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Cutting-Edge Advances in Nanofibers and Fibers:

Shaping Future Applications

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Chapter 6
Recycling Carbon Fibers: Environmental and Circular Economy Perspectives

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ABSTRACT

Carbon fibers are widely used in various industries due to their exceptional mechanical properties and lightweight nature. However, the increasing demand for carbon fiber-reinforced polymers has led to significant environmental concerns associated with their production and end-of-life disposal. This chapter explores the recycling of carbon fibers from an ecological and circular economy perspective, aiming to highlight the potential of recycled carbon fibers to mitigate these challenges. The environmental and social impacts of recycling are also analyzed, emphasizing reduced carbon emissions, energy savings, and the creation of sustainable supply

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chains. Ultimately, this chapter underscores the transformative potential of recycling in addressing environmental concerns and fostering a sustainable future for carbon fiber technologies.

1. INTRODUCTION

The demand for innovative materials with properties such as lightweight and exceptional strength in the aviation, construction, and automotive industries has driven scientists and engineers to increasingly adopt carbon fiber-based composites over traditional metal-based materials. Carbon fibers (CFs) are characterized by a high elastic modulus relative to bulk density, superior specific strength, excellent temperature resistance, high corrosion resistance, and outstanding electrical conductivity. Furthermore, CFs are distinguished as unique engineering materials due to their high strength-to-weight ratio, recyclability with low environmental impact, and remarkable wear resistance. These attributes have rendered CFs highly desirable in modern manufacturing, serving as essential components in the development of advanced composite materials. The utilization of CF waste in construction applications, particularly in cement composites, has demonstrated notable performance enhancements and garnered significant interest. Carbon fiber-reinforced polymer (CFRP), which combines CF with a polymer matrix, holds the greatest application potential among these composites. However, the extensive use of these materials across various industries has led to considerable energy consumption and material usage during production, resulting in the generation of substantial waste. Consequently, there is a pressing need to develop efficient, cost-effective, and rapid recycling approaches for CFs that preserve their quality and functionality (P. Y. Chen et al., 2023; Kumar & Krishnan, 2020; Naqvi et al., 2018; Verma et al., 2018).

CFRP materials are extensively utilized across diverse sectors, including the construction industry, aviation, wind turbines, marine and terrestrial vehicles, power tools, sports equipment, and storage tanks. In the automotive and construction industries, CFRPs can achieve weight reductions of up to 65% when replacing steel and up to 20% compared to aluminum components in aviation (Cecchel, 2020; Muhammad et al., 2021). The demand for CFs continues to grow due to their wide range of applications in various industries. With a substantial global market, the demand for CFRPs is steadily increasing. According to global data, approximately 40% of all virgin carbon fibers (vCFs) are discarded as material waste (Ateeq, 2023). This growing demand has driven an increase in the production of high-performance vCFs. The need for CFRP recycling is critical due to environmental challenges associated with incineration and traditional landfill disposal methods. The widespread use of CFRPs has also introduced significant recycling challenges related to leftover production

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materials, obsolete prepregs, and end-of-life components. Thermosets are commonly employed as matrices in CFRP production to ensure high performance. However, their insoluble and non-melting properties render them more difficult to recycle and reuse compared to thermoplastic resins. The extensive use of thermoset-based CFRPs has resulted in significant energy and material consumption during manufacturing, contributing to substantial waste generation. Among thermoset matrices, epoxy resins are particularly sought after due to their strong bond strength, excellent mechanical properties, thermal stability, and chemical resistance. However, their three-dimensional cross-linked network structure, while enhancing performance, also makes these composites inherently challenging to recycle. The recyclability of CFRPs largely depends on the nature of the resin matrix. Recycling processes that require extremely high temperatures and pressures can significantly degrade the mechanical properties of the recovered CF. Developing an epoxy resin capable of recovering CF without compromising its mechanical properties or chemical structure, even under stable conditions, could offer a viable solution for producing defect-free recycled CFRPs (rCFRPs). The primary factor influencing changes in mechanical properties is the degree of fiber orientation, which can vary based on the technological processes applied during production (Kumar & Krishnan, 2020; Meng et al., 2018; Rani et al., 2021).

CF is produced through the carbonization of resin and synthetic polymers via thermal treatment and oxidation at elevated temperatures. This carbonization process requires extremely high temperatures, resulting in a final product with a high concentration of carbon elements. The extensive utilization of CF-based materials necessitates significant energy and material consumption during production, leading to substantial waste generation. The high cost and energy-intensive production of vCFs highlight the importance of rCFs as a sustainable alternative. Utilizing rCFs after the end of their life cycle not only reduces environmental impacts associated with waste but also facilitates their regional reuse. Since rCFs retain a significant proportion of their original strength post-recycling, they present a viable substitute for vCFs, particularly in cement composite applications. Research has shown that rCFs can maintain 90–98% of the mechanical strength of vCFs, emphasizing their potential as an environmentally friendly and economically viable alternative (Ateeq et al., 2023; Danish et al., 2022). Next-generation rCFs exhibit desirable properties such as high strength and elasticity, excellent electrical conductivity, and corrosion resistance. These attributes make rCFs well-suited for a wide range of applications. Consequently, to mitigate the environmental impacts of post-life cycle waste, the recovery of CFRPs and the development of rCFRPs for diverse applications are essential (Kumar & Krishnan, 2020). One of the most comprehensive initiatives addressing recycling and its various applications is the Horizon-Europe project called Advanced Lightweight Materials FOR Energy-efficient STructures (FOREST). The

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FOREST project seeks to develop bio-composites comprising bio-based polymers and rCFs by integrating renewable and recyclable resources, thereby maximizing product sustainability. The project aims to advance promising technologies by addressing key economic, environmental, and social challenges. International efforts such as the FOREST project provide significant opportunities to reduce dependence on fossil-based resources and minimize CFs waste. Additionally, it is anticipated that the bio-composites produced within the scope of the FOREST project will offer recyclability, lightweight construction, and specialized functionalities, contributing to enhanced safety and cost-effectiveness. These attributes position the bio-composites as viable alternatives to traditional composite materials (*Advanced Lightweight Materials FOR Energy-Efficient STructures*, 2022; *Advanced Lightweight Materials for Energy Efficient Structures (RIA)*, n.d.). Reducing the challenges and overcoming legal barriers associated with recycling through such approaches are critical elements for achieving transformative success in CF recycling concepts.

Finding effective methods for recycling rCFRP waste and reusing rCFs has become a significant challenge. Technologically, recycling techniques differ in terms of energy consumption, processing methods, and costs, as well as fiber direction and length. Typically, mechanical, chemical, and thermal recycling methods are employed. Mechanical recycling involves a shredding process that reduces the size of the waste, facilitating its recycling. In thermal recycling, waste is decomposed through thermal disintegration, transforming it into material and energy. In chemical recycling, the matrix is separated from the fibers in a reactive environment. While mechanical recycling is not as attractive as before, it remains important as a pretreatment step for thermal or chemical recycling methods. Generally, the mechanical performance of rCFs produced by thermal and chemical methods is superior to that of rCFs obtained through mechanical recycling. A major issue with the mechanical recycling technique is the integrity, or bonding, between the recycled material and the new matrix material. Since the fiber length is typically reduced during this process, fibers may be damaged. To address this, advanced techniques such as electro-dynamic fragmentation are gaining attention. Thermal recycling methods, particularly pyrolysis, are effective in recovering CFs by heat, and the use of rCFs instead of new CFs may offer ecological benefits. Chemical recycling, regarded as one of the most efficient methods for recycling CFs, allows for easy separation of fibers and operates under environmentally favorable conditions. This method also facilitates the recovery of separated polymer matrix products, enabling their reuse in the production of new resin materials. However, in terms of structural applications, the use of rCFs is limited due to the long fibers required. Further research is necessary to overcome these limitations and encourage the industrial acceptance of rCFs. Life Cycle Assessments (LCAs) conducted in this area should be thoroughly examined. One of the most notable advantages of using rCFs in composite products

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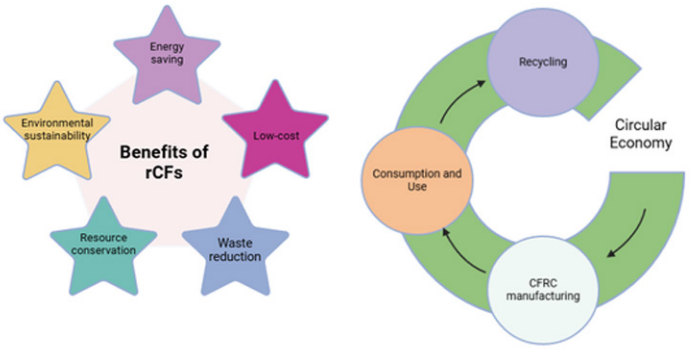
is their positive environmental impact. Recycling CFs to produce rCFs conserves energy, reduces greenhouse gas emissions, and decreases reliance on unsustainable resources. The environmental benefits of rCFs are illustrated in **Figure 1** (left side), where the recycling process prevents waste from being sent to landfills and incinerators. A circular economy, also known as waste-free production, enables products to be remanufactured, reused, and recycled at their end-of-life (EOL) stages (Butenegro et al., 2021; Li et al., 2016; Pimenta & Pinho, 2014). The links to the circular economy process of CFRP are shown in **Figure 1** (right side). The circular economy is an economic model focused on minimizing waste and maximizing resource efficiency by keeping materials and products in use for as long as possible (Balaji et al., 2020). Unlike the traditional linear economy, which follows a "take-make-dispose" approach, the circular economy promotes recycling, reuse, and remanufacturing to create a closed-loop system. Key principles include designing for durability and recyclability, extending product lifecycles, and using renewable resources. This model reduces environmental impact, conserves raw materials, and supports sustainable economic growth by reducing dependency on finite resources. Recycling CFRP contributes positively to the circular economy by reducing waste after its lifecycle in various applications.

Figure 1. Benefits of using rCF (left) and circular economy processes (right)



In summary, the rCFRP recycling process faces three main challenges. First, the reduction in fiber length results in a decrease in the performance of rCFs compared to vCFs. Second, energy recovery as a recycling method is not only ineffective in recovering the energy expended in the production of composite-based materials, but it may also cause the added value provided by long CFs to be lost. Finally, the adhesion between the new matrix and rCFs remains unstable, leading to suboptimal performance of composites made with rCFs. Both environmental and economic

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considerations have driven the development of recycling routes to manage the growing volume of CFRP waste. The energy required for recycling CFs is significantly lower than that needed to produce vCFs. In terms of both costs and energy efficiency, the recovery of rCFs is crucial for achieving the goals of a circular economy. This chapter provides an overview of the current state of CFRP waste and presents a systematic review of recycling technologies from an environmental and circular economy perspective. It also discusses key challenges in establishing a robust CFRP recycling industry and developing markets for recycled products. Furthermore, the potential for integrating rCFRPs into structural components and exploring possible applications is examined (P. Y. Chen et al., 2023; Holmes, 2018; Rani et al., 2021). This chapter also addresses the current challenges and modern trends in CFRP recycling. Innovations in recycling technologies play a crucial role in fostering a circular economy and promoting a sustainable environment, making this topic of study particularly significant.

2. FROM CARBON TO CARBON FIBERS

CFs derive their strength from the robust carbon-carbon (C-C) bonds, which enable the production of strong and lightweight materials. CFs are characterized by their material composition, which contains at least 99% carbon, and their cylindrical form, resembling textile fibers such as cotton or polyester. A notable historical example is Thomas Edison's search for a filament for use in an incandescent lamp, which led to the development of the first ‘CF'. The CF structures developed by Edison are remarkably similar to those used in contemporary automotive, aerospace, and aircraft applications. Edison successfully transformed a common material like rayon into a highly durable substance with excellent electrical and thermal conductivity, based on its carbon structure. In the 1970s, Union Carbide further developed high-strength CFs from this precursor material, leading to the CFs used today. The general structure of CFs consists of graphite layers twisted around the fiber’s C-axis. These fibers are predominantly composed of graphite layers stacked along the C-axis with a high degree of crystallinity, approximately 80%, and are considered to have an elastic modulus exceeding 365 GPa. The elastic modulus is a measure of the force required to displace an atomic plane by one lattice void, making it a fundamental property of CFs. This property describes a material’s stiffness or resistance to deformation and is determined by both the structure and chemistry of the material. CFs are classified into three categories based on their elastic modulus, with progressively higher carbon content. They are produced through the carbonization of rayon, resins, and synthetic polymers, using heat treatment and oxidation at high temperatures. The carbonization process employs extremely high temperatures, which results in an increased

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concentration of carbon in the final product. CFs can be further categorized into continuous and discontinuous types, depending on fiber length or orientation within the matrix. Due to their exceptional hardness, strength, low density, reactivity, and excellent resistance to high temperatures, CFs have found specialized applications across various industries. Additionally, their lubricating properties, high electrical and thermal conductivities, and low thermal expansion coefficients make them unique materials. However, despite these advantages, CFs are also associated with certain disadvantages, such as high cost and fragility (Ateeq, 2023; Giorgini et al., 2020; Pimenta & Pinho, 2011, 2014). The demand for carbon fiber is increasing day by day due to its wide application in different sectors (Harussani et al., 2022) which requires higher volume production of pure carbon fiber. The production of vCF requires a lot of power. The precursor material, which is subjected to oxidation, carbonization, and graphitization to form CFs, marks the starting point of the production process. The selection of a suitable precursor material depends on factors such as carbon content, cost, processability, and the ability to form the carbon layers that constitute the atomic structure of CFs. Common precursor materials include Rayon, Polyacrylonitrile (PAN), and pitch, with PAN and pitch being the most widely used. PAN is the most common precursor due to its low production costs and favorable physical properties. This material is often copolymerized to improve machinability and control the physical properties of the final product. High-purity PAN is preferred for producing aerospace-grade CFs.

Pitch, a high molecular weight byproduct of petroleum distillation, has a high carbon content. Its high molecular weight offers an advantage for producing CFs with high modulus and strength. Pitch-based CFs are commonly used in the automotive industry due to their favorable performance in low-cost CF production. Rayon, which is used in the production of first-generation CFs, has declined in usage due to the reduced availability of rayon production. Rayon is derived from naturally occurring cellulosic polymers, specifically regenerated cellulose. However, the environmentally harmful solvents used in rayon production have contributed to its decline, particularly in the textile industry.

As reinforcement for polymer matrices, CFs are promising and crucial materials for development. Various types of CFs exist, depending on the raw material, material properties, and the processing temperature during the heat treatment stage. The most common classification of CFs is based on fiber length or orientation in the matrix, distinguishing between staple fibers and continuous fibers. The fiber orientation is a key factor influencing the properties of the composite material. Staple fiber-based composites are typically preferred for high-volume applications where nearly isotropic properties are required. Continuous fiber-based composites, on the other hand, are favored for low-volume applications where enhanced mechanical properties in one

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or two directions are needed, such as in support beams, impact panels, and holding vessels (Hassan et al., 2020; Verma et al., 2018).

3. RECYCLING PROCESSES OF CARBON FIBERS

CFs are increasingly favored in industrial applications due to their high strength, lightweight nature, and exceptional reliability. The high price and energy consumption required to produce vCF enables rCF to be evaluated post-life cycle, reducing the environmental impact and land use from its waste. As their usage expands, a significant amount of CF waste is generated, which has become a global issue. Consequently, research efforts have focused on recycling CF waste. In this context, international projects play a crucial role. Among these, the FOREST project aims to lay the groundwork for the broader adoption of bio-composite materials in the transportation industry, including bus, aviation, and automotive sectors, through cost-effective, sustainable solutions based on lightweight, bio-based, and recycled CF composite materials. The project also seeks to develop CFs as a new, multifunctional, fully recycled product, offering a competitive alternative to traditional composites. Innovations in recycling technologies are aimed to help create a circular economy and a sustainable environment. Additionally, research is exploring the incorporation of polymer-based nanoparticles or hybrid materials to enhance the properties of recycled CFs, bringing them closer to those of pure CFs. The degradation of CF-based composite structures is influenced by exposure to specific conditions and environments. Understanding these transformations is critical for improving the properties, strength, safety, and durability of CF-based materials for use in future applications (Bai et al., 2010; Holmes, 2018; Isa et al., 2022). The changes that CF structures undergo during recycling are illustrated according to the processes shown in **Figure 2**.

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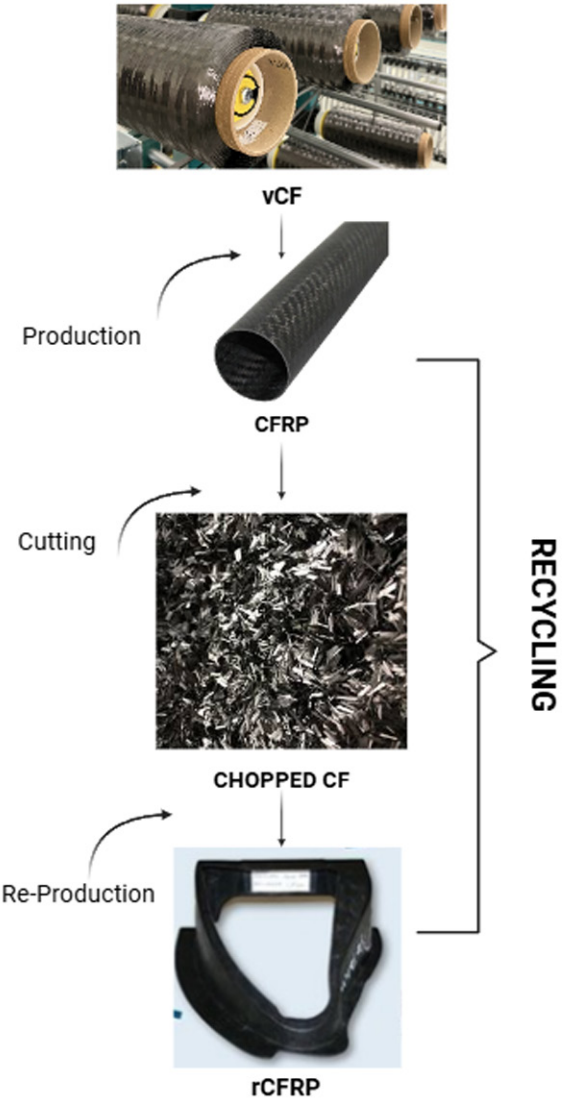
Figure 2. Change of CF in the recycling process



From an environmental and economic perspective, incineration and landfilling of CF-based composites are unsustainable practices. As a result, reuse and recycling have taken precedence. Recycling of CFRPs is essential to address the environmental challenges posed by traditional landfill disposal. Various recycling techniques are employed to recover CFs from waste materials; however, these processes face limitations, including the partial degradation of the mechanical properties of rCFs

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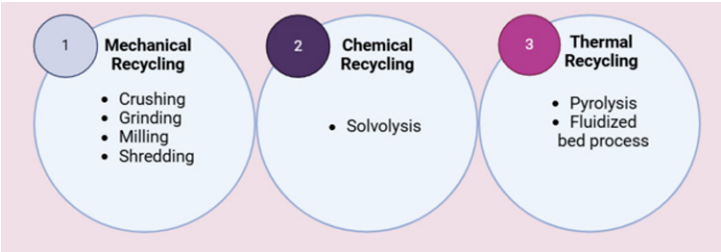
and the reduction in fiber length. While CFs are considered environmentally friendly materials due to their long service life, their production requires significantly more energy compared to steel—approximately 14 times higher. This high energy consumption results in substantial greenhouse gas emissions. Recycling offers one of the most effective approaches to meet global demand while mitigating environmental impact. In a report published by Balaji et al. (Balaji et al., 2020) on the cost analysis and market space for rCF in the automotive industry, they reported that carbon fiber recovery can be achieved at a cost of $5/kg or less based on a range of process parameters including 500 t/yr - 6000 t/yr plant capacity, accounting for approximately 15% of the cost of vCF. CF waste can be broadly categorized into two types. The first type consists of dry fiber waste, including vCF residues and unused or expired materials, commonly referred to as scrap. The second type arises from the processing of CFRP fibers (Almushaikeh et al., 2023; Bledzki et al., 2021; Pimenta & Pinho, 2014). Montagna et al., (Stieven Montagna et al., 2022) investigated the recycling of CFRPC in various sectors and the commercial prospects for these recycled materials. They reported the potential of rCFs with different recycling techniques and the potential for processing of rCF is quite clear. In **Figure 3**, the recycling processes of CFs are broadly categorized into mechanical, chemical, and thermal methods. Most recycling pathways involve two primary steps: a fiber recovery step, which includes shredding the waste to extract fibers, and a remanufacturing step, where the recovered fibers are re-impregnated into a new composite material. Mechanical recycling employs shredding techniques to reduce the size of waste materials, facilitating their subsequent recycling. Thermal recycling utilizes heat-based processes to break down waste materials, often generating energy as a byproduct. In chemical recycling, the polymer matrix is separated from the fibers within a reactive environment, enabling the recovery of both fibers and matrix components (Butenegro et al., 2021).

Figure 3. Common carbon fiber recycling processes, including mechanical, chemical, and thermal methods.



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- **Mechanical Recycling:**

In the mechanical recycling technique, grinding and shredding processes are employed to break down and reduce the size of composite materials. Following these processes, the primary composites are reduced to sizes ranging from 10 to 50 mm. The shredded products obtained as scrap are typically mixtures containing fibers, polymers, and filler materials. Generally, products that include resin and are reduced to powder form are rich in fiber content. This technique is particularly suitable for scrap composite materials with known, relatively clean, and uncontaminated content. An environmentally favorable method, mechanical recycling does not involve substances harmful to the environment. However, the potential for reusing powder recycling products in their original thermoset compounds is relatively low. A critical aspect of this technique is ensuring that the recovered fibers retain their mechanical properties. Nevertheless, the coarse, unstable, and unstructured nature of the fiber structures recovered through mechanical recycling presents a significant limitation, reducing their reproducibility (Aldosari et al., 2024).

The earliest technology employed for recycling CFRP is mechanical recycling. In this method, CFRP products are broken down into smaller pieces through mechanical processes. Subsequently, the pitch-rich material in the scrap is isolated, while the dusty and fibrous elements are separated. One of the key advantages of this technique is that it does not generate hazardous gases. Mechanical recycling of CFRPs is characterized by low energy consumption and minimal greenhouse gas emissions, offering enhanced environmental performance compared to traditional disposal methods such as landfilling or incineration. This method contributes to waste recovery targets and supports recycling initiatives. Key factors influencing the mechanical recycling of CFRPs include environmental considerations, fiber recovery rates, markets for rCFs, and the handling of residual materials, including final storage or incineration. Despite its advantages, mechanical recycling of CFs from CFRP waste has been less explored due to challenges such as the degradation of fiber surfaces during size reduction and a consequent decrease in fiber strength. The environmental and economic feasibility of mechanical recycling has been studied by Li et al., who reported that the substitution of vCFs with rCFs significantly improves the environmental and economic performance of CFRP recycling processes (Aldosari et al., 2024; Bledzki et al., 2021; Li et al., 2016).

- **Thermal Recycling:**

In the thermal recycling technique, scrap composites are broken down, and the resin matrix is burned at high temperatures to recover CFs. This method enables the reuse of CFs as reinforcement materials. However, it is not suitable for recovering the

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resin matrix, as it evaporates during the process. The polymer matrix decomposes into low molecular weight fragments and char, which can lead to secondary products accumulating on the surface of the CFs, negatively affecting their quality. Among thermal recycling techniques, pyrolysis and fluidized bed processes are the most commonly employed. The fluidized bed process operates by balancing the downward gravitational force of the particles with the upward force generated by a high flow of gas. This facilitates the thermal decomposition of the polymer matrix, allowing the release and collection of individual CFs. The selection of an appropriate operating temperature is critical, as it must be high enough to ensure complete decomposition of the polymer while preserving the quality of the fibers. The pyrolysis process has emerged as the most frequently selected process for developing a commercial-scale operation, but supercritical fluids are receiving considerable interest from researchers. The method involves the thermal decomposition of polymers in the absence of oxygen, typically in an inert gas atmosphere, at temperatures ranging from 350 °C to 700 °C. This technique is particularly advantageous for the recovery of long and high-modulus fibers. Several factors influence the efficiency and outcomes of the pyrolysis process, including the chemical composition of the waste material, reactor type, heating rate, pressure, heating time, and operating temperature. Among these, the operating temperature has a significant impact on the mechanical, electrical, and surface properties of the recovered fibers (Abdou et al., 2021; Butenegro et al., 2021).

Excessively high temperatures during thermal recycling can lead to the deterioration of the structure of recycled products. The fluidized bed process, in particular, is capable of purifying waste materials contaminated with metals, producing rCFs in a fluffy, short-fiber form. While the fibers produced via these process exhibit good properties, they differ from vCFs in structure and application. Although the fluidized bed process is theoretically simpler than pyrolysis, it can yield potentially useful organic products from the decomposed polymer matrix. Thermal recycling processes are especially advantageous for handling contaminated scrap materials. However, they involve costly steps for converting the recovered materials into new products. The presence of varying degrees of carbon remaining in CFs creates difficulties during reuse in thermal conversion, requiring additional processing steps. In the pyrolysis process, no chemical solvents are used; instead, gases provide the required energy. The properties of rCFs obtained through pyrolysis are highly sensitive to processing parameters. Notably, rCFs produced via pyrolysis retain mechanical properties comparable to those of vCFs, with a tensile strength reduction ranging from 4% to 20%. Pyrolysis is the only thermal recycling process currently used on a commercial scale, although the resulting rCFs often require additional crushing and grinding for further application (Abdou et al., 2021; Holmes, 2018).

- **Chemical Recycling:**

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The third technique for recovering CFs is chemical recycling, commonly referred to as solvolysis. This process has been developed to efficiently process materials that are challenging to handle with mechanical recycling while maintaining high performance. Solvolysis not only recovers clean fibers and fillers but also depolymerizes the matrix into monomers or petrochemical raw materials. The solvolysis process can be classified based on the use of catalysts, pressure, temperature, and a variety of solvents. Broadly, it is categorized into high-pressure and high-temperature processes (temperature >200°C) and low-pressure and low-temperature processes (temperature <200°C). Compared to pyrolysis, solvolysis typically requires lower temperatures for polymer degradation. In this method, temperatures below 350°C and reactive media such as catalytic solutions, alcohols, or supercritical fluids are employed to recover fibers. During solvolysis, the polymeric resin is decomposed into high-value oligomers that can be reused as chemical feedstock, while CFs remain inert and are collected for further use. The polymer matrix is dissolved in a solution containing acids or bases, with the concentration of the solution optimized to enhance polymer degradation and CF recovery efficiency. Ultrasonic solvolysis at specific temperatures, combined with diluted nitric acid and hydrogen peroxide, has proven highly effective in breaking down the polymer matrix. The use of solvents such as acetone and hydrogen peroxide, dimethylformamide, or combinations of hydrogen peroxide and peracetic acid in aqueous solutions results in matrix degradation efficiencies ranging from 90% to 97%. This high efficiency enables the recovery of high-quality rCFs (Ateeq, 2023; Ma et al., 2017; Pimenta & Pinho, 2014).

The rising costs of reagents and the environmental concerns related to toxic gas emissions are significant challenges in the chemical recycling of CFs. Sun et al. reported that the tensile strength of rCFs reaches approximately 80% of that of vCFs (Sun et al., 2024). Zhao et al. proposed a chemical recycling strategy for amine-cured CFRP composites using potassium hydroxide (Zhao et al., 2017). Their study demonstrated a degradation rate of approximately 98% for CFRP composites after 90 min of treatment at 160°C, with the tensile strength of the rCFs exceeding 93% of that of vCFs. Currently, chemical and thermal recycling dominate research in the recycling of CFs. The development of chemical recycling has been motivated by the need to obtain rCFs that retain their original mechanical properties and morphology, as well as to address the high energy consumption associated with thermal recycling processes. Chemical recycling methods have consistently demonstrated superior mechanical performance for rCFs, making them a focal point in many studies. The efficiency of chemical recycling is influenced by factors such as temperature, pressure, catalysts, and solvents. In addition to solvents, water can also be used for resin degradation, making the process more environmentally friendly. Hydrolysis is a specific type of chemical recycling that employs water or alcohol as the medium for matrix degradation. This method includes the dissolution of the polymer matrix

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in CFRPs and the recovery of clean rCFs. To mitigate environmental impacts, hazardous chemicals are increasingly being replaced with less harmful alternatives such as water or alcohol, ensuring that the recycling process is both effective and sustainable (Bledzki et al., 2021; Ma et al., 2017). The environmental impact of solvolysis largely depends on the choice of solvents and the management of chemical waste. Traditional solvents, including strong acids or aggressive organic chemicals, may pose risks such as toxicity, hazardous waste generation, and high energy demands for solvent recovery and reuse. To mitigate these issues, research has explored the use of greener, bio-based, or recyclable solvents that minimize environmental harm. Additionally, closed-loop solvent recovery systems can enhance sustainability by reducing solvent consumption and preventing hazardous emissions.

Overall, while solvolysis offers a promising route for high-quality carbon fiber recovery, its widespread adoption will require improvements in solvent sustainability, process efficiency, and cost-effectiveness. Further advancements in green chemistry and waste management strategies will be critical in making solvolysis a more viable option for circular economy integration.

4. TYPES OF RECYCLED CARBON FIBER

rCFs can take various forms depending on the recycling process, with the most common forms being ground, cloth, chopped, and entangled fibers. Ground fibers are typically obtained by grinding CF waste into particles smaller than 1 mm. However, due to their small aspect ratio, ground fibers have limited utility as reinforcement material, as the load transfer from the matrix to the fiber becomes highly inefficient. The recycling process often begins with the sorting of CF waste based on fiber type, resin type, and weaving style. While this classification step can improve the quality of the recycled product, it is labor-intensive and generally undesirable for waste producers and recycling facilities. An advantage of the grinding process is that it can handle CF waste regardless of the type of fiber or resin, as the grinding mechanism is designed to reduce waste into very small, uniform pieces. Consequently, the specific characteristics of the waste material, such as fiber type or resin composition, have little influence on the outcome of the grinding process. For applications where integration of rCFs into vCF processing methods is required, it is more advantageous to cut the rCFs into controlled, specific lengths rather than grinding them indiscriminately. Controlled cutting ensures better compatibility with existing vCF processing techniques and enables broader applicability of rCFs in composite manufacturing (Gao & Xia, 2023; Pimenta & Pinho, 2014). In pyrolysis and supercritical fluid recovery processes, CFs can be recovered in woven form. One challenge in pyrolysis recovery is achieving uniform heating and resin separation

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across a large fabric area, which complicates the recovery of large woven pieces. To produce fibers broken into smaller, more controllable pieces, it is essential to select raw materials that allow for high process controllability. Ground fibers, typically resulting from mechanical recycling processes, can be utilized in short fiber molding applications such as injection molding. In conventional practices, chopped vCFs are commonly employed in processes like injection molding, sheet molding, bulk molding, compression molding, or resin transfer molding. For these applications, shredded rCFs would serve as a more sustainable alternative, as they can fulfill similar functional roles while aligning with recycling objectives and environmental sustainability goals (Ateeq, 2023; Melinda et al., 2023; Scaffaro et al., 2021).

In both fluidized bed processing and pyrolysis techniques, if the raw material fibers lose their structural integrity during recovery, the resulting fiber bundles may become entangled. This entanglement occurs when waste products are broken into smaller pieces and subjected to high-speed airflows, causing the fibers to intertwine and form tangled masses. Once fibers reach this entangled state, they become unsuitable for reuse in their original form. While it is possible to manually separate the fibers or disperse them in a water bath to restore their usability, these methods are often costly and time-consuming. In cases where CF waste is not mixed with other materials, it can be directly converted into alternative products, streamlining the recovery process and enhancing the potential for recycling (May et al., 2021; Verma et al., 2018). However, special processes are needed for the effective use of CFRP waste. These processes are explained in the previous section. Current studies address the rCF form obtained from waste fiber generated during both CF production and CFRP waste recycling in five groups (Gao & Xia, 2023):

- Finished waste CF
- Semi-finished waste CF
- Pyrolysis CF
- Chopped CFRP fiber
- Chemically rCF

5. CHALLENGES IN THE RECYCLING PROCESS OF CARBON FIBERS

To address the primary challenges in the CFs recycling process, it is crucial to establish a robust recycling network that facilitates the effective commercialization of recycled products. Several key issues must be addressed to achieve this goal, including the following (Ateeq, 2023; Borjan et al., 2021; Y. Wang et al., 2023):

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- A global strategy for rCFRP recycling should be developed. Support should be provided for the establishment of organized platforms that unite industrial suppliers, recyclers, and researchers involved in composite materials.
- Incentives for recycling should be introduced by relevant government bodies. The recycling process should be supported through privileges and incentives for institutions involved in the recycling of CFRP waste.
- As recycling institutions become commercialized, specialized legislation should be enacted to regulate their operations effectively.
- Logistic networks should be established, fostering cooperation within the supply chain. This collaboration should be conducted in a certified manner between waste suppliers and recyclers.
- A clear market definition should be established to understand the characteristics and qualities of rCFRPs. Pricing strategies should be developed to determine product processing timelines.
- LCA studies should be conducted to assess the environmental impact and performance of rCFRP products and services. Comprehensive data from the entire product life cycle should be analyzed and evaluated.

The use of various recycling techniques for obtaining rCFRP results in differences in product properties, as well as environmental and financial implications. Utilizing rCF in diverse applications requires fewer natural resources, reduced power consumption, and less labor compared to the production of vCF. The adoption of rCFRPs in different applications helps lower the emission of harmful gases, thus reducing the environmental impact compared to using vCF-reinforced CFRPs in various industries. However, the recycling process often leads to a reduction in the tensile strength and surface quality of rCF, making it more challenging to reuse with different matrices. Some of the key challenges in obtaining rCF include (Feng et al., 2023; Giorgini et al., 2020; Rademacker et al., 2018; Vieira et al., 2017):

- CFRPs consist of multiple materials, such as matrix and fiber reinforcement, which create different phases. Due to the strong interfacial bond between the fiber and matrix materials, separating the fiber during recycling is challenging. While CFs can be recovered from waste products, extracting the shredded polymer matrix remains difficult.
- Financial constraints and industrial deficiencies are significant barriers to the widespread adoption of CFRP recycling processes. These challenges need to be addressed through appropriate legislation.
- CFs can be damaged or degraded during the recycling process. The mechanical properties of products made with rCF may be lower than those made

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with vCF. Maintaining the quality of CFs throughout the recycling process is critical to support their usability in new applications.

- The resins, coatings, or other components present in CFRP composites may be difficult to separate during the recycling process, potentially affecting the overall performance of rCFs. The use of biodegradable components in composite structures could mitigate pollution and improve recycling efficiency.
- Several factors affect the recycling process, including the matrix material content, fiber composition, mixing ratios, process temperature, and waste structure. These variables complicate the ability to produce high-performance fibers. Optimizing these factors is essential to achieving good mechanical properties in rCFs.
- The disposal of hazardous chemicals used in some CF recycling processes must comply with environmental standards to prevent contamination and ensure safety.

To address these challenges, it is crucial to establish recycling procedures that enhance fiber recovery rates, improve fiber performance, and develop sustainable, cost-effective technologies for recovering CFs from CFRP composite waste. Solving the recycling issue and ensuring the broader integration of CF within the circular economy is a key component of this solution. The growing demand for CFRPs should be closely aligned with advancements in recycling processes and technological innovations. Technological progress, including digitalization and artificial intelligence, can significantly contribute to overcoming challenges. These technologies can streamline complex processes like collection, sorting, and fiber identification, which are often the most challenging aspects of CFRP recycling. By improving these areas, we can pave the way for more efficient and effective recycling systems, supporting the long-term sustainability of CFs within the circular economy (Amantayeva et al., 2022; Pimenta & Pinho, 2014). After being extracted from CFRP waste, the main problem of the industry is that rCFs obtained from recycling technologies are discontinuous, filamentous, randomly oriented and low-density. The reason for the difficulty is that continuous vCFs are cut according to the designed shape during CFRP production and broken into shorter lengths before recycling. Effective recycling techniques should be used to recover carbon fibers with minimal loss of mechanical properties and remanufacture them into high-performance engineering parts. Wei et al. (Wei et al., 2018) developed a technique that blends rCFs with nylon fibers to make composite products that increase the usability of amorphous rCF. In another study, Huan et al. (Huan et al., 2020) modified the surface of rCF with polydopamine to increase the dispersion of rCF in suspension.

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In summary, the recycling of CFRP faces three primary challenges. First, the reduction in fiber length, which is a common consequence of recycling processes, diminishes the mechanical performance of rCF compared to vCF. Second, the energy recovery in the recycling process not only fails to recover the energy originally invested in the production of the composite material but also reduces the added value associated with longer CFs. Finally, the adhesion between the new matrix and rCFs is suboptimal, which negatively impacts the properties of composites produced with rCFs. Given the significant environmental concerns at the end of life, driven by the increasing demand for CFRP and the growing volume of waste, research is being actively pursued to address these issues (Ateeq, 2023; Pimenta & Pinho, 2014).

6. CONTRIBUTION OF RECYCLING TO THE CIRCULAR ECONOMY

Carbon fiber recycling aligns closely with circular economy principles by promoting resource efficiency, waste reduction, and material reuse. In a circular economy, materials are kept in use for as long as possible, minimizing the reliance on virgin resources and reducing environmental impacts. Efficient recycling of CFRPs enables the recovery of high-value fibers, which can be reintegrated into new products, reducing the demand for energy-intensive virgin carbon fiber production. However, to fully integrate CFRP recycling into a circular economy, advancements in cost-effective and environmentally friendly recycling methods, as well as product designs that facilitate recyclability, are essential. A circular economy is a production and consumption model designed to enhance the life cycle of products. This model focuses on minimizing waste generation throughout the entire product life cycle. In contrast, the traditional linear economic model, characterized by the extraction of raw materials, consumption of products, and the creation of non-recyclable waste, contributes significantly to environmental pollution (Aldosari et al., 2024; C. H. Chen et al., 2022). This economic system, previously called waste-free production, is a manufacturing process that allows products to be remanufactured, reused and recycled after they reach their EOL stage. The circular economy is inherently tied to sustainable development. Profit-driven approaches, when unchecked, can lead to irreversible damage to the environment and human health. The benefits of the circular economy model include (Arif et al., 2022; Balaji et al., 2020; C. H. Chen et al., 2022; Naqvi et al., 2018):

- Efficient resource use and cost savings through recycling.
- Increased efficiency in materials and production by rethinking and reusing resources.

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- Development of innovative products and services driven by a circular economy perspective.
- Promotion of environmental awareness through responsible production and consumption.
- Energy savings and emission reductions achieved through the efficient use of resources.
- Protection of the natural balance by minimizing environmental impact.

appCost and benefit analysis shows that rCFs are more economical to obtain than vCFs. The economic evaluation should take into account various cost factors involved in the recycling chain, such as waste collection, storage, transportation, pretreatment, recycling, remanufacturing and labor. All of these objectives can be realized through the transition from a linear economy model to a circular economy model. The process is outlined schematically in **Figure 4**. In a broader context, the key actions required for the successful implementation of the circular economy model are outlined below (Aldosari et al., 2024; Arif et al., 2022; Naqvi et al., 2018):

- Emission reduction
- Waste management and recycling Environmentally friendly products
- Use of renewable energy
- Replacement of old products
- Innovative product design
- Adoption of transparency
- Ensuring cooperation

In the transition from the traditional linear economy to the circular economy model, which is characterized by a holistic approach, there are notable differences in the waste reuse strategies. For instance, the linear economy predominantly emphasizes downcycling, whereas the circular economy prioritizes upcycling approaches (C. H. Chen et al., 2022; George et al., 2015).

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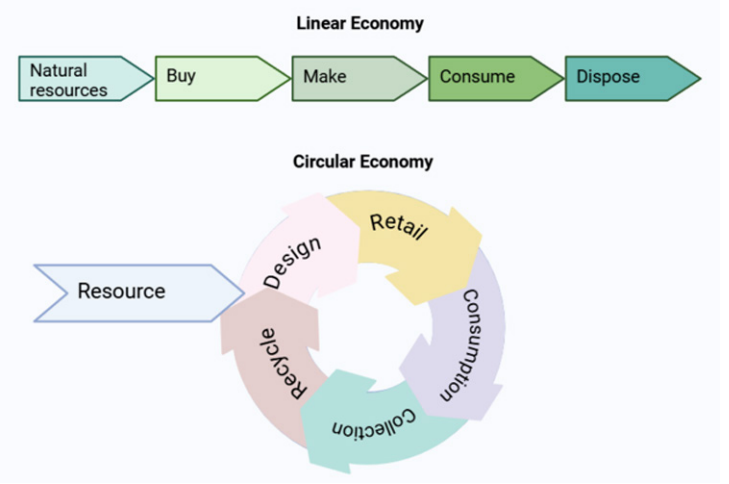
Figure 4. Transition Process to the Circular Economy Model



To achieve the goals of the circular economy, the reuse and recovery of high-performance rCFs from CFRPs are critical. For example, rCFs can be used to create thermoelectric composites without compromising the conductivity of the CFs, or high-value, high-performance rCFRP composites can be produced from recycled wind turbine blades using hot pressing technology. CFRP materials are utilized in various industries, including construction, aerospace, automotive, wind energy, and sports equipment. The growing demand for CFRPs is driven by their low density, high specific strength and stiffness, ease of integration for part consolidation, multifunctionality, and design flexibility. With new targets for reducing CO2 emissions and the need for lighter vehicle structures, global demand for composites in aerospace, construction, wind energy, and automotive industries is expected to grow at a compound annual growth rate (CAGR) of approximately 6%, with the total market value increasing from $26 billion in 2018 to $41.4 billion by 2025 (Arif et al., 2022; C. H. Chen et al., 2022). The rapid growth in the use of CFRPs across various existing and emerging industry sectors presents significant environmental challenges, especially in terms of waste. This includes residuals generated during composite manufacturing and the waste produced by end-of-life CFRP products. It is projected that global CFRP waste will increase to 20 kilotons per year by 2025. With approximately 10,000 commercial aircraft expected to reach the end of their life by 2030, there is considerable opportunity to develop economically sustainable waste management and recycling techniques for CFRPs. The production of CFs is highly energy-intensive, requiring approximately 198-595 MJ/kg, making it more energy-demanding than other synthetic fibers, such as glass fibers. Recycling spent CFs can significantly reduce their environmental impact. Research indicates that

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38.4 MJ/kg of energy is required to recycle CFRP using a chemical-based process, which is about 10-30% of the total energy needed to produce vCFs. CFRP recycling is generally determined by the properties of the polymer matrix used. Thermoset polymers, which are widely employed as matrices for structural CFRPs, account for about 80% of polymer matrix composites (PMCs). Thermoset polymers are favored in CFRPs due to their high mechanical strength, dimensional stability, durability, and resistance to chemicals and high temperatures. However, the irreversible cross-linked structure of these cured thermoset polymers complicates the recovery of fibers and the thermoset polymer itself. After the curing process, these polymers cannot be melted, remolded, or re-crosslinked into solid forms, creating challenges in recycling. Chemical degradation of these cross-linked networks under aggressive chemical or high-temperature conditions can also damage rCFs. The development of recyclable thermosets is essential, encouraging the increased use of thermoplastic matrices, which are more advantageous in terms of recyclability. As a result, industrial-scale research has shifted towards the circular economy, an industrial system aimed at reusing, remanufacturing, and recycling products at the EOL stage. When reuse or remanufacturing is not possible, closed-loop recycling systems are implemented to preserve materials. These systems are particularly effective when the physical properties of materials are conducive to easy recycling. The circular economy focuses on using renewable energy, eliminating toxic chemicals, and preventing waste by improving the design of materials, products, systems, and business models. This chapter provides a comprehensive review of CF recovery, the current state of rCF applications, and discusses the future potential of rCFs within the context of the circular economy in the recycling of CFRPs (Arif et al., 2022; Balaji et al., 2020; George et al., 2015; Naqvi et al., 2018).

To enhance the recognition of recycled materials as structural components within the circular economy, it is crucial to improve the mechanical properties of rCFs and rCFRPs. To accurately evaluate the financial and ecological impact of rCFs, it is necessary to assess the life cycle of various recycling processes. A strong correlation exists between recycling techniques and the final properties of recycled materials, which influences the position of rCFs in the circular economy. Thus, it is essential to investigate CFRP recycling processes, techniques, performance, commercialization, and market dynamics. Studies indicate that CFRP composites with a fiber volume fraction of approximately 50-70% exhibit superior mechanical properties, including impact resistance, corrosion resistance, electromagnetic shielding, and high strength. This highlights the significant demand for fast, simple, and cost-effective CF recycling methods that do not compromise performance. In recent years, it has been reported that certain recycling and remanufacturing processes have reached maturity, with commercial-scale applications now in operation, and rCFRPs demonstrating competitive structural performance. Nevertheless, while

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the CFRP recycling industry is steadily advancing, markets for recycled materials continue to face significant challenges. Despite this, the potential for incorporating rCFRPs into structural components offers promising applications, suggesting that further development of this sector could unlock valuable opportunities in the circular economy (Arif et al., 2022; Balaji et al., 2020; George et al., 2015).

The automotive and construction industries are among the largest revenue-generating sectors in the global economy. These industries are constantly evolving and entering the market with new products to stay competitive. The FOREST project, which involves Mercedes-Benz, aims to pave the way for the more widespread use of biocomposite materials in the transportation sector. By focusing on sustainable solutions, the project promotes bio-based and rCF production. As competition intensifies in the industry, manufacturers are continually seeking advanced technologies that enhance performance, cost-efficiency, and enable the increased production of innovative products. One of the most notable trends in recent years is the growing use of CF in the production of industrial components. CFRPs have gained significant attention due to their lightweight nature and superior properties compared to traditional metals. These composites offer a variety of advantages, such as improved fuel efficiency and enhanced vehicle speed, making them particularly valuable in industries like automotive manufacturing. In fact, a 10% reduction in weight in vehicles can result in fuel savings of up to 6-8%. As a result, CFRPs are commonly used in the production of high-end vehicles and racing cars, where performance and efficiency are key priorities.

On the other hand, recognizing the benefits and growing demand for CFs, automobile manufacturers have planned to replace traditional metal automotive components with CFRPs across a broad range of high-end luxury cars and trucks (Aldosari et al., 2024; George et al., 2015). Some components, such as roof and body panels, rims, sill panels, and air separators, are manufactured using CFRPs. However, the increased use of CF raises concerns regarding waste management, particularly when industrial parts reach the end of their lifespan. CFRP products typically have a negative environmental impact as they are either landfilled or incinerated after their useful life. In response, researchers and industry professionals have developed various recycling and recovery technologies to reclaim CFs and repurpose them for subsequent applications, embracing the principles of a circular economy. In addition to the benefits of efficient waste management, adopting circular economy practices in CF production and application helps integrate CFs into a closed-loop system, thereby enabling the extended use of limited resources and expensive fibers, ultimately maximizing their value over time. Generally, the circular economy is defined as 'an industrial system that is restorative or regenerative by intention and design (George et al., 2015; Naqvi et al., 2018). Some common approaches in the circular economy include prevention, repair and reuse, and recycling. Prevention focuses on

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developing products that extend their lifespan, minimizing material usage during production, and designing products for easier recycling. Repair and reuse involve the inspection, cleaning, repair, and renewal of components, as well as repurposing parts for new applications, typically of lower value than the original. Recycling and recovery refer to the process of reclaiming used materials and repurposing them for applications of similar or higher value. These approaches, when combined, enable the successful implementation of circular economy principles for any product or composite. This section specifically addresses the reuse processes within the circular economy framework, focusing on how CFs can re-enter the system at the highest possible quality.

As various industrial sectors integrate circular economy principles into their business and process models, CF waste will increasingly be viewed as a valuable resource. The previous section outlined the main drivers pushing CFs toward a circular economy. To demonstrate the potential impact of circular economy adoption in industry, a comprehensive review of the use of rCFs in the production of parts for commercial vehicles currently on the market is presented. Achieving the goals of a circular economy, the recovery of CFs becomes a critical factor. In terms of both cost and energy savings, the recovery and reuse of rCFs is essential. While the production of vCFs is highly energy-intensive, recycling CFs offers significant economic benefits, reducing energy costs by 82-98% (Arif et al., 2022; Balaji et al., 2020; George et al., 2015).

7. ENVIRONMENTAL AND SOCIAL IMPACT ANALYSIS

The motivation driven by recycling not only addresses environmental issues but also fosters the creation of a promising market. CFRP recycling has emerged as a promising sector focused on converting waste products into high-value materials. This approach revitalizes the economy, boosts employment, and reduces the production costs of CFRP through long-term savings. According to recent data, the market for rCFs and CFRPs is expected to reach $31.5 billion by 2025, with a CAGR of 12.4% (Ciacci et al., 2022). The increasing use of CFRPs has sparked both environmental and economic awareness, emphasizing the need for sustainability and recycling of CF-based waste. CFRPs are widely used across many modern industries due to their outstanding properties, but the difficulty in processing these materials and their limited service life generates significant amounts of CF waste. As a result, there will be growing concerns about environmental pollution and resource wastage due to high waste generation in the coming years. Therefore, efficient recycling and the sustainability of reuse processes are critical issues that must be addressed. The FOREST Project, which aims to provide new and innovative sustainable green

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composites, 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 (May et al., 2021; Meng et al., 2020; Pakdel et al., 2021; Vo Dong et al., 2018; B. Wang et al., 2019).

Petrakli, et al. (Petrakli et al., 2020) reported a fairly comprehensive analysis of the environmental impacts of different EOL routes for CFRP: (i) recycling via pyrolysis, (ii) incineration with energy recovery, and (iii) disposal in landfill. Recycling should consider reuse possibilities. Incineration with energy recovery also has a lower environmental impact than landfill disposal. The exceptional lightness of CFRPs significantly enhances resource efficiency and reduces emissions during their use. As the effects of climate change become more evident, the recycling of CF-based products is growing increasingly vital for sustainability and minimizing the carbon footprint. The resource efficiency of products is influenced not only by their performance during use but also by their management at the end of their life cycle. These processes are crucial for effectively managing waste streams. However, CFRPs inherently pose challenges in meeting many of the design guidelines required for recycling-friendly products, as they involve complex recycling processes. Due to their rapidly increasing use across various industries, economical and environmentally friendly recycling methods for CFRPs are becoming more essential. It is particularly important to consider the costs associated with both the production and end-of-life stages when developing these solutions (George et al., 2015; Li et al., 2016; Pimenta & Pinho, 2011).

A comprehensive overview of the state-of-the-art in CFRP recycling operations is provided, focusing on recycling and remanufacturing processes, commercialization challenges, and potential markets for recycled materials. Each recycling process offers distinct advantages and drawbacks. Optimizing these processes, where e competition turns into complementarity, will help achieve products with high mechanical properties. Although remanufacturing CFRPs presents challenges, mainly due to the irregular shape of rCFs, the mechanical performance of some recycled CFRPs can surpass that of traditional structural materials. LCA studies suggest that such applications can offer significant environmental benefits. It is evident that rCFRPs can be used in various structural areas within advanced industries, as well as in non-safety-critical structural applications (Bledzki et al., 2021; Meng et al., 2020). Economic indicators and market dynamics suggest that the growth of composite materials will accelerate significantly, with CFs becoming the dominant material in the reinforcement segment and polyester resin leading in the resin segment. However, challenges arise during the processing and recycling of CF-reinforced materials, such as CFRP and glass fiber-reinforced composite (GFRC). These challenges include global issues such as environmental constraints, government regulations, produc-

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tion costs, resource management, and processing methods aligned with economic opportunities. It is crucial to recognize that converting this composite waste into a valuable resource is essential for ensuring the continuous use of materials within the circular economy. To achieve this, a technological readiness level and a robust waste management system should be established, based on a comprehensive review of recycling strategies (Bledzki et al., 2021; La Rosa et al., 2016; Meng et al., 2020; Pimenta & Pinho, 2011; B. Wang et al., 2019).

8. CONCLUSIONS AND FUTURE PROSPECTS

Recycling and reusing rCFs is an emerging field that is expected to play a crucial role in the future sustainable development of CFs. This section provides an overview of the current status of CFRP waste management and presents a systematic review of recycling technologies from both environmental and circular economy perspectives. Various recycling technologies (including mechanical, chemical, and thermal methods) are discussed, along with the factors influencing these processes and their effects on the properties of rCFs. Optimization strategies for recycling are essential to make the processes feasible and sustainable. Academic and industrial researchers are actively working to enhance the performance of rCFs, with a focus on improving the mechanical properties of remanufactured CFRP products. However, their EOL disposal remains problematic, as thermoset-based CFRPs cannot be easily remelted or reshaped, necessitating alternative recycling methods. The primary challenges include the degradation of fiber properties during processing, the high energy consumption of recycling techniques, and the economic viability of recovered fibers compared to vCF.

Current recycling technologies include pyrolysis, solvolysis, and mechanical grinding. Pyrolysis, which involves the thermal decomposition of the polymer matrix at high temperatures, effectively separates carbon fibers but may lead to reduced mechanical performance due to fiber oxidation. Solvolysis, which employs chemical solvents to break down the matrix, enables higher-quality fiber recovery but is often associated with high costs and environmental concerns. Mechanical grinding, while cost-effective, results in shorter fiber lengths, limiting their application in high-performance composites. These limitations highlight the need for more efficient and sustainable recycling strategies.

To address these challenges, research efforts should focus on developing low-energy, environmentally friendly recycling processes that preserve the mechanical integrity of reclaimed carbon fibers. Advancements in low-temperature solvolysis, the use of bio-based solvents, and surface treatment techniques to restore fiber properties could enhance the viability of recycled carbon fibers. The use of environmentally

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friendly products instead of hazardous chemicals is currently being investigated. By selecting the appropriate recycling method and matrix, rCFRPs can be employed in numerous industrial applications. Production processes that are compatible with rCFRPs include injection molding, prepreg lamination, compression molding, additive manufacturing, and resin transfer molding (RTM). Given that reusing rCFs offers significant advantages in terms of cost and energy consumption compared to virgin CFs, it plays a crucial role in the circular economy approach (Meng et al., 2020; Oliveux et al., 2015).

The trend towards developing and applying complex materials with functional properties presents new challenges for the circular economy. The increasing use of CFs in CFRPs and the growing waste problem have made recycling a necessity. While high-performance recycling remains challenging, the idea of recycling and reusing these materials offers numerous benefits. The value of recycled fibers is largely determined by their quality and size. Although the conditions for accepting recycled fibers for reuse are often less stringent, various possibilities for their reuse have been explored. Some of these opportunities have already been industrialized, allowing CF structures to be incorporated into the circular economy. However, there remains a pressing need to develop new technologies that enable more cycles of use for high-tech products such as CFs. Current technological capabilities often require that most of these products be discarded after only a few recycling cycles. The recycling of CFs is critical for the sustainable use of lightweight composite materials, particularly in industries such as construction, transportation, energy, and sports equipment. This issue requires long-term efforts and will be further advanced through international projects, R&D studies by recycling companies, and academic research. The FOREST project, aimed at developing new multifunctional biocomposites as competitive alternatives to traditional composites, represents one of the initiatives that will significantly contribute to the advancement of biobased and recycled CF composites. The FOREST project will emphasize sustainability in the circular economy by analyzing effective recycling methods applied to biocomposite components containing more than 50% sustainable materials. The success of such projects will play a crucial role in determining the future of CF structures in the circular economy. Additionally, designing CFRC components with EOL recyclability in mind, such as through the use of reversible polymer matrices or hybrid material systems, would facilitate a more circular economy in the composites industry.The following key points should guide future research (P. Y. Chen et al., 2023; Oliveux et al., 2015; Zhang et al., 2023):

- Landfilling or incineration of wastes from composite products containing CF should be avoided.

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- New technologies should be developed to improve the product quality of rCFs, and their economic applicability should be thoroughly evaluated.
- A detailed investigation of the fiber properties used in CFRP wastes is necessary to accurately assess the suitability, cost, and environmental impact of rCFs.
- The potential for reuse should be explored to develop new, high-value applications for rCFs.

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