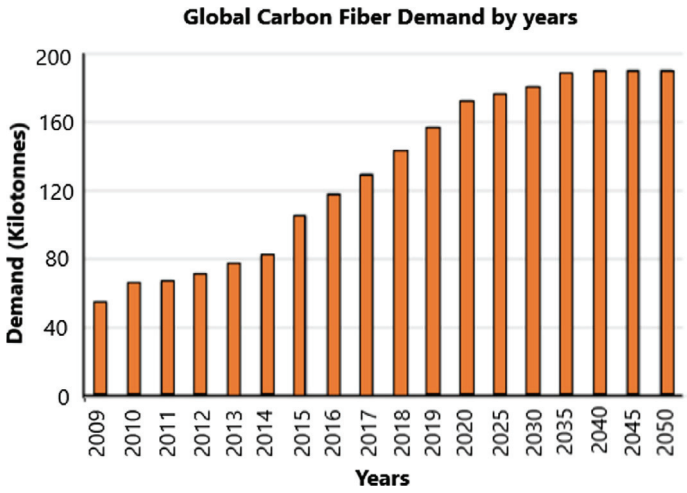

Fig. 3 Increase in global CF demand by year

CFs (Butenegro et al., 2021). CF waste can be transformed into new, high-value products through upcycling processes. These processes involve reprocessing waste into composite materials or new construction materials. For example, recycled CFs (rCFs) can be used in the automotive and aerospace industries to create lightweight and durable parts (Ahmad et al., 2020; Samant et al., 2022). Both industry and academic institutions are conducting research and development activities to manage CF waste more efficiently and sustainably. New recycling techniques and material processing methods are being developed to make the management of CF waste more economically and environmentally viable.

Industrial CF waste is a significant issue concerning both environmental sustainability and economic efficiency. Effective management and recycling of CF waste are critical for conserving natural resources and improving waste management strategies (Bianchi et al., 2021). Continuous improvement of industrial processes and recycling technologies is essential for the sustainable utilization of CF waste. Some well-known companies in the sector are carrying out important studies on the recycling of CF waste. ELG Carbon Fiber is a pioneering company in the recycling of CF waste (Davison & Heinz, 2021). ELG recycles CF waste through mechanical methods, making it reusable. This process involves cutting, breaking, and grinding the waste. ELG processes CF waste through high-temperature pyrolysis, allowing the recovery of CFs. This method separates the resin from the fibers to obtain pure CF. rCFs are used in various industries, including automotive, construction, and sports equipment. Toray Industries, a global leader in CF production, also undertakes various projects in recycling and managing CF waste. Toray works on transforming CF waste into new materials using advanced recycling technologies (*Realizing a Circular Economy*, n.d.). These technologies retain the properties of CFs,

making them reusable. Toray uses rCFs in renewable energy projects and applications that enhance environmental sustainability. For example, rCFs are used in wind turbine blades. Another company, Carbon Conversions, specializes in recycling and reusing CF waste (*Carbon Fiber Recycling*, n.d.). The company recycles CF waste through various chemical and thermal processes to obtain high-quality CF. These processes largely preserve the original properties of CFs, making them reusable. Carbon Conversions develops new and innovative products using rCFs. For instance, lightweight and durable composite materials for the automotive and aerospace industries. The company's efforts reduce the environmental impact of CF waste and promote sustainable material usage. Aerospace giant Boeing engages in several initiatives to recycle CF waste (*Carbon Fiber Recycling: How Boeing Turns Scraps Into Better Use*, n.d.). Boeing collaborates with ELG Carbon Fiber to jointly run projects aimed at recycling CF waste (Sloan, 2018). This collaboration aims to make CF waste from aircraft manufacturing reusable. Boeing recycles CF waste generated from production processes and end-of-life aircraft, increasing the use of sustainable materials in the aerospace industry. Automotive leader BMW takes significant steps in managing and recycling CF waste (Seidel, 2021; Wienstroth, 2012). BMW uses rCFs in automobile production to enhance vehicle lightness and durability while reducing environmental impacts. rCFs are used in models like the BMW i3 and i8 (*BMW i Production CFRP Wackersdorf*, n.d.). BMW runs various projects to recycle CF waste generated during production processes. This waste is reprocessed for use in automotive parts. The FOREST project, in which Mercedes-Benz is also involved, aims to lay the foundation for the wider use of biocomposite materials in the transportation industry by providing sustainable solutions with bio-based and recycled CF production. Within the scope of the project, sustainable EoL alternatives suitable for closing the biomaterial cycle of rCF composite products targeted for use in ceiling, floor, and side wall panels in cabin interiors will also be determined. These companies' efforts demonstrate significant strides in managing CF waste in a more sustainable and environmentally friendly manner. The development of recycling and upcycling technologies reduces the environmental impact of CFs and broadens their industrial applications.

5 Recycling of Carbon Fiber Structures

CFs are widely used in modern industrial applications due to their superior properties. The increased use of CF creates a significant amount of waste. This has become a global problem as valuable CF waste is dumped in landfills. There is a great need to recycle CF-reinforced polymers due to the environmental challenges caused by conventional landfilling. There is a great need to recycle CFRPs due to the environmental challenges caused by conventional landfilling. Although various recycling techniques have been used to recover CFs from waste materials, recycled fibers have limited applications due to partial degradation in mechanical properties and shortening of fiber lengths. From an environmental and economic perspective, burying

or burning these wastes is highly unattractive. Therefore, the recycling process may be one of the best ways to reduce environmental impact while meeting the global demand for this material in industrial applications (Arif et al., 2022).

5.1 Mechanical Recycling

This process involves grinding or shredding CFRCs into smaller pieces. The fibers are then separated from the resin matrix and reused in lower-grade applications, such as reinforcement for concrete or injection-molded parts. Mechanical recycling is relatively straightforward but can damage the fibers, reducing their mechanical properties. Mechanical recycling is suitable for scrap composite materials that are relatively clean, uncontaminated, and of known origin. It is an advantage that it recovers both fibers and resins without using or producing hazardous substances. It is important that the recovered fibers maintain their mechanical properties. Fibrous structure has limited reproducibility because their structure is rough, inconsistent, and unstructured. Mechanical recycling is the first technological process used to recycle CFRP. In this technique, CFRP is ground into small pieces by mechanical processes to ensure that the solid material is crumbled and broken into small pieces. The rich pitch in the scrap can then be isolated by sieving the dusty and fibrous structure. The advantage of this process is that no harmful gases are formed. When applied to CFRP waste treatment, mechanical recycling can recover a significant fraction of CF from waste, as well as provide residual materials suitable for recycled powder and possibly energy recovery for polymer filler applications, thus avoiding landfills. In general, CFRP mechanical recycling has low energy consumption and associated greenhouse gas emissions (Butenegro et al., 2021; Demski et al., 2024). Figure 4 shows the process flowchart of CF recycling by mechanical method as an example. Balıkoğlu et al. (Balıkoğlu et al., 2018) examined the mechanical recycling process and reuse of thermoset-based glass fiber-reinforced polymer (GFRP) plates. The authors used recycled products in proportions of 4, 8, 12, and 16 wt.% in the bulk molding compound (BMC) composition, replacing the original fibers with recycled ones through hot press molding. Tensile and flexural tests were performed on the samples cut from the produced BMC plates according to ISO 527-4 and ISO 178 standards. The results of this study showed that the tensile strength, Young's modulus, and elongation values of the samples were within the acceptable range of $\pm$ 5%. The sample containing 16 wt.% recycled material exhibited the highest tensile strength, Young's modulus, and elongation values. In the flexural test results, the strength values of the samples containing 4, 12, and 16 wt.% recycled glass fiber decreased. The sample containing 12 wt.% recycled glass fiber showed an acceptable decrease in flexural strength, below 10%. The flexural strength of the sample containing 8 wt.% recycled product increased compared to the original sample. Except for the sample containing 4 wt.% recycled product, all samples showed acceptable mechanical performance. In another scientific study, Colucci et al. (2015)

conducted research on the recycling and mechanical performance of a PP-based GF-reinforced polymer composite material (PP40GF), which is commercially used in the automotive sector. Tensile and flexural test results of the samples prepared with recycled material, containing 0, 50, and 100% original raw material. According to the results obtained, all of the recycled PP40GF composites exhibited high-quality performance.

5.2 Thermal Recycling

Also known as pyrolysis, this method involves heating CFRCs in an inert atmosphere to break down the resin matrix, leaving behind clean CFs. Thermal recycling can preserve much of the fiber's original strength and quality, making it suitable for high-performance applications. However, the process requires significant energy and can generate harmful emissions if not properly managed. It allows the recovery of long, high modulus fibers and is therefore one of the most common recycling processes. The composition of the waste feedstock, reactor type, and process parameters affect the pyrolysis procedure. Operating temperatures have significant effects on the mechanical, electrical, and surface properties of the fiber. A higher temperature can be used, but this may cause serious deterioration of recycled products. The most commonly used thermal recycling techniques are pyrolysis and fluidized bed procedure. Although the fluidized bed process is generally simpler than pyrolysis in theory, pyrolysis can produce potentially useful organic products from the polymer. Further processing would be needed to separate these from the product mix and so is likely to be cost-effective on an industrial scale. Recycled fibers may contain varying degrees of charcoal; this may limit reuse options or require further processing to remove them. It is a great advantage that chemical solvents are not used in the pyrolysis process and all results can be recovered and reused. Generally, gases are reused to obtain the energy required for the process. Recovered CFs have mechanical properties similar to virgin fibers (4–20% loss in tensile strength) and are reproducible. However, the properties of recycled fibers are sensitive to processing parameters. The only process used commercially is pyrolysis, but rCFs are chopped or ground (Butenegro et al., 2021; Pakdel et al., 2021). Figure 5 shows the basic steps of thermal recycling method of production of rCF. Yip et al. (2002) conducted the recovery process of carbon fibers through thermal conversion. They recovered carbon fibers with an average length of up to 10 mm. According to the mechanical test results indicated in the study, it was reported that the tensile strength of the carbon fibers retained 75% of their original strength after thermal recycling, the modulus of elasticity remained unchanged, and the surface condition showed similar characteristics to the original fibers. The results obtained demonstrated that the partial or complete replacement of carbon fibers has the potential for reuse. In another study on thermal conversion, Akesson et al. (Åkesson et al., 2012) applied the process to composite samples containing 0, 50, 75, and 100 wt.% of vFs. According to the flexural test results of GFRP recovered through thermal treatment, it was observed that

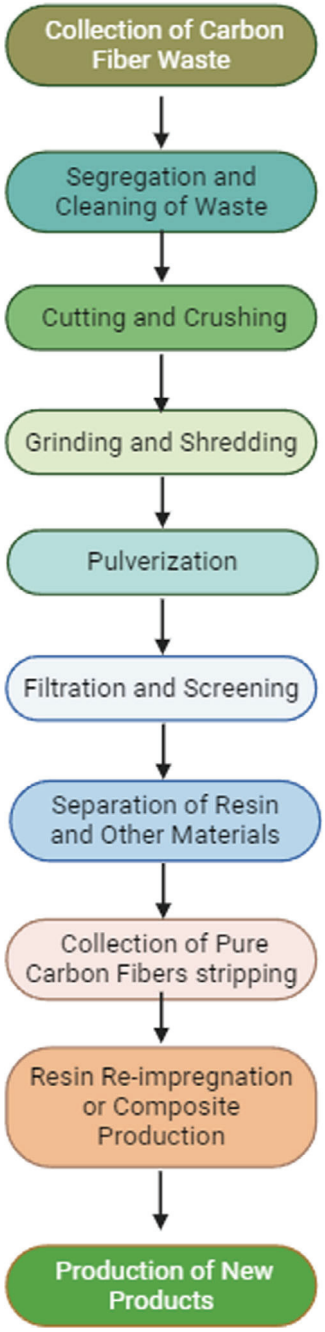

Fig. 4 Process flowchart of mechanical recycling method

composites produced with 25 wt.% recycled fiber exhibited good mechanical properties. Thermal conversion is a widely accepted and commercially used technology on an industrial scale.

5.3 Chemical Recycling

In this method, solvents or chemical agents are used to dissolve the resin matrix, allowing the recovery of intact CFs. CF waste is collected from production processes and end-of-life products. The CF waste is sorted from other types of waste and cleaned. Large pieces of CF waste are cut and shredded into smaller pieces. The shredded CF waste is treated with a specific chemical solvent (e.g., acid or base). This solvent helps break down the resin and other organic materials from the CFs. The solvent dissolves the resin and other organic materials, separating them from the CFs. The clean CFs are extracted from the chemical solvent. The extracted CFs are cleaned to remove any residual solvent and impurities and then dried. The cleaned CFs are reprocessed or used to produce composite materials, making them ready for reuse. The rCFs are used to manufacture new products. Chemical recycling can produce high-quality fibers with minimal degradation, but it often involves the use of hazardous chemicals and complex processing steps. Chemical methods for CFRP recycling are based on low-temperature (typically below 350 °C) reactive media (e.g., catalytic solutions, alcohols, and supercritical fluids). While the polymeric resin is decomposed into relatively high-value oligomers (which can be reused as chemical feedstocks), the CFs remain inert and are subsequently collected. In this technique, the polymer is dissolved with a solution consisting of acid, base, and solvents. The concentration of the solution must be adjusted on the matrix. Compared to sulfuric and hydrochloric acids, nitric acid enables the degradation of polymer resins (i.e., epoxy) and greater recovery of CF. Increasing reagent costs and production of toxic gases are the biggest challenges in chemical recycling of CF. The motivation behind the development of chemical recycling is based on achieving rCF whose mechanical properties or morphology do not change after recycling, as well as reducing the high energy consumption of thermal recycling. The best mechanical performance for rCF is generally achieved by chemical recycling methods. Some of the factors that affect the outcome of the process are temperature, pressure, catalysts, and solvents used (Ateeq, 2023; Butenegro et al., 2021; Manarin et al., 2024). Figure 6 shows production steps of the chemical recycling method of rCF. Yang et al. (2014) carried out the recycling of carbon fibers and glass fibers through chemical conversion. They aimed to optimize the reaction conditions, such as temperature, reaction time, and solvent (NaOH) amount, which varied depending on the type of fiber. They determined the mechanical properties as a function of increasing temperature. When the experiment duration reached 4 hours, the tensile strength of the recycled carbon fibers was found to be 96% of the original fibers, non-alkali glass fibers 94%, and medium-alkali glass fibers 89%.

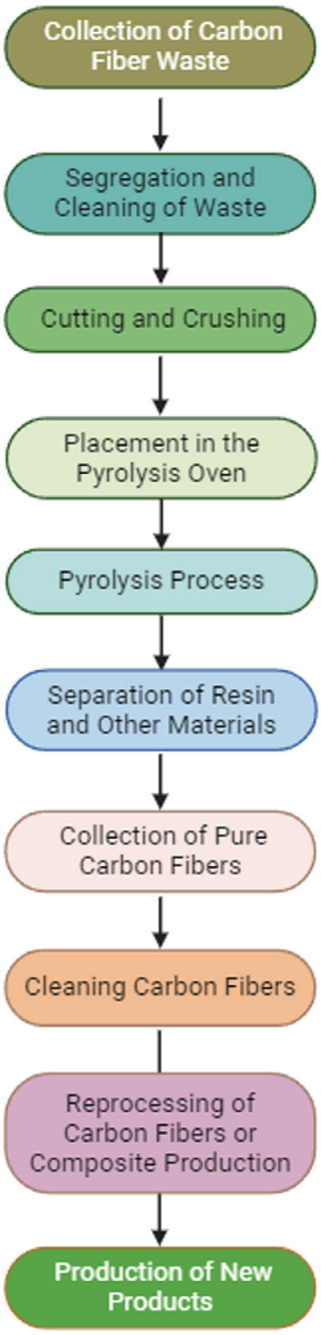

Fig. 5 Process flowchart of thermal recycling method

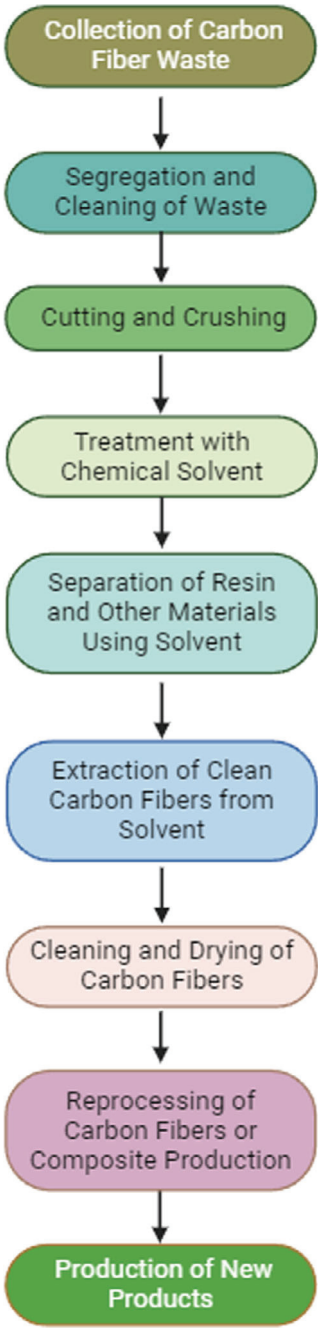

Fig. 6 Process flowchart of chemical recycling method

5.4 Supercritical Fluid Recycling

This innovative method uses supercritical fluids, such as supercritical carbon dioxide, to break down the resin matrix. Unlike other methods, the supercritical fluid reactor is used after collecting and classifying the waste. Waste CFs placed in the supercritical fluid reactor are processed with supercritical fluid. The reactor is filled with a supercritical fluid, typically supercritical CO_2. In this state, CO_2 has unique properties that allow it to penetrate materials like a gas but dissolve substances like a liquid. The supercritical fluid dissolves the resin and other organic materials surrounding the CFs, effectively separating them. After, the clean CFs are extracted from the reactor. Then, a similar process flow is applied again. The use of supercritical fluids, particularly supercritical $CO_{2,}$ allows for an efficient and environmentally friendly separation of resins from CFs. The process operates at relatively low temperatures and pressures, reducing energy consumption and preserving fiber quality. While promising, supercritical fluid recycling is still in the research and development stage and has not yet been widely adopted (Butenegro et al., 2021; Pakdel et al., 2021). Figure 7 shows the steps of supercritical fluid recycling method. In Table 1, studies in the literature that have addressed CF recycling with various methods are given.

Recycling CF structures offers numerous environmental and economic benefits. When the production cycle of CFs is examined, the first advantage is waste management and pollution prevention. It significantly reduces the amount of waste sent to landfills, addressing the pressing issue of industrial waste management (Meng et al., 2018). rCFs reduce the need for vCF production, conserving raw materials such as polyacrylonitrile (PAN) or pitch. Producing rCF consumes less energy compared to manufacturing new fibers from raw materials, leading to lower overall energy usage (Balaji et al., 2020). Recycling reduces the demand for vCF, conserving the raw materials and energy required for their production (Meng et al., 2018). By diverting CFRCs from landfills and incineration, recycling helps to reduce waste and minimize the environmental impact of disposal (Danish et al., 2022). rCFs can be significantly cheaper than vCF, making them an attractive option for manufacturers seeking to reduce material costs. According to previous studies (Meng et al., 2017), while the amount of energy required for vCF production is ~198–595 MJ/kg, this amount decreases to 60–90 MJ/kg in rCF production. Considering mass production, this means a significant gain in energy. Also, recycling supports the circular economy by promoting the reuse of materials and reducing the carbon footprint associated with manufacturing (Balaji et al., 2020). This contributes to a lower carbon footprint for industries that utilize CF materials, such as aerospace, automotive, and sports equipment manufacturing (Zhang et al., 2023). Additionally, rCFs can be used to create high-performance, lightweight materials, enhancing the sustainability of various products without compromising quality (Balaji et al., 2020). Furthermore, the development and implementation of advanced recycling technologies can spur innovation and create new job opportunities in the green technology sector. The growing demand for sustainable products creates new market opportunities for rCFs in various industries, including automotive, aerospace, and consumer goods.

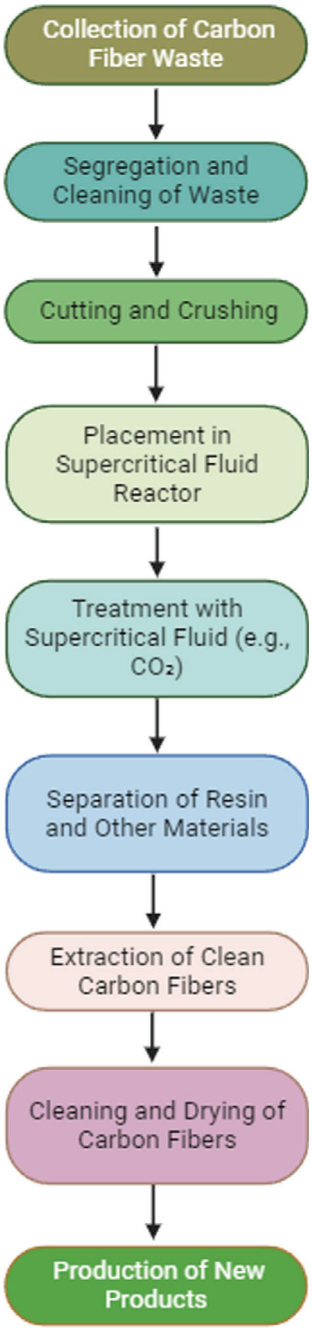

Fig. 7 Process flowchart of supercritical fluid recycling method

Table 1 Studies on the recycling of various CFRCs with different methods

Method	Material	Efficiency	Reference
Mechanical	Epoxy-CF	–	Durante et al. (2023)
	Polyamide 66-CF	–	Colucci et al. (2015)
	Polyamide 66-CF	–	Pietroluongo et al. (2020)
	Polypropylene-CF	–	Evens et al. (2019)
	Poly(aryl ether ketone)-CF	–	Oliveira et al. (2024)
Pyrolysis	Epoxy-CF	94.49%	Deng et al. (2020)
	Epoxy-CF	96.5%	Ren et al. (2022)
	Poly(benzoxazine)-CF	–	Lopez-Urionabarrenechea et al. (2020)
	Epoxy-CF	–	Guo et al. (2019)
	Epoxy-CF	–	Abdou et al. (2021)
	Epoxy-CF	60%	Yatim et al. (2020)
Chemical	Epoxy-CF	97.77%	Wang et al. (2015)
	Epoxy-CF	96.9%	Lee et al. (2020)
	Epoxy-CF	95%	Jiang et al. (2017)
	Epoxy-CF	–	Yang et al. (2014)
	Epoxy-CF	83%	Schamel et al. (2021)
Supercritical fluid	Epoxy-CF	94–97%	Bai et al. (2010)
	Epoxy-CF	–	Pinero-Hernanz et al. (Ul et al., 2008)
	Epoxy-CF	–	Jiang et al. (2009)
	Epoxy-CF	100%	Shetty et al. (2022)
	Epoxy-CF	–	Okajima et al. (2014)

Recycling supports the principles of a circular economy by promoting the reuse and repurposing of materials, extending the lifecycle of CFRCs. Increasingly stringent environmental regulations encourage the adoption of recycling practices, helping companies meet legal requirements and improve their environmental performance. Overall, the recycling of CF structures is a pivotal step toward a more sustainable and economically viable future, aligning with global efforts to reduce environmental impact and promote resource efficiency.

rCFs offer numerous benefits but also present certain challenges. Understanding these advantages and disadvantages is crucial for developing effective recycling strategies and advancing the sustainable use of CF materials (Ateeq, 2023; Butenegro et al., 2021). Mechanical recycling processes can damage CFs, reducing mechanical properties such as strength and stiffness (Gopalraj & Kärki, 2020). This limits the use of rCF to lower-grade applications. The recycling process can shorten the fibers, which impacts their performance and restricts their application in high-performance composites (Hofmann et al., 2023). Some recycling methods, particularly thermal and

chemical processes, can be expensive due to the energy and specialized equipment required (Bledzki et al., 2021). The economic viability of recycling depends on the market demand for rCF, which can fluctuate and affect the profitability of recycling operations (Meng et al., 2018). CFRCs often consist of various fiber types, resin systems, and manufacturing methods, complicating the recycling process and making it challenging to achieve consistent quality (Asmatulu et al., 2013). Contaminants in the composite materials, such as adhesives, coatings, and other additives, can hinder the recycling process and reduce the quality of the rCF (Stieven Montagna et al., 2022). Developing efficient and scalable recycling processes that can handle the diverse range of CFRC remains a significant challenge (Giorgini et al., 2020). Continuous innovation and technological advancements are required to improve the efficiency, cost-effectiveness, and environmental friendliness of recycling methods (Koumoulos et al., 2019). The absence of standardized recycling methods and quality benchmarks for rCF can pose challenges in ensuring consistent performance and reliability (Danish et al., 2022). Navigating complex regulatory frameworks related to waste management and recycling can be cumbersome and may vary across regions, impacting the implementation of recycling programs.

The recycling of CF presents a balanced mix of significant advantages and notable challenges. While it offers substantial environmental, economic, and sustainability benefits, it also requires addressing quality degradation, high processing costs, material complexity, and technological hurdles. As the demand for sustainable materials continues to grow, advancements in recycling technologies and the development of standardized processes will be crucial for maximizing the benefits and overcoming the disadvantages of rCF structures. Through ongoing research, innovation, and collaboration, the industry can enhance the viability and effectiveness of CF recycling, contributing to a more sustainable future. Various methods for recycling CFRP have been investigated; most recycling routes involve shredding waste and recycling fibers to recover products and then re-impregnating the recovered fibers in a new composite (Borjan et al., 2021; Pimenta & Pinho, 2014). Although the mechanical recycling method is economically advantageous and can be applied on an industrial scale, rCFs have poorer mechanical and physical properties. This shows that this technology is not suitable for structural applications with high loads. Chemical recycling methods can produce rCFs with clean and smooth surfaces, and vCFs can maintain their mechanical properties. However, it is difficult to gain commercial ground due to the high cost of solvents and equipment, harsh conditions, and the formation of hazardous gases and waste. For all these reasons, thermal recycling methods such as pyrolysis, steam, and fluidized bed methods have been developed to recycle CFRPs more efficiently. These processes include chemicals in the supercritical phase to dissolve the polymer matrix, and the tensile strength of rCFs can reach 80–95% of vCFs. The biggest problem is that the coke formed during the heat treatment accumulates on the surfaces of rCFs. The success in rCFs recycling processes will provide an important research area for the future development of CFs and CFRPs. Therefore, it is necessary to develop sustainable recycling processes. Developing reuse strategies for rCFs is part of ongoing research, such as spinning them into yarns, producing nonwoven fabrics and crimp-free prepreg fabrics using combined rCFs and vCFs,

Table 2 Pros and cons of different recycling process

Method	Pros	Cons	Required energy (MJ/kg)
Mechanical recycling	Cost-effective, efficiency, well-known	May adversely affect mechanical properties	0.1–4.8
	Both resin and fibers can be recycled	Fibers may be irregularly shaped and short	
	No harmful products or uses	Limited recycling	
Pyrolysis recycling	Highly efficient recycling	Requires additional equipment due to off-gases	21–91
	Better adhesion between resin and rCFs	There may be residual resin on the fiber surface	
	Commercially applied	Fiber quality is sensitive to processes	
Chemical recycling	Highly efficient recycling	Chemical use poses a threat to the environment	24–30
	Recycling is possible for both fiber and matrix material	Suitable for low quantities	
		Fiber adhesion to resin matrix is generally reduced	

and new composite materials (Das et al., 2018; Wu et al., 2022; Yan et al., 2016). Table 2 compares the pros and cons of the mentioned recycling methods.

6 Challenges in the Recycling Process of Carbon Fibers

While recycling processes have reached a certain degree of maturity, the biggest challenge for CF recycling operations is the introduction of a robust CFRP recycling process that supports the effective commercialization of recycled products. Here are some basic challenges to overcome these problems (Ateeq, 2023; Naqvi et al., 2018).

- **Creating a global recycling strategy:** It is necessary for composite-related industries, suppliers, recycling facilities, and research centers to come together and plan technological and industrial needs.
- **Giving incentives for recycling:** Incentives in the name of carbon credit should be given to institutions that recycle CF. As recycling companies become commercialized, specific legislation covering their activities needs to be implemented.

- **Logistics and collaboration in the supply chain:** Waste suppliers should collaborate with recyclers, which includes ensuring a continuous and appropriate supply of waste and providing material certification to recyclers where possible. Conversely, recyclers must ensure that materials and components supplied are not reverse engineered.
- **Market identification and product pricing:** To determine the value of recycled products, it is necessary to know the characteristics of different rCFs and evaluate processing times and costs.
- **Performing life cycle analysis (LCA):** Knowing the recycling process efficiency, environmental, economic, and technical advantages of rCF materials can be determined by life cycle analysis.
- **Establishing the market:** The current biggest challenge for the success of CFRP recycling is the establishment of a market for recycled products. Since creating a market requires overcoming all previous problems, rCFs are considered an environmentally friendly, sustainable, and cost-effective material.

Recycling of composites difficult due to reasons such as the presence of complex compositions such as fibers, matrix, and fillers, the presence of thermoset resins that cannot be remolded, and its combination with other materials. Today, most CFRP waste is generally disposed of in desert cemeteries, airports, or landfills. However, these are not environmental and sustainable solutions for the following reasons (Balaji et al., 2020; Bledzki et al., 2021):

Environmental impact: Increasing production of CFRP increases concerns about waste disposal and consumption of non-renewable resources.

- **Legislation**: Recent European legislation imposes strict control on the disposal of composites; Responsibility for disposing of EoL composites now lies with the component manufacturer, legal disposal of CFRP is limited and, for example, 85% of automotive vehicles disposed of after 2015 must be recyclable (EU 1999/31/EC; EU 2000/53/EC).
- **Cost of production:** CFs are expensive products, both in terms of energy consumed during production and material price.
- **Management of resources:** demand for vCFs often exceeds supply capacity, so recycled rCFs can be reintroduced to the market for non-critical applications.
- **Economic opportunity:** The cost of disposing of CFRP through landfill is quite high. Recycling CFRPs offers the opportunity to transform very expensive waste disposal into economical and reusable materials.

Research and market studies show that commercialization of rCF components may be possible by overcoming several challenges that have not yet been resolved. Studies show that Mercedes-Benz, Chevrolet, BMW, Ford, and many other major automobile manufacturers have paid attention and possibility to use rCF composite part in large-scale automobile production.

7 Opportunities for Sustainable Recycling

The sustainable recycling of CF materials presents a plethora of opportunities that can significantly impact various industries and contribute to environmental preservation. By advancing recycling technologies and implementing innovative approaches, the potential for sustainable recycling can be fully realized. The development of advanced chemical recycling processes can enhance the efficiency and effectiveness of recovering high-quality CFs from composite waste. By utilizing environmentally friendly solvents and catalysts, chemical recycling can minimize environmental impact and produce rCFs with properties comparable to vCF. Leveraging supercritical fluids, such as supercritical carbon dioxide, offers a promising method for decomposing resin matrices at relatively low temperatures and pressures. This approach preserves the integrity of CFs, making them suitable for high-performance applications while reducing energy consumption and emissions.

Integrating closed-loop recycling systems within manufacturing processes can ensure that CF waste generated during production is efficiently reclaimed and reused. This approach not only reduces waste but also decreases the reliance on virgin materials, promoting a circular economy. Designing CFRCs with recycling in mind can facilitate easier disassembly and material recovery. By selecting compatible resin systems and minimizing the use of contaminants, manufacturers can enhance the recyclability of their products and reduce the complexity of the recycling process.

Establishing specialized companies that offer recycling services for CFRCs can create new business opportunities and encourage more industries to adopt sustainable practices. These companies can provide expertise, technology, and infrastructure for efficient recycling, making it accessible to a broader range of manufacturers. Forming partnerships between manufacturers, recycling companies, and research institutions can drive innovation and share the financial and technical burdens associated with developing sustainable recycling solutions. Collaborative efforts can accelerate the adoption of best practices and technological advancements across the industry. Many studies have made a techno-economic evaluation of the application of rCF in an automotive part, taking into account weight reductions and fuel consumption reductions compared to steel. A 35% cost reduction was determined for the rCF part with oriented fibers compared to the steel part. Considering the current market volume and the growth of CFRPs, these amounts seem achievable in the future. At this stage, the attractiveness of rCF materials stems not only from their cost advantages but also from their superior mechanical and physical properties (May et al., 2021; Meng et al., 2018). Considering all these, the multifunctionality provided by the use of rCF, shown schematically in Fig. 8**,** appears as a promising opportunity.

FOREST, which aims to develop recycled CF and produce new and innovative green composites for increased resource efficiency and sustainable and safe transportation practices, offers new suggestions in line with these goals. This chapter of current sustainable indicators in biocomposite production, conversion of 100% rCF into new intermediate products; assessing the potential suitability of technologies

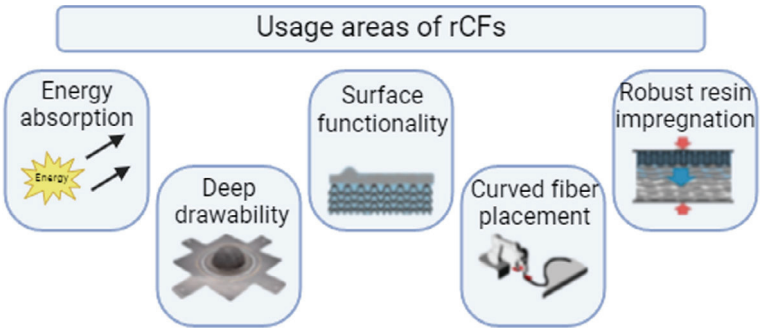

Fig. 8 Versatile functionality achieved using rCF (May et al., 2021)

applied to biocomposites and testing them at the laboratory and pilot plant level; determining the technical feasibility of the selected material and process route; and establishing clear criteria for CE. Implementing supportive regulations and policies that encourage the recycling of CFRCs can drive industry-wide adoption. Governments can introduce mandates for recycling, provide funding for research and development, and offer tax incentives for companies that invest in sustainable recycling technologies. Developing industry standards and certification programs for rCFs can ensure consistent quality and performance, fostering market acceptance and consumer confidence. Standardized processes and benchmarks can streamline recycling operations and facilitate the integration of rCFs into new products.

Investing in R&D to develop new resin systems and composite materials that are easier to recycle can significantly enhance the sustainability of CF products. Innovations such as thermoplastic composites and reversible adhesives can simplify the recycling process and improve material recovery rates. Conducting comprehensive lifecycle analyses of CFRC can identify key areas for improvement in recycling and overall sustainability. By understanding the environmental impact of each stage of a product's lifecycle, from production to end-of-life, manufacturers can make informed decisions to optimize their processes and reduce their ecological footprint. The FOREST Project, which aims to provide new and innovative sustainable green composites for safe transportation practices, is a great opportunity for the development of sustainable recycling of CFs. The FOREST project will also provide opportunities for new eco-design and recycling practices based on the life cycle approach of bio-based and recycled CFs.

8 The Future of Recycled Carbon Fiber Structures

The future of rCF structures is poised to be transformative, with advancements in technology, increasing environmental awareness, and industry collaboration driving significant growth and innovation. As the demand for sustainable materials continues

to rise, rCFs are expected to play a crucial role in various high-performance applications. Here are several key trends and developments that will shape the future of rCF structures:

Future advancements in chemical and thermal recycling processes will enable more efficient and effective recovery of high-quality CFs. Innovations such as green chemistry approaches and more energy-efficient pyrolysis techniques will reduce environmental impact and improve the economic viability of recycling. The development of supercritical fluid technology for rCFs will become more prevalent. This method offers lower energy consumption and better preservation of fiber properties, making it a promising avenue for future recycling efforts.

The integration of artificial intelligence (AI) and machine learning in recycling facilities will enhance the sorting and separation of CFRCs from other materials. Automated systems will increase efficiency, reduce contamination, and ensure a consistent supply of high-quality recycled fibers. AI-driven process optimization can improve the efficiency and yield of recycling operations. By analyzing data and predicting outcomes, AI can help fine-tune recycling processes, reducing waste and maximizing fiber recovery.

The automotive industry will increasingly adopt rCFs to produce lightweight, fuel-efficient vehicles. rCF components will be used in structural parts, body panels, and interior components, contributing to lower emissions and improved performance. The growing EV market will drive demand for rCF due to its lightweight and high-strength properties, which can enhance battery range and vehicle efficiency. Aerospace and defense sectors will turn to rCF for cost-effective, high-performance materials. The ability to recycle CFs without significant loss of properties makes them suitable for various aerospace applications, including aircraft interiors, structural components, and unmanned aerial vehicles (UAVs). Aerospace companies are increasingly prioritizing sustainability, and rCF will play a vital role in meeting environmental goals and reducing the carbon footprint of aircraft production. rCFs will be used in the construction industry to create innovative, sustainable building materials. rCF-reinforced concrete, composites for bridges, and modular construction components will benefit from the strength and durability of CFs. Infrastructure projects will leverage rCF for its corrosion resistance and long-term durability, leading to more resilient and sustainable construction practices.

As recycling technologies advance and more companies invest in rCF production, the cost of rCFs will decrease. Economies of scale will make rCF more competitive with virgin CFs, driving broader adoption across industries. Greater integration of rCF into supply chains will streamline production processes and reduce material costs, further enhancing the economic feasibility of using rCFs. Supportive regulations and incentives will encourage the use of recycled materials. Governments may implement policies that mandate recycling or provide financial incentives for companies that use rCF, promoting a more sustainable materials economy. Stricter environmental standards will drive the adoption of rCF as industries seek to meet sustainability goals and reduce their carbon footprint.

The future of rCF structures is bright, with technological advancements, expanding applications, market growth, and regulatory support all contributing to their increasing adoption. As industries continue to prioritize sustainability, rCFs will play a critical role in reducing environmental impact, conserving resources, and driving innovation in high-performance applications. The continued development and integration of rCF will lead to a more sustainable and efficient use of CF materials, shaping a greener future for various industries. The development of more efficient and cost-effective manufacturing and recycling technologies will further enhance the role of CF materials in modern engineering and environmental sustainability.

The success of FOREST, which aims to develop new multifunctional biocomposites as a competitive alternative to traditional composites, will make significant contributions to the development of bio-based and recycled CF composites. Additionally, the FOREST project will increase the focus on sustainability in the circular economy (CE) through the analysis of effective recycling methods applied to biocomposite components containing more than 50% sustainable materials. In terms of rCFs, the success of FOREST and similar projects will be the determining factor in the role that CF structures will play in the future.

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