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The 3R (Recycling, Recovery, and Reuse) of Fiber Reinforced Thermoset Composite: Paving the Way for a Circular Economy

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Abstract

The rising popularity of fiber-reinforced polymer (FRP) composites in aerospace, automotive, and energy industries leads to waste management difficulties. This review critically considers 3R (recycling, recovery, reuse) options for thermoset-based FRP composites, contrasting traditional (landfilling, incineration) and developing (solvolysis, microwave-assisted recycling, catalytic) approaches. As the thermal recycling method leads to industrial recycling, it has a detrimental effect on the fibers' characteristics and demands high energy input. Advanced solvolysis techniques, such as Fenton-based degradation, enable effective resin decomposition under mild conditions while retaining approximately 90% of the fiber strength. This review article emphasizes the practical applications of recycled carbon fibers (rCFs) in the automotive sector and the aerospace industries, highlighting their economic as well as environmental benefits. Lifecycle assessments show that solvolysis is the most sustainable option, reducing greenhouse gas emissions by ~30-50% compared to landfilling. The challenges of scalability, cost, and policy alignment are highlighted, along with future possibilities in hybrid recycling and advanced applications. This study proposes an outline for conveying FRP waste to a circular economy while balancing technical feasibility and industrial sustainability.

Keywords: Circular economy, Carbon fiber recycling, Catalytic solvolysis, Epoxy vitrimers, Biological degradation

1. Introduction

In the modern era, the need for lightweight materials with higher strength properties has garnered significant attention across a wide range of industrial sectors, including defence, automotive, and aerospace.[1-3] Composite materials have contributed to the improvement of human civilization,

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from primitive mud-and-wood huts to the current emergence of advanced structures. **Figure 1a** depicts the gradual development of composite materials and their utilisation in various sectors, including infrastructure, transportation, and communication, from 3400 B.C. to the present. In this context, fiber-reinforced polymer (FRP) composites have been widely adopted as an alternative to metal-matrix composites. This is because metal-embedded composite materials have higher density and are more susceptible to corrosion, which restricts their broader applications compared to epoxy-based FRP composites.[4,5] Advanced composites are manufactured using a wide range of reinforcing fibers, such as synthetic (carbon fiber (CF), basalt fiber (BF), aramid fiber, and Kevlar fiber) and natural fibers (including hemp, jute, flax, and sisal fibers). However, due to growing environmental concerns, the researchers have increasingly focused on developing composites reinforced with natural fibers. Among the various natural fibers, flax and hemp fibers provided satisfactory mechanical characteristics at a cheaper cost. However, natural fibers cannot meet the desired goals for advanced composite applications due to their hydrophilic nature, poor compatibility with the polymer matrix, and flammability.[6-8] Among the various fibers, CF was utilized widely due to its exceptional thermal and mechanical stability compared to the other fibers. CF reinforced polymer (CFRP) composites are commonly utilized in aerospace, automotive, defense, and heavy-duty applications due to their excellent mechanical strength, stiffness, lightweight properties, and environmental resistance.[7] Therefore, the development of CFRP-based composites or materials is gaining more attention in academia and industry to develop advanced technology for defence, aerospace, and automotive applications. The global market size of using CF in the composite is projected to be worth around USD 39.39 billion by 2034 from USD 21.95 billion in 2024 at a CAGR of 6.02% from 2025 to 2034, as shown in **Figure 1b**.[9] The rising CF production capacity boosts the expansion of the CFRP composite market. Although FRP possesses

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excellent properties and is gaining more attention worldwide, it faces issues regarding the recycling and reuse of used fiber. The present global need for CF is predicted to be ~115 kilotons per year as of 2023, and projected to increase to 280 kilotons per year by 2030.[10] Thermoset polymers are predominantly employed in FRP composites for high-load bearing applications. However, the recycling of fiber from thermoset composites is challenging due to the higher cross-linking density of the thermoset-based polymer composite. The approximate value of CF waste was ~50,000 tons to 62,000 tons per year and is expected to increase significantly in the upcoming year, reaching 100,000 tons per year after 2029, as shown in **Figure 1c**.[11] These wastes were mostly coming from industrial waste and end-of-life (EoL) waste from the aviation and wind sectors.

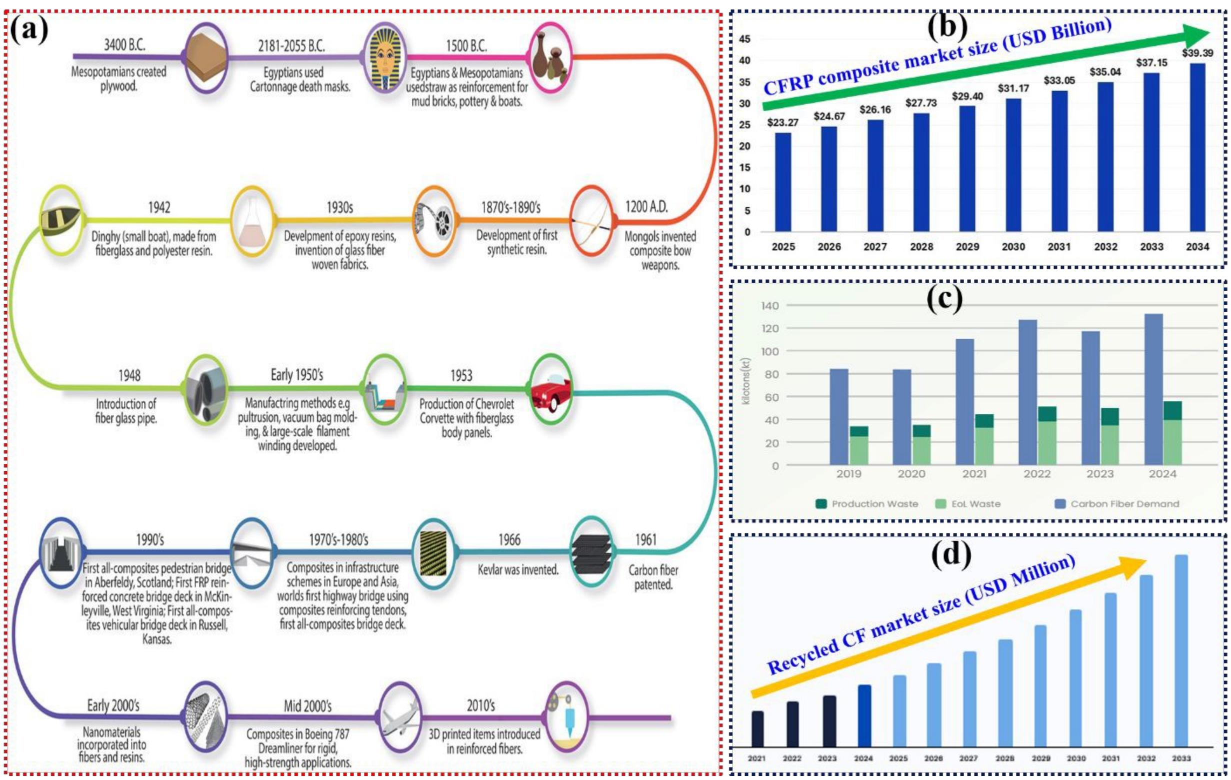

Figure 1 (a) Chronological development of composites manufacturing for several industries. Reproduced with permission from **Ref. [24]**. (b) global market size for CFRP composites from

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Ref. [9]. (c) CF demand and estimated waste (2019-2024) from **Ref. [11]**, and (d) global market size of recycled CF from **Ref. [13]**.

In the absence of recycling initiatives, the aviation industry is projected to produce approximately 500,000 tonnes of CFRP waste by 2050.[12] This waste has severe detrimental effects on the overall environment and human health due to the accumulation of non-biodegradable waste in landfills. To tackle this challenge, researchers are attempting to recycle the fiber from the composite for further use as fillers or as a reinforcing agent in composite preparation. The market size of rCF was ~ USD 234.43 million in 2024. It is estimated to surge from USD 264.79 million in 2025 to USD 701.43 million in 2033, with a CAGR of 12.95% over the forecast time frame (2025-2033) (**Figure 1d**). rCF provides an economical alternative to traditional materials, such as metals and virgin carbon fibre.[13] rCF composites are rapidly being utilized in various industries, including automotive, aerospace, wind energy, and sports equipment, to reduce weight, enhance fuel efficiency, and improve energy efficiency.

To date, published review articles have focused on the different types of reinforcing fibers (natural and synthetic), as well as their thermal and mechanical properties in detail, along with a few applications and conventional recycling procedures.[14-19] Previous reviews focused on the recycling of CF from thermoplastic materials, but an in-depth review on the recycling of thermoset-based composites remained unexplored.[20-23] Therefore, this review provides an in-depth study of the 3R (Recycling, Recovery, and Reuse) strategies for FPR composites, including the latest advancements with sustainable economic ideas. Initially, the challenges associated with recycling CF from FRP composites are discussed, along with possible paths to overcome these obstacles. Then, various emerging methods (e.g., Fenton-based catalytic reaction, microwave-assisted treatment) were correlated with conventional methods to recover the fibers from the composite

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specimens. This review also discusses the next-generation advanced applications in thermal management, the aviation sector, energy storage, and conversion, supported by real-world industry sectors. The review also comprehensively discusses the technological, economic, and social perspectives on lifestyle, addressing gaps in current reported works by analyzing cost-benefit trade-offs for sustainable composite waste management. By reviewing the latest research (2020-2025) and summarizing some key points regarding the recycling of FRP composites, challenges, and our insights to overcome the obstacles, and sets a direction for future research in the composite field. It is presumed that this article serves as a crucial reference for advancing the recycling of CFRP towards a circular economy. Additionally, this review also presents a unique "3R-to-commercialization" framework that systematically links material performance metrics with industrial scalability factors. A comprehensive multi-criteria assessment matrix is proposed, enabling a clear comparison of technology readiness level (TRL), energy consumption, and cost analysis, thereby addressing a significant gap in current research. The studies establish hybrid processing pathways to developing technically feasible and economically viable circular ecosystems for advanced composite materials.

2. Challenges in Recycling Thermoset Composites

A polymer composite consists of two phases: one continuous and the other discontinuous. Generally, the continuous phase is the polymer matrix, and the discontinuous phase is the fiber used as reinforcement. Polymers assist the fibres while also transferring load to them.[25] Generally, thermosetting polymers used to fabricate FRP composites are epoxy resins, polyesters, vinyl esters, cyanate esters, and phenolic resins, etc.[24] Several reviews have already discussed the fundamental structure and properties of various thermoset polymer matrices in detail.[23-27] Therefore, this section

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only focuses on the key challenges observed during the recycling of fibers from thermoset composites.

Why Recycle Fibre-Reinforced Polymers? Research on the recycling of thermosets has gained attention in recent years due to the utilization of lightweight materials with superior strength in a wide range of applications and the limitations of landfills. Despite ecological advantages, the significant cost of pure fibre production emphasises the importance of recycling fibres from thermoset polymer composites.[28,29] Recycling of costly fiber is more important than the polymer matrix. The matrix is much cheaper compared to the fibers. According to the report, the energy consumption for producing virgin CF is 183-286 MJ kg^{-1}, which is 14 times higher than that for steel production.[30,31] CF manufacturing consumes 100 to 900 MJ kg^{-1} and emits 24 kg CO_2 eq. kg^{-1} of fibres generated, which is considerably more than steel (20-30 MJ kg^{-1} and 1.7-2.1 kg CO_2 eq kg^{-1}) and glass fibre production (45 MJ kg^{-1} and 2.0-3.0 kg CO_2 eq. kg^{-1}).[32] Therefore, the recycling of CF from the FRP composite waste is very crucial, and the utilization of recycled fiber is more useful for the global economy and environmental health. Annually, thousands of tonnes of thermoset composites are generated worldwide, as shown in **Figure 1b**.GF and CF are effective reinforcement materials for many applications, although they become alarming to the ecology after EoL.[29] Toyota manufactured the hatch door frame using Mitsubishi Rayon's sheet moulding material, and BMW Group used rCF to strengthen the C-pillar with sheet moulding compound.[33-35] In March 2025, Syensqo and Vartega groups announced the development and promotion of the use of rCF from industrial waste in high-performance applications, especially in the automotive industry. Additionally, in December 2023, Toray Industry successfully fabricated and developed Boeing 787 components by using the rCF.[36]

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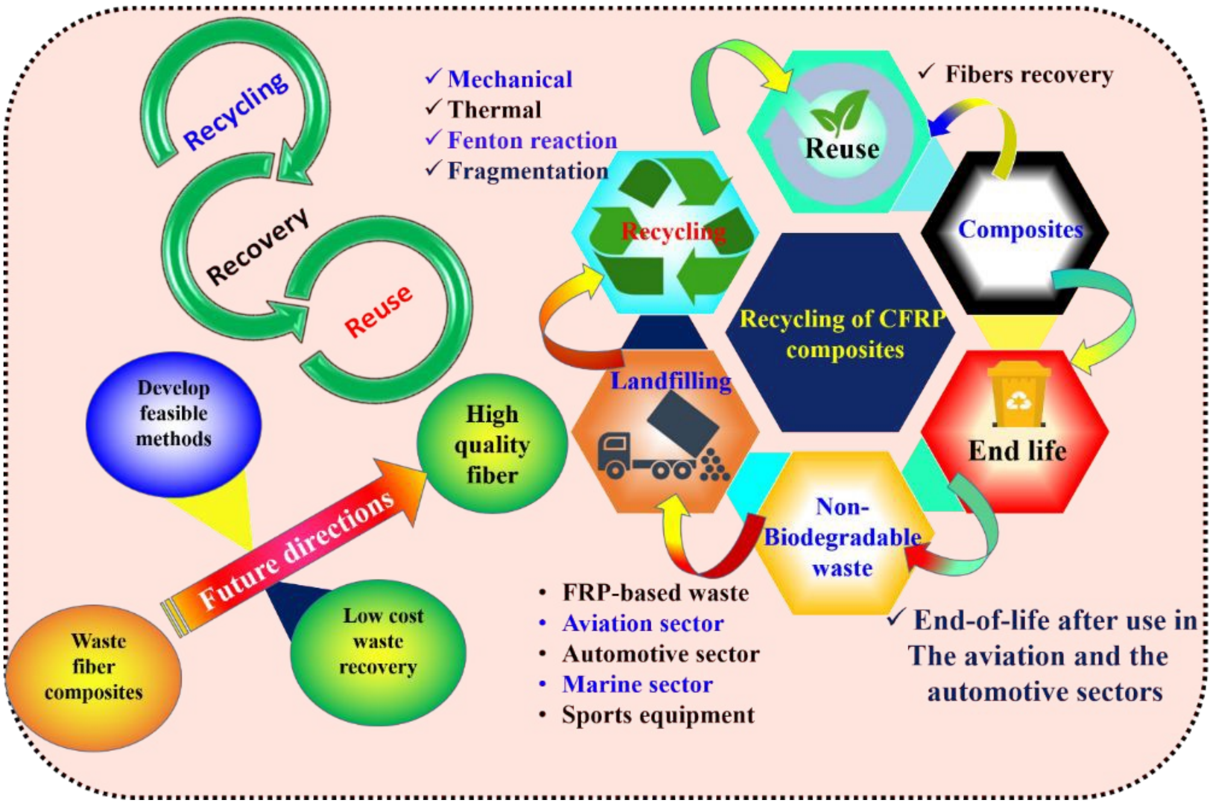

Figure 2 Schematic representation of the Recycling of high-performance fibers from the FRP composite specimens.

The increasing demand for EVs and environmentally friendly transportation solutions has heightened the need for weight reduction, thereby increasing the vehicle's mileage, which benefits both the economy and the ecological system. The rCF's resilient strength-to-weight ratio and endurance render it a great choice in achieving rigorous safety requirements while minimizing the overall vehicle mass. The aerospace industry's commitment to producing lightweight components is exemplified by Airbus' ambitious target to recycle ~95% of its CFRP waste.[37] However, rCF from the FRP composites is not an easy task. The most commonly used matrix in composite fabrication is thermoset resins. After the addition of the curing agent, it forms a highly cross-linked structure upon curing. This rigid and stiff structure makes it extremely difficult to recover the fibers. Nowadays, researchers are attempting to recycle fibers from waste composites, but they are

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facing significant challenges. Firstly, the composite material comprises fibers and a polymer matrix, which has distinct chemical and physical properties, making separation challenging.[33] Secondly, obtaining high-performance fiber without compromising the mechanical properties is a challenging task. Third, reshaping and remoulding are almost impossible after the curing of the thermoset polymer matrix.[38] During the most efficient recycling process, solvolysis, it produces chemical wastes such as bases, acids, harmful gases, and solid wastes.[29,39] Therefore, it is highly essential to develop a feasible strategy that enables the recycling of high-performance fiber through a suitable pathway for an economical and sustainable society.

3. Approaches to Recyclable Thermoset Composites

In this section, the conventional and advanced recycling of fiber from thermoset composites is discussed in detail. A detailed discussion of the pros and cons of the approaches is also presented, summarized in **Table 1**. This section covers the latest breakthroughs in recycling, including traditional and innovative technologies. After the EoL of the composites, questions arise in the mind: *What to do with the waste composites*? *Can it be recycled*? What are the feasible routes for recycling *the fiber for reuse?* There are various conventional and advanced strategies for recycling, recovering, and reusing fibers.

3.1. Conventional methods

The solutions for EoL composite waste: Landfill, Incineration, or Recycling? The recycling of thermoset composites is a challenging task, as discussed earlier. Disposing of the rCF is the alternate way if it is not recycled properly. There are two main conventional methods for disposing of waste: landfilling and Incineration. Landfilling is the cheapest and easiest method to dispose of the CFRP waste composites. However, the European Union's (EU) Waste Management Directive

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ranks landfilling as the least preferred waste management alternative, despite its cost-effectiveness.[40] CFRP solid wastes continue to be a critical threat to the ecology. As of 2025, it is estimated that 20,000-30,000 metric tons of waste will be generated annually worldwide due to the inadequate availability of recycling facilities.[41] The EU landfill directive and UK landfill fee attempt to prevent landfill utilization while encouraging sustainable disposal methods.[42] In this regard, the EU waste management directive has increased the transport and gate fees, including late fees for the disposal of EoL composite waste. Consequently, the cost associated with landfilling such waste has significantly risen. This highlights the necessity for innovative disposal techniques for FRP composite waste and will encourage the recycling of FRP composites. [43,44] Another conventional disposal method, incineration, is a waste treatment procedure by which the waste is combusted at high temperatures. After combustion at high temperature, various types of hazardous gases are emitted, and a minimal amount of degraded fibers is recovered from the process.[23,40,45] The recycled fibers may not be suitable for high-quality composites, as elevated temperatures can negatively impact their overall performance. Meanwhile, incineration turned half of the waste into ash, which then had to be landfilled. Therefore, this method has a detrimental effect on the environment as well as on the overall properties of the rCF.[46,47] This approach may be regarded as a final recourse when landfilling is not a viable option. However, this method has the advantage of recovering energy used in cement kilns.[48] Landfilling and incineration are not the ultimate solution to recycling the CFRP waste. Therefore, the necessity for innovative techniques (such as catalyst-assisted solvolysis, microwave-assisted pyrolysis, etc.) for FRP composite waste will encourage the recycling of FRP composites. Several reviews on the recycling of fiber from the waste FRP composite via thermal treatment have been reported.[19,51,23,52] These reviews discussed the thermal treatment process in detail and conducted a literature survey. Therefore, the

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current discussion does not review the fundamentals of thermal treatment procedures. Instead, we focus on concisely presenting their notable advantages and the primary challenges faced during recycling.

In thermal treatment, the FRP wastes are treated at ~350-450 °C to decompose the polymeric matrix.[49,50] Therefore, the recovery step for the waste composites was carried out above 800 °C. Generally, thermal treatment techniques are various types, i.e., aerobic (combustion), anaerobic (pyrolysis), fluidized bed process (FBP), and microwave-assisted thermal treatment (**Figure 3a-d**).[68] During the combustion process, i.e., presence of oxygen, the waste can be transformed into considerable heat and gases (volatile organic compounds, CO_2, CO, water vapour, etc.), which are released from the combustion of the polymer matrix in the presence of oxygen and rCF. The overall properties of rCF were degraded due to oxidation of the fibers. Therefore, the combustion method is not an efficient route for recycling high-performance fibers.[53,54,57] The advantages and disadvantages of the various recycling methods are summarized in **Table 1**. The pyrolysis method converts the thermoset composites into useful fuels, chemicals, and fibers. The pyrolysis was conducted under an inert atmosphere at a temperature range of 450-800 °C to recycle the fibers. It can be utilized in a wide range of applications, including biofuel and chemical production. The pyrolysis process is a facile approach to handling and recycling the fibers. The rCF has the retention of thermal and mechanical properties of ~85-90%. But there are some challenges in recovering the high performance of pristine fiber. During pyrolysis, there is a chance of deposition of carbon on the fiber surface.[53-57] Kim and co-workers are trying to optimize the temperature conditions to recover high-quality fiber. They analyzed the thermal decomposition of CFRP composites, exhibiting two-stage degradation where aliphatic chains broke down at ~350 ^{0}C, followed by aromatic network disruption at > 400 ^{0}C. This work quantified that pyrolysis under

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an N_2 atmosphere at 500 °C with a slow heating rate of 5 °C min^{-1} resulted in near-complete resin removal (~99 wt.%) while retaining approximately 92% of the original CF properties. On the contrary, faster heating rates in an air atmosphere lead to significant fiber oxidation and a reduction in strength of up to ~35%, providing critical data for optimizing thermal recycling to balance efficiency with fiber quality.[56] In another study, *Matsuda et al.* introduced an energy-efficient hybrid method that combines thermal decompositions with electrical (Joule) heating to recycle CFRP composites. This method utilizes CF itself as internal heating elements to rapidly decompose the polymer matrix, resulting in reduced energy consumption compared to conventional pyrolysis. This strategy is primarily effective for prepreg waste, enabling the recovery of high-quality fibers with minimal degradation of their properties.[58] The carbon residue on the surface of fibers must be removed via combustion in the presence of oxygen, which compromises the overall efficiency of rCFs, limiting the utilization of the pyrolysis method for recycling processes.[59] The microwave-assisted pyrolysis method has the potential to recycle and recover fibers from thermoset composite waste. Before the microwave-assisted thermal recycling process, the composite specimens are chopped, and the crushed material is put in the microwave reactor at 300-600 °C under an inert atmosphere to avoid oxidation. The obtained fibers were post-treated to remove the residual char on the rCFs and to reuse the VOCs as fuel or chemical feedstocks. The main advantages of this method are that it requires less energy compared to the pyrolysis method.[42] The microwave-assisted pyrolysis method was more environmentally friendly and cost-effective compared to other pyrolysis methods. This method releases 544 tons of CO_2 eq., while conventional pyrolysis emits 744 tons of CO_2 eq. It required low costs of EUR 5.60/kg, compared to EUR 12.00 kg^{-1} for the conventional pyrolysis method.[60-62] However, scaling up the approach to an industrial scale has not yet been demonstrated. Fluidized bed pyrolysis (FBP) of

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composites has undergone significant progress since the initial attempts at the University of Nottingham in the early 1990s, and it is now successfully functional at a small-scale stage for treating fibre-reinforced thermoset polymers.[63]

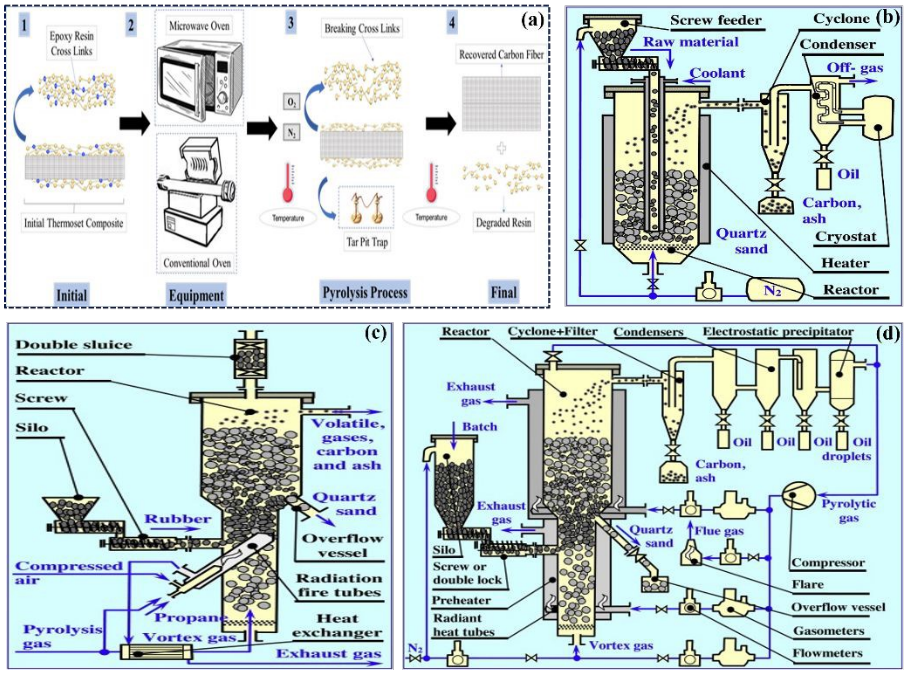

Figure 3 (a) Pyrolysis system: (1) CF/epoxy resin laminates. (2) microwave or conventional oven. (3) breaking epoxy resin cross-links. (4) rCF. Reproduced with permission from **Ref. [68]**. (b) laboratory fluidised bed reactor for polymer pyrolysis Reproduced with permission from **[73]**, (c) Fluidised bed pyrolysis reactor **[65]**, and (d) FBP plant. Reproduced with permission from **Ref. [66]**.

Utilizing this technique, both the fiber and filler can be recovered from the FRP composite waste. This method proceeds through disintegrating shredded composite components in a silica bed and fluidizing them at 450-500 °C temperature under an oxygen atmosphere, as shown in **Figure 3b-d**.[65,66,69,73] The organic resin undergoes degradation, allowing the filler particles and fibers to be extracted as needed. Reported works on recycling of fibers by using the FBP method, the tensile

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strength of recycled fibers was ~75% of the virgin fibers.[64-66] Fibers with a length of 5-10 mm can be extracted using fluidized bed pyrolysis, which is further defined by a low energy consumption as compared to the manufacturing of virgin fibers.[67] However, fiber recovery from thermoset composite waste remained constrained, as the process yielded only short-length fibers, limiting their suitability for diverse structural applications. Therefore, the development of cost-effective and more sustainable procedures for recycling and recovering high-performance fibers from thermoset composite waste is crucial.

3.2. Mechanical recycling

Mechanical recycling involves reusing EoL waste FRP as filler or reinforcement in new composites following size reduction and powder generation.

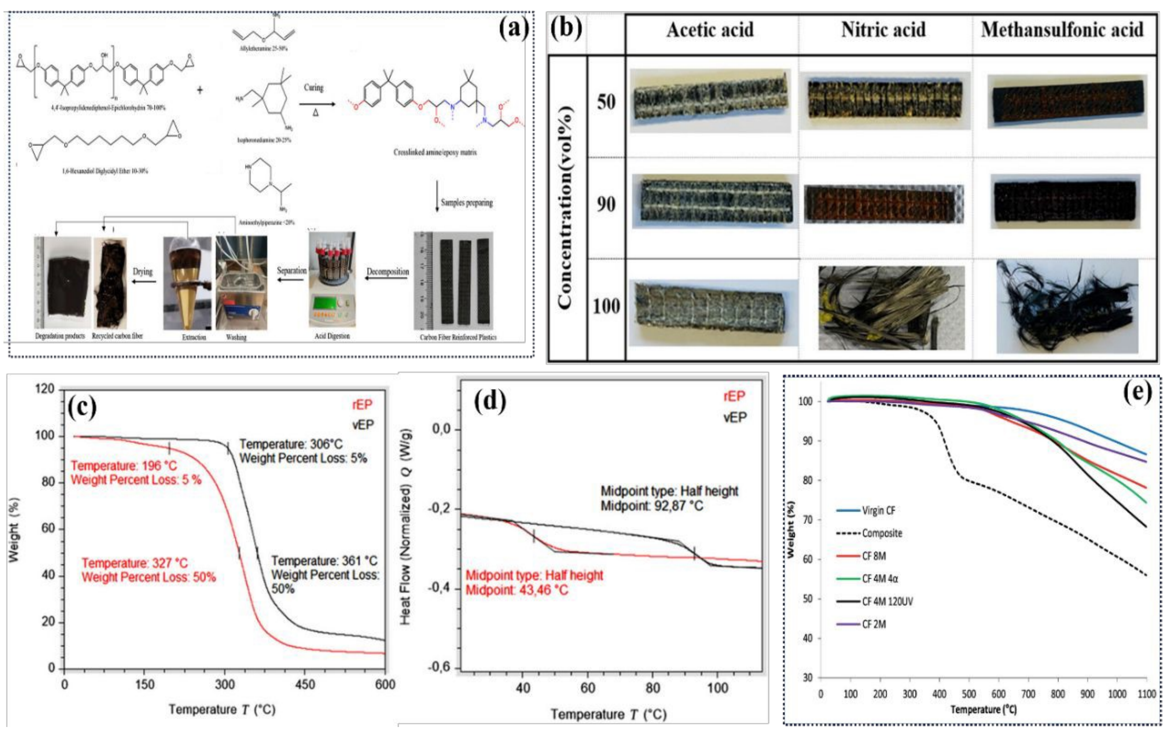

Figure 4 (a) schematic illustration of the recycling method, (b) acid-treated rCFs samples at different acidic concentrations, (c) TGA, and (d) DSC analysis of rEP and vEP. Reproduced with

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permission from **Ref. [100]**. (e) TGA analysis of the recovered CFs. Reproduced with permission from **Ref. [101]**.

In this process, FRP wastes are crushed, followed by grinding, milling, and sieving to obtain the final recycled products, which are mixtures of ground powder and fiber.[70] This method is more cost-effective and sustainable than the thermal recycling procedures.[71] There are several reports on the recycling of fibers from the FRP waste and their reuse in various applications.[72-74] Although the mechanical recycling process is cost-effective and has a less impact on the environment, its utilization is limited due to several reasons. First, the dust or short recycled fibers or fillers can only be used in downgraded applications. The recycled fibers from mechanical processing have a chance of residual polymer matrix on the fibers, which will degrade the mechanical properties of recycled fibers compared to the pristine fibers.[75] Another limitation is filler loading- using ground fiber in epoxy composites. Exceeding 10 wt.% reduced the mechanical properties due to agglomeration.[76,77] This recycling method is only useful for a large amount of EoL FRP composite waste to recover short fibers. However, only minimal amounts of filler obtained from the FRP waste can be used in composite fabrication due to agglomeration issues, making it insufficient to meet all the requirements for recycling high-performance fibers. Therefore, the development of novel strategies to recycle high-performance fibers was needed.

3.3. Advanced Physical Recycling (High-Voltage Fragmentation)

This review discussed the recent progress in composite recycling strategies, including the conventional and advanced methods. Although mechanical recycling is a well-established process, its inefficacy in fiber recovery hinders its broader utilization. Advanced techniques, including pyrolysis and solvolysis, provide higher recovery purity but suffers from low production yield and high cost. Emerging methods, such as high-voltage fragmentation (HVF) and solvent-based

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chemical recycling, show promising results for long-term, cost-effective fiber recovery.[78] Advancing further traditional approaches, innovative physical technologies such as HVF provide an important paradigm shift by precisely decomposing composites through their intrinsic material interfaces. HVF is a process that employs rapid, high-voltage electrical discharges, usually in a liquid medium such as water, to break down composite materials to recover high-quality fibers for reuse. [79, 80] HVF was initially employed in rock mining in the 1960s to break down rocks and minerals.[81] The latest research has shown that pulsed high-voltage discharges in a water-filled chamber cause plasma-induced shockwaves predominantly spread via the fiber-matrix interface owing to differences in their dielectric characteristics. [82] This method provides a sustainable and precise degradation than the mechanical recycling process, successfully retaining fiber length while minimizing damage to the fiber surfaces. Though this method exhibits promise, the industrial adoption of HVF faces significant challenges. A key disadvantage is its high utilization of energy sometimes hundreds of kJ kg^{-1}), which remained a vital economic and ecological obstacle as opposed to the other conventional recycling methods.[79] Current research focuses on optimizing pulse energy and repetition rate for specific FRP composites to recover long, high-quality fibers suitable for reuse in secondary structural components, thereby enhancing the value of recycled materials.

3.4. Design for recycling via covalent adaptable networks

A significant solution to the recycling dilemma is to build the polymer matrix itself molecularly via the invention of vitrimers- a class of polymers with dynamic covalent adaptive networks (CANs). In contrast to traditional thermosets with irreversible cross-links, vitrimers have dynamic covalent bonds that undergo thermally stimulated exchange mechanisms. This distinctive chemistry allows the polymer chain to reconfigure its structure without altering its cross-linking

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density, resulting in thermoset-like properties at operating temperatures, as well as thermoplastic-like reprocessability and recyclability when heated. [83] Although comprehensive studies have been previously discussed on the fundamental chemistry of CANs elaborately, including transesterification, Diels-Alder/retro-DA chemistry, imine bonds, and disulfide metathesis. [84-91] However, this section will concisely highlight their utilization in the recycling of the thermoset composites. The discussion of the "best" CAN chemistry is application-dependent, as it involves a difficult trade-off between quality and endurance, as well as recycling potential.

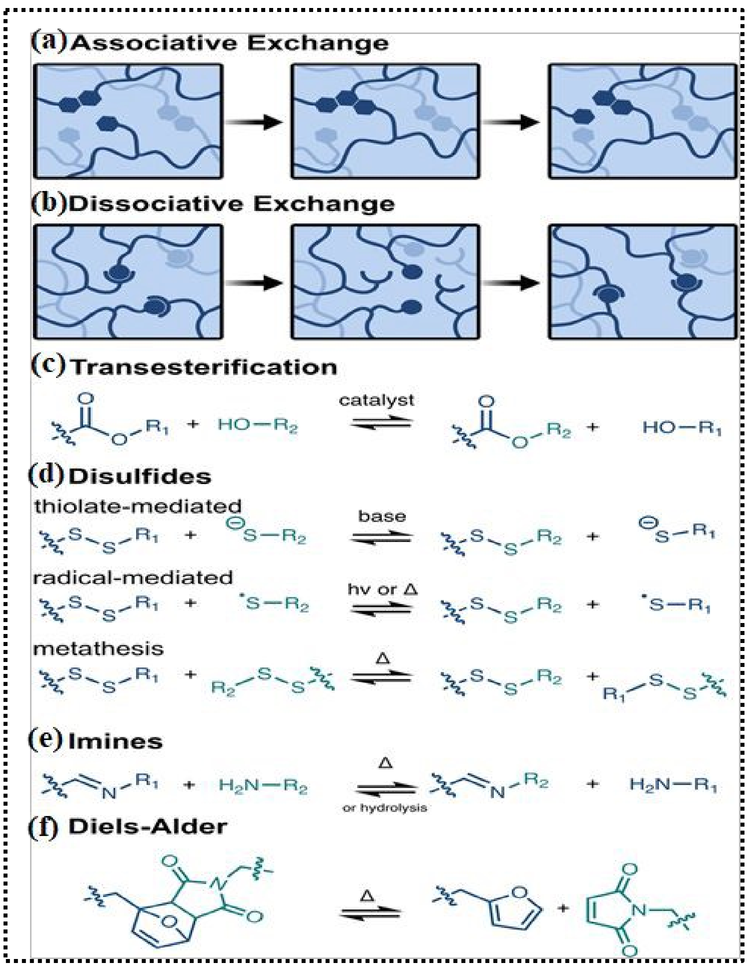

Figure 5 CAN based mechanism included (a) associative mechanism (vitrimers) or (b) dissociative mechanism. Examples of dynamic covalent chemistries (c) transesterification, (d)

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disulfides exchange, (e) imine exchange, and (f) Diels–Alder chemistry. Reproduced with permission from **Ref. [84]**.

To develop high-performance composites with high thermal and mechanical stability, *catalyzed transesterification-based* vitrimers, typically catalyzed by Lewis acids like Zn (II) acetates, where ester bonds exchange with the adjacent hydroxyl groups, are often the leading material (**Figure 5c**). The material undergoes thermally activated bond exchange without dissociative degradation, maintaining the same structural integrity and overall thermal-mechanical properties as conventional epoxies up to their topology freezing transition temperature (T_v).[85-87] In contrast, dissociative systems, such as Diels-Alder or acteal linkages, can exhibit a reduction in modulus as the cross-links are broken, thereby reducing the overall structural integrity of the polymer. While *disulfide exchange and imine chemistry* offer excellent features, including catalyst-free exchange or stimuli responsiveness, they follow an associative exchange mechanism.[88] In this mechanism, broken bonds are exchanged simultaneously with newly formed bonds and maintain the cross-link as well as the overall structural integrity. However, compared to transesterification, the thermal and mechanical properties of the recycled composites were lower. Therefore, transesterification vitrimers have become the most durable and commercially viable approach for developing recyclable structural composites that must resist harsh operating conditions. This intrinsic reconfigurability enables the full depolymerization of FRP composites in a closed-loop process, allowing for the recovery of both the remoldable matrix and reinforcing fibers with minimal degradation. Although obstacles remain in achieving aerospace grade epoxy quality and scaling up. However, vitrimers composites offer a clear path to a sustainable economy for high-performance materials through molecular innovation.

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4. Advanced Chemical recycling processes

Instead of thermal and mechanical recycling, the chemical recycling procedure has the efficiency to recycle high-performance fibers with low energy consumption. This section provides a brief overview of conventional methods and then offers a detailed review of advanced chemical recycling methods. Additionally, the most sustainable and efficient recycling procedures will be discussed elaborately.

4.1. Solvolysis

Chemical recycling, also known as solvolysis, is a process in which the resin (i.e., polymer matrix) is decomposed or dissolved into different monomers, oligomers, or other forms in the presence of various solvents.[77,78] This method has garnered significant attention among the research community due to its sustainability and the retention of ~95% of the thermal and mechanical properties of recycled fibers compared to virgin fibers.[92] The most common chemical recycling procedure is the oxidation method by using various oxidants such as nitric acid, hydrogen peroxide (H_2O_2), peracetic acid, etc. The rCF obtained from this recycling procedure retains its maximum physical and chemical properties. However, the limitation arises from environmental issues related to the preparation of hazardous chemicals during the chemical recycling process. Generally, solvolysis is operated under higher (≥ 200 °C) or lower (≤ 200 °C) temperatures.[93] Water and co-solvents such as alcohol, phenol, and amine have been utilized effectively in the solvolysis process .[94] Acidic or basic catalysts are used to promote the reaction, and it is essential when the epoxy is highly stable towards degradation.[29,95] Solvent-based methods, including subcritical and supercritical fluids, are considered effective methods for recycling fibers from FRP composite waste.[96] However, the energy consumption by this recycling requires a higher amount of energy compared to the other methods.[97] Another limitation of this method was controlling the reaction

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conditions, i.e., maintaining the required high pressure and temperature of the overall setup, which proved to be challenging. Under high-temperature solvolysis, the FRP wastes are cut into small pieces and poured into a round-bottom flask containing strong acid (generally nitric acid) under heating (above 90 °C) and stirring overnight. During vigorous stirring, a brown fume evolved due to the emission of hazardous nitrogen dioxide (NO_2) or nitrous oxide (N_2O) gas. Zhang et al. recovered CFs from the CFRP composites via the acid digestion method, as shown in **Figure 4a**.[98] In this method, the fabricated composites with dimensions of $50 \times 10 \times 2$ mm³ were dipped in 25 mL glass tubes with mild and strong acids (such as nitric acid, methanesulfonic acid, and weak acetic acid) to investigate the recyclability and the quality of the rCFs (**Figure 4b**). The images demonstrated that concentrated nitric acid (100%) and methanesulfonic acid effectively recycle the fibers while maintaining high performance. Additionally, the thermal properties of the virgin EP and rEP were investigated by TGA and DSC analysis, as shown in **Figures 4c** and **4d**. The thermal properties of EP were affected under vigorous conditions. Therefore, the solvolysis in the presence of strong acids has a negative impact on both the environment and the overall properties of the fibers (**Figure 4e**).[99] Additionally, the reaction at high temperature generates enormous heat as the reaction is exothermic, which poses a risk of safety issues. Therefore, the recycling should be carried out under mild conditions to retain the maximum properties of the fibers and avoid environmental/safety concerns. To overcome these issues, researchers are utilizing mild reaction conditions at a lower temperature during the recycling steps. The recycling steps include two steps: firstly, the CFRP was pre-treated with citric acid at ~120 °C for 6 h, followed by washing and drying. The obtained composite was poured into mCPBA and DCM solutions in a 250 mL flask at 40 °C for 6 h, as shown in **Figure 6a**. [102] After completion of the reaction, the fibers were separated out and can be used for further utilization in the preparation of composites. The

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depolarization mechanism of mCPBA with EP was illustrated in **Figure 6b**. Mechanical properties of single rCF and vCF were investigated. The tensile strength of v-CF was ~4.70 GPa, while r-CF was 4.40 GPa (**Figure 6c**). The Young's modulus was ~228 GPa for v-CF and 214 GPa for r-CF, as shown in **Figure 6d**.

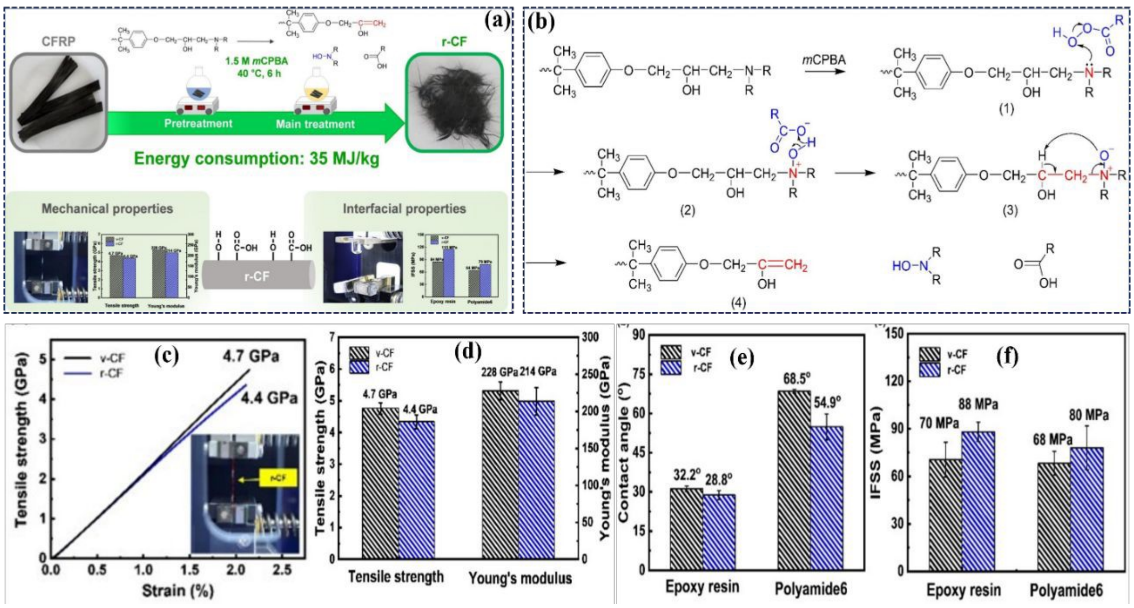

Figure 6 (a) chemical recycling of CFRP and analysis of the interfacial shear strength on rCF, (b) depolarization mechanism of EP using mCPBA, (c-f) the mechanical properties of vCF and rCF. Reproduced with permission from **Ref. [102]**.

r-CF exhibited minimal degradation of ~93.6% in comparison to v-CF, and maintained mechanical qualities at a similar or higher level than reported in earlier research, even after the recycling procedure. To investigate the interfacial bonding between the epoxy matrix, a rCF/EP composite was prepared, and contact angle and interfacial shear strength (IFSS) measurements were made. The outcomes of contact angle and IFSS, as depicted in **Figure 6e, f**, suggest that rCF enhances the interfacial bonding between the fiber and matrix.[100] Other works emphasize the recovery of fibers from FRP composite waste using mild chemicals, such as acetic acid, tartaric acid (TA), and

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alcohol. Additionally, a few researchers tried to recycle fibers by using an alcohol/water mixture.[101-105] Recycled CF reinforced composite retained ~90% of the tensile strength and ~82% of the tensile modulus compared to a virgin CF reinforced composite.[105] Mild solvolysis is a promising recycling method for sustainable chemistry, but it faces challenges in speed, completeness, solvent management, and scalability.[106] Another limitation was the recovery of the matrix, which was dissolved in the solvent used. Under mild conditions, undissolved matrix may be present on the fiber surface, which requires advanced catalyzed-based sustainable strategies and methods to recycle high-performance fibers in a short time. Therefore, it is very crucial to upcycle all waste components, including the matrix, into a new high-value product for economic sustainability. Rather than disposing of the damaged polymer matrix as a low-value waste, innovative recycling techniques are being developed to transform it into a high-value product. Solvolysis produces re-polymerizable oligomers for new resins, pyrolysis oils are used as chemical feedstocks, and solid char is modified into conductive fillers or reinforcement additives. This multi-stage valorization converts recycling from a waste management cost into a sustainable resource recovery activity, dramatically altering the economic equation and ecological impact of the CFRP lifecycle.[87-91] A part of these solvolysis processes, plasma-assisted solvolysis has emerged as a promising hybrid technique due to undergoing fast reaction under mild conditions. It utilizes non-thermal plasma (e.g., nitrogen plasma) to generate a flux of reactive species, such as radicals, ions, and excited molecules, directly within the reaction medium. [107,108] When combined with a solvent such as nitric acid, this plasma generates a highly aggressive but regulated environment that breaks down the polymer network.

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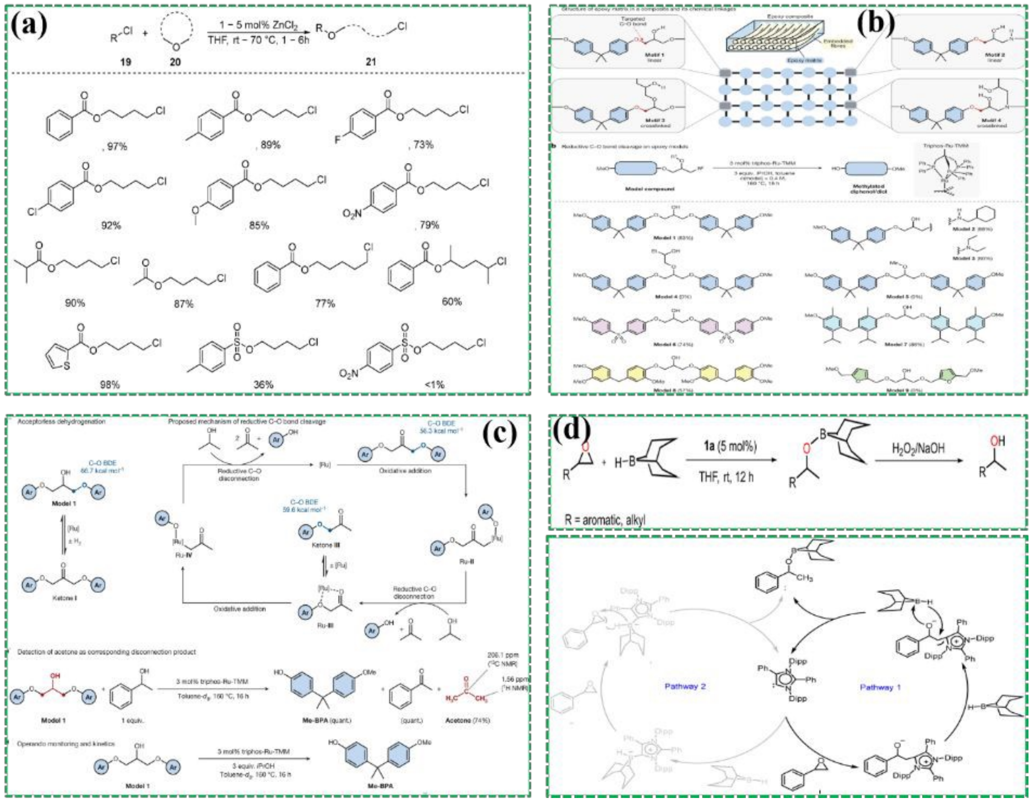

Figure 7 (a) $ZnCl_2$-catalyzed ring opening of cyclic ethers. Reproduced with permission from **Ref. [115]**. (b,c) Mechanism of Ru-catalysed C–O bond disconnection. Reproduced with permission from **Ref. [116]**. (d) plausible ring opening of the epoxy ring. Reproduced with permission from **Ref. [117]**.

The plasma-solvent synergy greatly enhances epoxy matrix degradation, enabling faster reactions under milder chemical conditions and lower temperatures than conventional solvolysis. This approach represents a significant step towards making chemical recycling more efficient and less energy-intensive.

4.2. Recycling using an advanced catalyst

Various solvolysis methods were investigated to depolymerize the polymer matrix of FRP composites as discussed above. Polymer matrices undergo decomposition under elevated

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temperature and pressure, resulting in the separation of carbon fibers. To tackle this challenge, the solvolysis method was investigated under mild conditions (>100 °C) as discussed above. However, FRP could not be completely depleted due to plenty of persistent carbon-carbon bonds in the viscous decomposed product.[109] Therefore, to facilitate the reaction rate under mild conditions, the utilization of various catalysts (such as metal-based catalysts, ionic liquids, bio-catalysis, redox catalysis, etc.) has gained significant attention among the research community.[110-113] Among these methods, metal-based catalytic solvolysis and catalytic oxidation process (mainly Fenton's reaction) are efficient vis-à-vis the bio/ionic liquids-catalysis method. Although these methods are more sustainable and operate at temperatures below 100 °C, their application remains limited due to slow reaction kinetics and high costs, restricting their use to a narrow range of epoxy resins.[114] Metal catalysis can boost the reaction kinetics and break down the epoxy matrix very easily under mild conditions. The cleavage of the epoxy moiety proceeds via different mechanisms, including Lewis acid-base reaction, redox reaction, and hydrogenation mechanism, as depicted in **Figure 7a-d**.[115-117] The most commonly used metal-based catalysts are $ZnCl_2$, Ru-based catalyst, and the Fe-based catalyst, which is also known as the Fenton reaction. *Liu et al.* have developed a unique recycling approach, using a mixture of deep eutectic solvents (DESs) and metal salt catalysts (e.g., $ZnCl_2$, $FeCl_2$, and $FeCl_3$) has resulted in the successful recovery of both valuable long CFs and epoxy resin from CFRP. The reaction was completed in the presence of mild conditions. The decomposition of highly cross-linked epoxy moieties was facilitated via diffusion of Zn^{2+} in the polymer matrix to break the C-N and C-O-C bonds. The rCFs retained ~94.5% of the original properties.[118] Fenton reaction was carried out to recycle the fibers from the composites. *Wang et al.* have developed a novel method to recycle CF from UPR composites without compromising the thermal and mechanical properties.[119] The mild nano-Fe^0 in situ formation technique

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significantly increased the degrading performance. During the recycling process, H_2O_2 was added to accelerate the reaction rate to decompose the thermoset polymer to recover the fibers. The C=O in hydrolysed resin was rapidly weakened by radicals than the aromatic ring owing to its adverse electrical potential. More than 90 wt.% of thermosetting UPR was degraded at ~80 °C. This method could be appealing for recycling CF from composites without affecting the fibers' properties.[119] Fenton reaction proceeds through radical formation as – ($Fe^{2+} + H_2O_2 = Fe^{3+} + 2{\cdot}OH$) to decompose the CFRP composite.[119] However, it has several disadvantages during the recycling process. Although the Fenton reaction is a low-temperature sustainable method compared to pyrolysis, fiber deterioration, chemical costs, and waste products concerns have limited the widespread application in industry. During the reaction, the possibility of metal contamination on the fibers may require additional purification steps. Lab-scale preparation is usual, rendering large-scale recycling issues. This method generates acidic, iron-based materials with residual toxic organic solvents or compounds, requiring significant rehabilitation before waste disposal. Recently, a ruthenium (Ru) catalysed method was used to tackle these issues. The authors reported a transition-metal-catalysed technique for recovering bisphenol-A and high-performance fibers from the epoxy composites. They illustrate the use of this technique on crucial virgin amine-cured epoxy resins alongside conventional composites, including the shell of a wind turbine blade (**Figure 8a, b**). The obtained results suggest that chemical recycling using a catalyst can be successfully carried out under mild conditions (temperature less than 100 °C).

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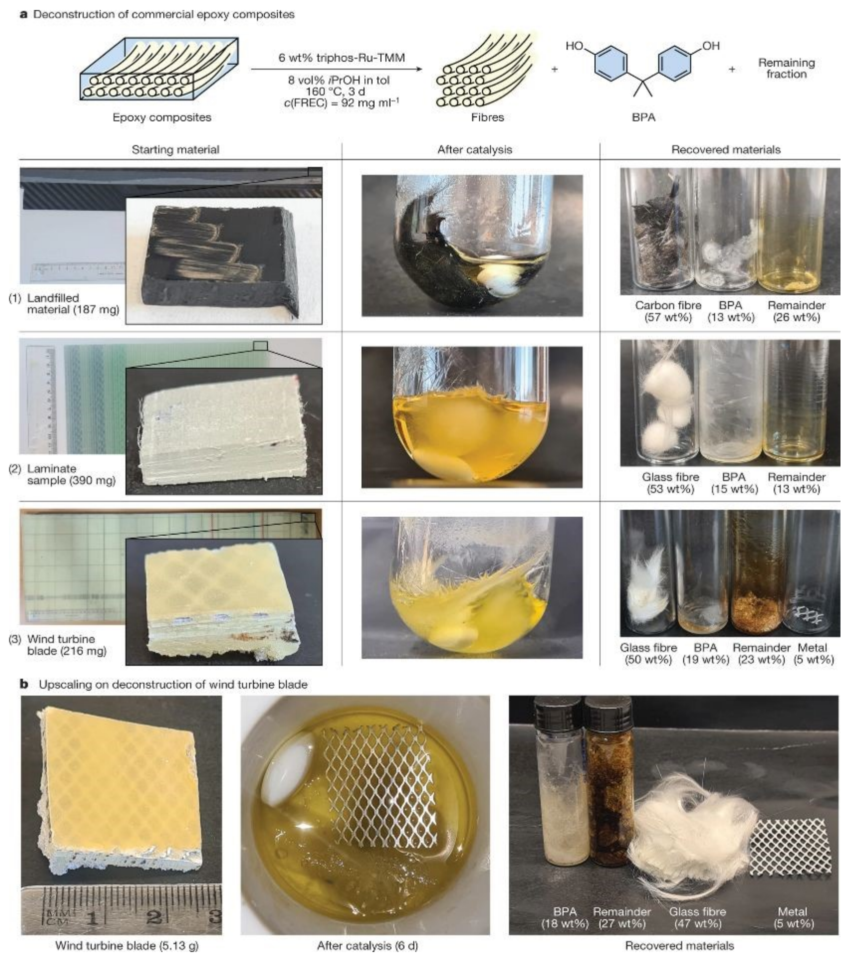

Figure 8 (a) The scope of the catalyzed composite samples. Composite pieces 1, 2, and 3 measured 1.0-1.5 cm in length and width. (b) Increased deconstruction circumstances on wind turbine blades. Reproduced with permission from the **Ref. [116]**.

However, the novel strategy cannot be implemented on an industrial scale due to different factors, such as the fact that Ru is an expensive metal, leading to high-cost recycling and the formation of toxic by-products. As a result, the next steps for industrializing this technology include enhancing the effectiveness of the catalytic system and designing cost-effective catalysts. Additionally, the development of waste treatment management is also a task to be explored in the future to develop sustainable and cost-effective methods. A major aspect of the industrial practicality of catalytic solvolysis is the recovery and reuse of the catalyst, which directly impacts process cost and

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ecological sustainability. Since homogeneous catalysts are highly active, separating them from the post-reaction solution can be challenging and expensive. A recent study addressed this obstacle by designing smart catalytic systems that promote facile separation. A prominent example is the use of potassium phosphate (K_3PO_4), potassium carbonate (K_2CO_3) in ethanol-based solvolysis.[120] These catalysts are highly soluble at elevated reaction conditions, resulting in high catalytic efficiency; however, they separate out of the solution when cooled to room temperature, allowing for straightforward filtering and reuse in the next cycle. Developing self-separating, supported, and recyclable catalysts is crucial to bridging the gap between lab-scale advances and economically viable large-scale catalytic recycling.

4.3. Microwave-assisted recycling

Microwave-assisted recycling method is gaining attention among researchers as an alternative pathway of thermal treatment/pyrolysis at high temperature to recover high-performance fiber. Microwaves are a type of electromagnetic radiation characterized by frequencies ranging from 300 MHz to 300 GHz. The microwave furnace consists of three main components (such as source, transmission lines, and applicator). Microwaves are generated by the source, sent to the applicator via transmission lines, and then transferred to the material that is being heated.[120] The microwave will heat the dielectric materials such as epoxy matrix via the following mechanism steps, including - the electromagnetic field interacts with the material and transmits energy with different polarization modes such as dipole polarization and interfacial polarization (Maxwell-Wagner). The dipole polarization involved the molecules changing their positions to match the electromagnetic fields. During the reorientations of the molecules, generating friction in turn, the molecule becomes heated, and decomposition occurs.[121] *Shu et al.* recovered CFs via a molten salt pyrolysis-oxidation recycling method.[122]

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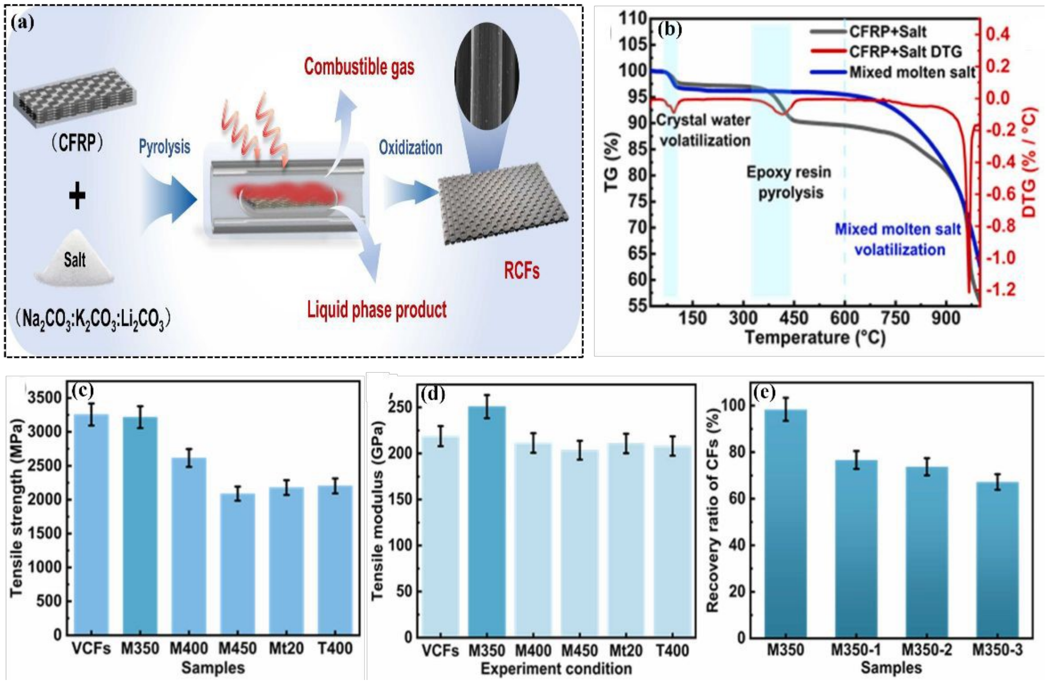

Figure 9 (a) Recovery of CFs by microwave-molten salt pyrolysis and oxidation, (b) TG-DTG of CFRP/Salt and mixed molten salt, (c, d) tensile strength and modulus of rCFs, (e) recovery ratio of CFs of composite molten salt reuse. Reproduced with permission from **Ref. [122]**.

The molten salt consisting of Na_2CO_3, K_2CO_3, and Li_2CO_3 in a mass ratio of 6:3:1, respectively, was mixed thoroughly. Subsequently, the CFRP composite was coated with a salt mixture in a 1:3 ratio and positioned within a crucible, as illustrated in **Figure 9a**. The reaction was performed under microwave radiation at a frequency of 2450 MHz and at various temperatures (300, 350, 400, and 450 °C). Epoxy resins are dielectric materials that absorb microwave energy, resulting in localized heating and bond cleavage. The thermal and mechanical properties of rCFs under different temperatures were investigated and illustrated in **Figure 9b-d**. The composite molten salt utilized in the microwave molten salt pyrolysis investigation was recycled, and the recovery ratio of CFs for each period was obtained, as shown in **Figure 9e**. The mechanical properties of the rCFs gradually decreased with the increase in pyrolysis temperature. This investigation revealed

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that the microwave-molten salt pyrolysis-oxidation approach could recover CFs to their desirable mechanical qualities. The different types of recycling methods, along with their advantages and disadvantages, are summarized in **Table 1**. The microwave-assisted recycling method is an efficient strategy owing to its energy efficiency, short time, and high-performance fiber recovery. However, challenges, including non-uniform heating and scalability, must be addressed to utilize it for industrial applications. Future research should focus on hybrid methods of microwave-assisted recycling, followed by chemical methods and the design of large-scale reactors for industrial applications.

Table 1: Summarization of advantages and disadvantages of various recycling methods

Recycling Methods	Advantages	Disadvantages	Pristine CF (GPa)	rCF(GPa)	Points of attention	Ref.
Thermal recycling	High-performance fiber recovery	High energy consumption, risk of fiber damage	σ=3, E=210	σ=2.89,E=225.5	Fiber quality, safety concerns	**[135]**
Thermal recycling	Energy Savings, Performance Retention	Aggressive thermal degradation	σ=3-5, E=210-250	σ=2.8-4.2, E=180-240	Post-recycling treatments	**[136]**
Chemical recycling	Retain stiffness (85-95%), low energy consumption	rCF loses 10–30% strength	σ=4.7, E=228	σ=4.4, E=214	Solvent selection, fiber quality control	**[100]**
Chemical recycling	Reducing environmental impact	Limited industrial scalability, residue contamination	σ=4.8, E=241	σ=4.31, E=221	Scalability and practical implementation	**[99]**
Chemical recycling	Used biodegradable solvents	Incomplete resin removal	σ=4.48, E=200.56	σ=4.07, E=190.52	Lifecycle analysis, fiber quality control	**[137]**
Chemical recycling	Mild conditions and energy savings	Recovery cost	σ=3.49	σ=3.34	Environmental and safety risks	**[138]**
Catalyst-assisted solvolysis	Selective cleavage in epoxy bonds	Catalyst cost and slow reaction kinetics	-	-	Environmental and economic balance, surface integrity	**[116]**
Catalyst-assisted solvolysis	Mild solvolysis	Limited to a specific epoxy resin	-	-	Replace with a cheaper functional catalyst, monomer purification	**[139]**
Microwave-assisted pyrolysis	Selective heating and high-purity recovery	Incomplete polymer removal	E=71.12	E=66.53	Handling molten salts	**[122]**
Microwave-assisted pyrolysis	Efficient polymer removal, fast reaction rate	Fiber properties degradation	-	-	Byproduct management, reusability in composites	**[140]**

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4.4. Enzymatic and Microbial Degradation

Biological recycling represents an evolutionary shift towards low-energy, highly specific, and environmentally benign alternative to the harsh thermal and chemical methods of polymer matrix using biocatalysts (such as esterases, lipases, cutinases, and microorganisms). The biocatalysts promote the hydrolytic cleavage of specific covalent bonds within the thermoset network. [123,124] The mechanism involves the enzyme's active site preferentially binding to the polymer chain, allowing for the attack on the carbonyl carbon of an ester bond, which results in the breakage into smaller, soluble oligomers and monomers. [125] Using electrospinning/electrospraying, researchers are developing nano-fibrous biodegradable membranes using esterase and cellulase enzymes for a wide range of applications, including oil removal, water treatment, etc. [126-130] Microbial degradation provides an alternate route in which microorganisms release a set of extracellular enzymes that depolymerize the matrix as a metabolic substrate. The main advantages of this pathway are its exceptional selectivity under very mild conditions (<60 ^{0}C). As a result, the mechanical and surface properties of the rCFs are preserved, mitigating oxidative and thermal damage. Regarding the bio-degradation of epoxy resin-based FRP composites, multiple approaches have been employed. [114] *Min et al.* developed a green chemical recycling approach for anhydride-cured epoxy-based CFRPs using a β-phenylethanol/TBD catalytic system. The process achieved over 99% resin degradation within 2 h at mild conditions, with rCF retaining 93.2% of their original tensile strength. XPS and XRD analyses confirmed retention of surface chemistry and graphitic structure, suggesting efficient closed-loop recyclability. [131] *Deng et al.* studied the biodegradation of epoxy resin varnish coating in seawater influenced by *Bacillus flexus*. Electrochemical and spectroscopic analysis revealed significant loss of corrosion resistance and structural integrity due to microbial activity. [132] Another bacterium, *Pseudomonas aeruginosa,*

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induced microbiological deterioration of epoxy-coated carbon steel by promoting biofilm formation and corrosion, highlighting the need for antimicrobial measures to improve coating durability in marine environments. [133] *Mikel Dolz et al.* used fungal *peroxygenases* to investigate the capability of degrading the epoxy resins. This approach offers a biotechnological route for recycling and upcycling of epoxy-based FRP composite. [134] However, challenges remain due to slow reaction kinetics, enzyme instability, and the poor degradability of dense aromatic epoxy networks typical of aerospace composites. Current ongoing research is focused on the evolution of enzymes and metabolic engineering of microbes, aiming to enhance the catalytic activity and position this recycling method as a promising and sustainable.

5. Emerging Applications

The thermoset resin industry is substantially more diversified than the thermoplastics industry. The increased utilization of thermosetting materials leads to more waste and a larger demand for recycling pathways. The existing waste management procedures are energy-intensive and lack the aspect of recycling the polymer matrix. [27] Each technology has specific benefits and shortcomings, making it difficult to find a universal solution. The main focus of recycling is to recover and reuse expensive fibers; hence, most innovations focus on structural composites. After recycling and recovery of the fibers from the CFRP waste, reusability is also crucial to developing composites. The practical application of rCFs in composite materials is still in its early stages. However, rCF reinforced composites are increasingly utilized in wide sectors, including automotive, aerospace, thermal management, and energy applications as shown in **Figure 10**. In this section, the review discusses the utilization of rCF in various fillers as reinforcing agents as well as fillers to develop advanced composites.

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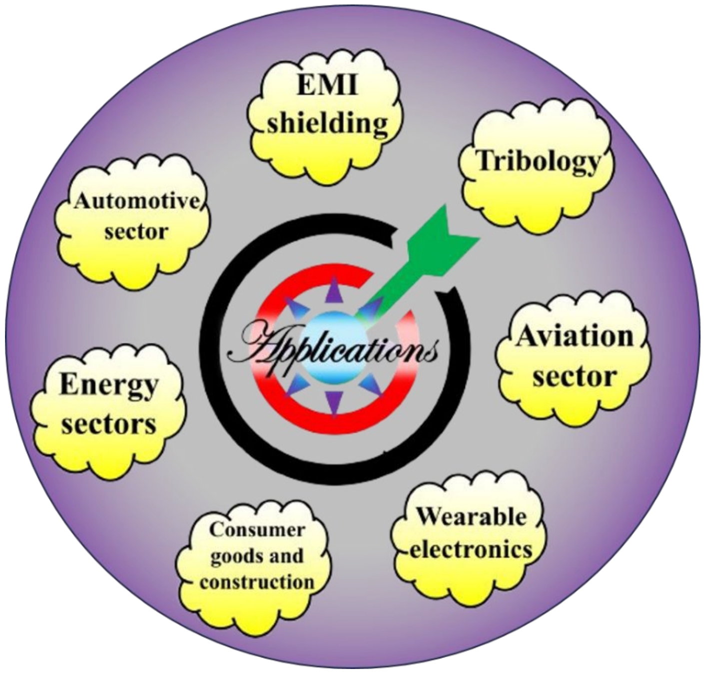

Figure 10: Potential application domains of recycled carbon fibers and recovered matrix by-products across industrial sectors

5.1. Automotive and aviation sector

rCFs recovered from CFRP waste have emerged as an appealing alternative to pristine CFs, particularly in the automotive and aviation sectors, where lightweight and environmental considerations drive the development of these materials.[35,67] By 2024, global CFRP waste generation reached approximately 62,000 tons, with nearly 30% originating from European markets. Currently, only 15% of the composite wastes are recycled, with the majority being landfilled and incinerated. However, the application of rCF is limited due to the deteriorated mechanical properties after recycling compared to the pristine CFs. The primary goals of the automotive and aviation sectors are to minimize total weight and reduce environmental pollution. Reducing overall weight leads to lower fuel consumption, benefiting both economic efficiency and environmental sustainability. The utilization of rCFs was widely used in the automotive sector.

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Primarily, BMW and Airbus groups agreed to consider the reutilization of rCFs, and BMW started series production of i3 and i8 models in 2013.[141] BMW utilized rCFs in seat frames and C-pillar for the i-series EV, reducing the weight by ~30% compared to aluminium. The Toyota group is also actively involved in using rCFs in automotive applications to reduce the overall weight and enhance sustainability.[35] Additionally, Tesla is exploring the rCFs in the battery enclosure to improve the energy density and reduce weight.[142] Therefore, the utilization of rCF as an alternative to pristine CFs opens up new opportunities for the automotive sector. In the aviation sector, rCF is widely used to reuse the waste of costly CFRP composites. Airbus, with its participation in the Clean Sky Program, is working on rCF reinforced panels for A320 airplane cabins, with an ambition of 50% recycled materials by 2030.[143] Recently, the utilization of rCF in military drones has gained more attention due to a reduction in processing cost by ~40%.[144] Additionally, the recycled fibers are utilized for secondary aircraft structures, aligning with the circular economic goals.

5.2. Consumer goods and construction

rCF is gaining popularity in consumer products and construction due to its lightweight, strong, and economical benefits. It is impregnated in consumer items such as sports equipment (bike frames, bicycles, tennis rackets), and electronic devices like laptops and smartphones, providing an excellent strength-to-weight ratio and superior aesthetics. The wide utilization of rCF in different fields is summarized in **Table 2**. Additionally, the overall price of the instruments was also reduced after the utilization of rCF instead of costly pristine CF.[145-147] In constructions, it can enhance the crack resistance, durability of the concrete, and also be used for restoring aged structures with fibre covering.[148,149] Furthermore, rCF is commonly used in architectural renovation, especially to improve the aging bridges, columns, and beams. Beyond its load-bearing

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applications, rCF is currently being considered in 3D printed designs as a reinforcing filler in geopolymer, enabling complex, waste-minimized architectural designs. [150-153] The use of rCF aligns with global environmental goals by recycling and reutilizing waste CFRP from landfills, while providing economical and efficient alternatives to traditional building materials.

5.3. Energy sectors

Beyond its structural applications, rCF is utilized in the energy industry, including wind energy, energy storage (batteries and supercapacitors), solar energy, grid infrastructure, geothermal energy, and marine energy. rCF was utilized in wind turbine (WT) blades, resulting in a reduction in weight and production cost without compromising structural properties. Mainly, rCFs are implemented in non-critical components (spar caps and shear webs), which aids the efficiency and durability of the blade as depicted in **Figure 11a**.[154-156] *Upadhyayula et al.* investigate the life-cycle environmental sustainability of blades incorporating pristine CF and rCF hybrid shells and shear webs. rCF impregnated blades exhibited 12-89% greater sustainability efficiency in nine out of ten impact categories, including retaining the structural integrity.[155] The use of rCF contributed to circular economy goals to circular economy goals by transforming the CFRP wastes into superior renewable energy products. rCF has two primary applications in energy storage: as activated electrode materials and as structural components for battery housing, hydrogen tanks, and fuel cells. Chen et al. (156,157) have used the rCF and activated it at ~700 °C for ~80 minutes, resulting in a specific surface area of 68.39 $m^2 g^{-1}$.[158] This work reports an affordable method for recycling CF and assembling it into energy storage devices, thereby increasing the reuse value. The mechanical and electrochemical analysis was conducted, and the obtained specific capacitance of the rCF-based device (7.87 mF g^{-1}) is almost similar to the virgin CF (10.17 mF g^{-1}). They also

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fabricated a unibody multifunctional energy storage composite (UBMESC) and investigated the electrochemical and mechanical properties as depicted in **Figure 11b-k**.[158]

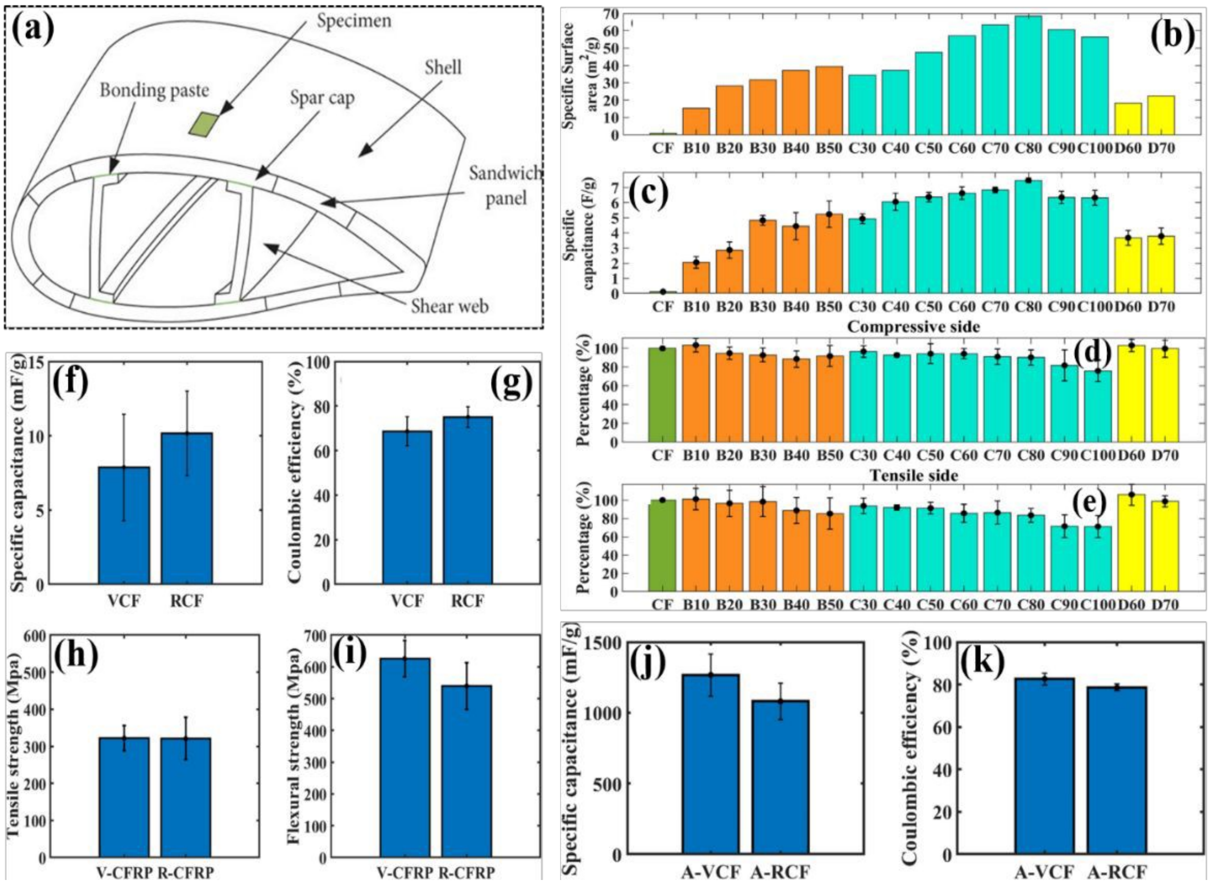

Figure 11 (a) Components of the turbine blade. Reproduced with permission from **Ref. [156]**. (b) Specific surface areas and (c) specific capacitances of various specimen groups; Flexural strengths of various specimen groups at the (d) compressive and (e) tensile sides. (f-k) Electrochemical and mechanical properties. Reproduced with permission from **Ref. [158]**.

The results indicate that the utilization of rCF by replacing pristine CF retained both properties. This research opens up new avenues for utilizing recovered CFs in the energy storage industry. rCF can be utilized as a reinforcing agent to fabricate liners that have improved burst pressure resistance in a Type IV hydrogen tank.[158]

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Table 2: Summarization of various applications of rCF in a wide range of sectors

Sectors	Applications	Benefits	Ref.
Automotive	Engine covers, interior parts, structural components, bumper beams	Weight reduction, cost savings	**[35]**
Aerospace	Fuselage, wings, tails, landing gears, seat frames, and Interior panels	Light weighting, reduced material costs, and environmental sustainability	**[141], [174]**
Construction	Concrete reinforcement, bridges, architectural panels	Improved durability, corrosion resistance, reduced construction weight	**[150-153]**
Consumer Goods	Sports equipment, drones, furniture, skis, and snowboards	High strength-to-weight ratio	**[145-147]**
Energy	Wind turbine blades, battery casings for EVs, **and** Hydrogen storage tanks	Improved material efficiency, lower production emissions	**[154-157]**
Electronics	Consumer electronics casings, heat sinks, EMI shielding components	Thermal conductivity, electromagnetic protection	**[175]**

However, the recycled and recovered fibres from the CFRP waste are widely used in other energy sectors, including rCF replaced the aluminum solar panel to reduce the weight and installation costs; rCF composites are utilized in geothermal reservoir liners and tidal turbine blades because of their saltwater resistant; transformer and switchgear components due to high dielectric constant and thermal stability.[159-162] The rCF can be transformed into filler by grinding, followed by thermal treatment. The obtained powder can be utilized in various applications such as piezoresistive strain sensors, thermal management, and electromagnetic interference (EMI) shielding, where conductive carbonaceous material was crucial.[163-167,176,177] This substitution promotes ecological viability by decreasing dependency on virgin resources and minimizing carbon emissions.

6. Life Cycle Assessment (LCA) and Economic Viability

To figure out the affordability and prospective market of rCF fibres, a thorough techno-economic analysis is necessary. There are numerous ways available for recycling and recovering end-of-life CFRP waste, each having its own set of pros and cons.[19] The circular economy concept should serve as an initial basis for choosing a suitable recycling procedure. The shift to a green economy for FRP composites is dependent on assessing environmental and economic applications. The

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thermoset polymer composites, widely utilized in aerospace, automotive, marine, and wind energy sectors due to their excellent mechanical properties and durability, pose significant environmental challenges at the end of their service life owing to their cross-linked, non-melting resin systems.[168]As discussed in the review about the different types of conventional and advanced recycling methods are discussed in detail. LCA studies suggest that conventional disposal methods (landfilling, Incineration) are inexpensive in the short term. However, these activities contribute to environmental degradation, including global warming and pollution, resulting from resource depletion and the challenges associated with long-term waste management.[169] Waste from the transportation production process and EoL products is a worldwide threat. As a result, solutions for managing waste must be developed to mitigate greenhouse gas (GHG) emissions.[170] Advanced recycling methods, such as catalytic solvolysis and microwave-assisted strategies, have exhibited promising results in terms of low energy consumption and reduced GHG emissions. However, the ecological advantages must be balanced with the processing costs and technological complexity. *Wei et al.* investigated the environmental and economic sustainability of 10 different CFRP and GFRP waste treatment technologies using LCA, cost-benefit analysis (CBA), and technology readiness level assessments. The CBA analysis outcomes indicate that the solvolysis procedure provides the highest returns/profits among the recycling methods. Global warming potential impact (GWP) results suggest that solvolysis and electrochemical techniques can reduce GHG emissions during the FRP life cycle. [171] The implementation of 3R strategies offers a transformative path toward circular material use, waste composites for reuse as fillers or reinforcements, and contributes to significant reductions in GHG emissions, energy demand, and water consumption. Although mechanically rCF may exhibit reduced mechanical properties, it remains viable for low to medium-performance applications such as automotive interiors, panels, and construction

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boards. Although the recovered fibers and fillers possess slightly lower performance characteristics, they still provide adequate value for applications in cost-driven markets. However, the initial capital investment required for setting up recovery infrastructure, such as thermal reactors or solvent recovery systems, can be a limiting factor, particularly in regions lacking policy or regulatory incentives.[170-172] Market demand for recycled composite materials is still emerging, and product standardization and certification remain key challenges for their widespread adoption. However, new legislation, such as carbon pricing and increased producer responsibility (EPR) initiatives, is encouraging companies to implement recycling methods. [173,174] Overall, the integration of 3R strategies into the lifecycle of thermoset polymer composites demonstrates a compelling synergy between environmental responsibility and economic feasibility. To achieve the goal of a circular economy, subsequent efforts must focus on enhancing the efficiency of recycled fibres, reducing costs through advanced recycling strategies, and strengthening industrial supply chains for recovered FRP composites.

7. Future perspectives and conclusions

The growing demand for FRP composites, primarily CFRPs, in advanced structural applications has led to significant waste generation, necessitating long-term recycling solutions. This review focuses on 3R (recycling, recovery, and reuse) strategies for thermosetting FRP composites, comparing conventional methods with advanced recycling methods, including catalytic solvolysis, Fenton-based degradation, microwave-assisted techniques, biological degradation, and vitrimer-based CANs. A critical assessment reveals distinct technology readiness levels (TRLs) across these recycling methods as depicted in **Table 3**. Among these different types of recycling procedures, mechanical recycling is economically feasible (high TRL), but is primarily restricted to down-cycled items. Pyrolysis and solvolysis function at a medium TRL, demonstrated at the pilot scale.

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On the other hand, new technologies like vitrimer composites and enzymatic degradation are still at low TRL and have major performance and scalability issues. Future composite evolution may incorporate living materials, in which engineered biological systems combine into a synthetic matrix. These bio-hybrid composites could perform independent, life-like behaviours such as self-healing and controlled deconstruction at the end of their lives. [187, 188] This approach represents the frontier of materials design, creating truly adaptive structural components.

Table 3 Comparative analysis of CFRP recycling technologies

Recycling methods	**TRL**	**Estimated energy consumption (MJ kg^{-1})**	**Fiber retention (%)**	**Qualitative Cost Analysis**	**Waste generation**	**Ref.**
Mechanical Recycling	9	5-15	60-80	Low	Dust, short fibers	**[178]**
Conventional Pyrolysis	7-8	40-80	80-90	Medium-High	VOCs, char, bio-oil	**[179]**
Microwave-assisted Pyrolysis	5-6	20-40	85-95	Medium	VOCs	**[180]**
Solvolysis	6-7	25-50	90-98	Medium-High	Chemical solvents, wastewater	**[181-183]**
Catalytic Solvolysis	4-5	20-35	92-98	High	Catalyst residues, solvents	**[183]**
Biological Recycling	2-3	5-15	95-99	Low (potential)	Biomass, nutrients	**[184]**
Vitrimers composites	3-4	15-30	98-100	Medium-High	Minimal	**[107,108,185,186]**

To move forward toward a circular composite economy, three key strategic moves will be essential. First, a viable route toward high-efficiency, low-energy recycling is the emergence of hybrid catalytic-microwave technologies. Rapid depolymerization under mild conditions can be achieved by combining molecular catalysts with selective microwave heating, which significantly reduces energy consumption while maintaining the mechanical properties of the fiber. These technologies may be utilized in continuously flowing reactors, which could enable thermoset composite to be processed in a scalable manner while recycling high-quality fibers and chemical raw materials that could be reused. Second, to close the material loop, a circular supply chain that includes recovered fibers in prototype fabrication must be established. Standardized testing and

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evaluation protocols are necessary for rCF to ensure their accuracy in crucial applications. Additionally, the creation of digital material passports for composite components will make more effective sorting and reprocessing possible. Industrial implementation will be further accelerated by incorporating rCF into the design of next-generation composites from the beginning, especially in automotive and 3D-printed structure development. When used together, these strategies can significantly reduce dependence on virgin resources and foster a more sustainable composite economy. Third, economic models and supporting policies are essential for the expansion of composite recycling technology. To determine the best recycling routes and assess their financial and environmental feasibility, a systematic techno-economic study and lifecycle evaluation must be implemented, as discussed in **Section 6**. Green public procurement and carbon pricing schemes are examples of policy tools that might stimulate investment in recycling infrastructure and establish stable markets for rCF. International standards for tracking and reporting composite waste will further enhance responsibility and accessibility throughout global supply chains. In conclusion, the prospects for composite sustainability depend on collaborative use of cutting-edge recycling techniques, circular supply chain planning, and supportive legislative frameworks rather than on individual technological advancements. These collaborative methods offer a sustainable, closed-loop ecosystem that achieves both high performance and ecological objectives.

Author contributions

The manuscript was written through the contributions of all authors. C. Kuila and A. Maji wrote the main manuscript text and prepared figures. N. C. Murmu and T. Kuila have conceptualized the idea and reviewed the entire manuscript. All authors have approved the final version of the manuscript.

Conflicts of interest

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There are no conflicts to declare.

Data availability

No primary research results, software, or code have been included, and no new data were generated or analyzed as part of this review.

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No primary research results, software, or code have been included, and no new data were generated or analyzed as part of this review.