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## The 3R (recycling, recovery, and reuse) of fiber reinforced thermoset composites: paving the way for a circular economy

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The rising popularity of fiber-reinforced polymer (FRP) composites in the aerospace, automotive, and energy industries leads to waste management difficulties. This review critically considers 3R (recycling, recovery, and reuse) options for thermoset-based FRP composites, contrasting traditional (landfilling and incineration) and developing (solvolysis, microwave-assisted recycling, and 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 and 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.

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### 1. Introduction

In the modern era, the need for light weight materials with higher strength properties has garnered significant attention across a wide range of industrial sectors, including defence, automotive, and aerospace.<sup>1–3</sup> Composite materials have con-

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tributed to the improvement of human civilization, from primitive mud-and-wood huts to the current emergence of advanced structures. Fig. 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 a higher density and are more susceptible to corrosion, which restrict their broader applications compared to epoxy-based FRP composites.<sup>4,5</sup> Advanced composites are manufactured using a wide range of reinforcing fibers, such as synthetic (carbon fibers (CFs), basalt fibers (BFs), aramid fibers, and Kevlar fibers) and natural fibers (including hemp, jute, flax, and sisal fibers). However, due to growing environmental concerns, researchers have increasingly focused on developing composites reinforced with natural fibers. Among the various natural fibers, flax and hemp fibers provide 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.<sup>6–8</sup> Among the various fibers, CFs

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, light weight properties, and environmental resistance.<sup>7</sup> 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 CFs 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 Fig. 1b.<sup>9</sup> The rising CF production capacity boosts the expansion of the CFRP composite market. Although FRP exhibits excellent properties and is gaining more attention worldwide, it faces issues regarding the recycling and reuse of used fibers. The present global need for CFs is predicted to be ~115 kilotons per year as of 2023, and is projected to increase to 280 kilotons per year by 2030.<sup>10</sup> Thermoset polymers are predominantly employed in FRP composites for high-load bearing applications. However, the recycling of fibers from thermoset composites is challenging due to the higher cross-linking density of the thermoset-based



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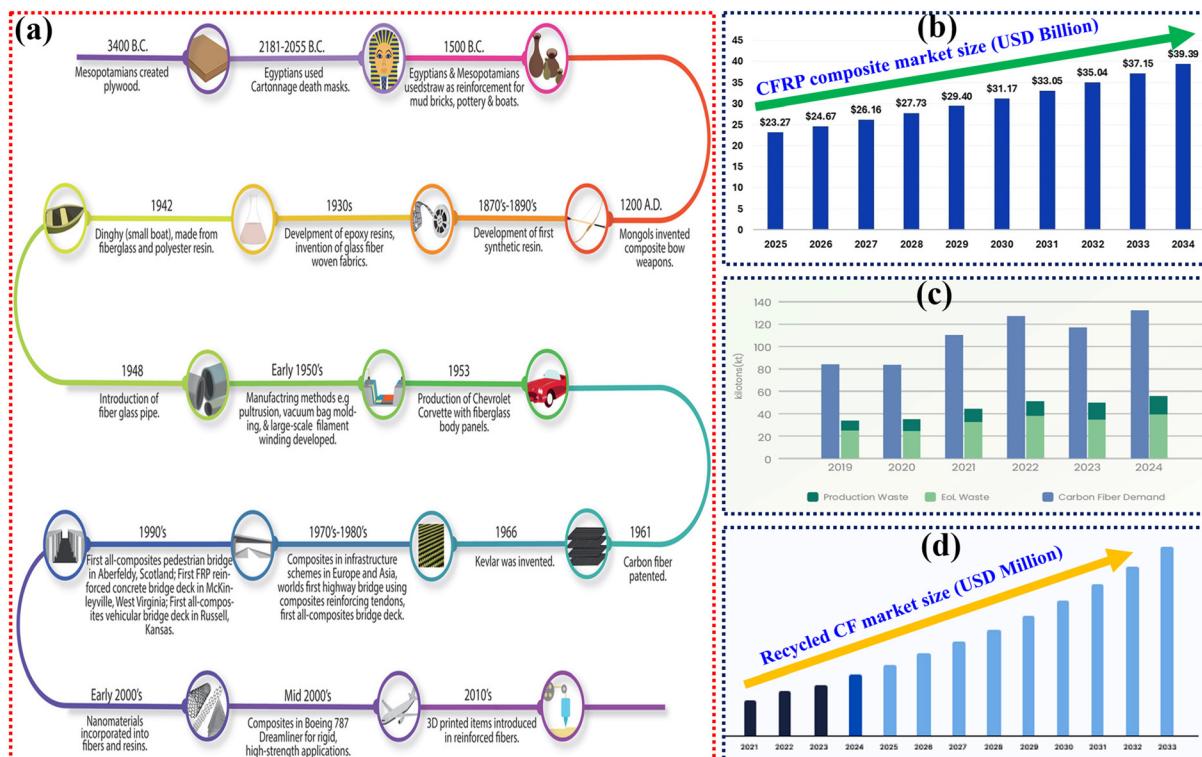
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**Fig. 1** (a) Chronological development of composite manufacturing for several industries. Reproduced with permission from ref. 12. (b) Global market size for CFRP composites from ref. 9. (c) CF demand and estimated waste (2019–2024) from ref. 11, and (d) global market size of recycled CFs from ref. 13.

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 years, reaching 100 000 tons per year after 2029, as shown in Fig. 1c.<sup>11</sup> These wastes were mostly coming from industrial waste and end-of-life (EoL) waste from the aviation and wind sectors.

In the absence of recycling initiatives, the aviation industry is projected to produce approximately 500 000 tonnes of CFRP waste by 2050.<sup>14</sup> 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 rCFs 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) (Fig. 1d). rCFs provide an economical alternative to traditional materials, such as metals and virgin carbon fibre.<sup>13</sup> 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, the 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.<sup>15–20</sup> Previous reviews focused on the recycling of CFs from thermoplastic materials, but an in-depth review on the recycling of thermoset-based composites remained unexplored.<sup>21–24</sup> Therefore, this review provides an in-depth study of the 3R (recycling, recovery, and reuse) strategies for CFRP composites, including the latest advancements with sustainable economic ideas. Initially, the challenges associated with recycling CFs from FRP composites are discussed, along with possible paths to overcome these obstacles. Then, various emerging methods (e.g., Fenton-based catalytic reaction and microwave-assisted treatment) were correlated with conventional methods to recover the fibers from the composite specimens. This review also discusses 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, it sets a direction for future research in the composite field. It is presumed that this article will serve 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 develop 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.<sup>25</sup> Generally, thermosetting polymers used to fabricate FRP composites are epoxy resins, polyesters, vinyl esters, cyanate esters, phenolic resins, etc.<sup>12</sup> Several reviews have already discussed the fundamental structure and properties of various thermoset polymer matrices in detail.<sup>12,24–27</sup> Therefore, this section 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 light weight 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.<sup>28,29</sup> Recycling of costly fibers 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 CFs is  $183\text{--}286\text{ MJ kg}^{-1}$ , which is 14 times higher than that for steel production.<sup>30,31</sup> CF manufacturing consumes 100 to 900  $\text{MJ kg}^{-1}$  and emits 24 kg CO<sub>2</sub> eq. per kg of fibres generated, which is considerably more than steel (20–30  $\text{MJ kg}^{-1}$  and 1.7–2.1 kg CO<sub>2</sub> eq. per kg) and glass fibre production (45  $\text{MJ kg}^{-1}$  and 2.0–3.0 kg CO<sub>2</sub> eq. per kg).<sup>32</sup> Therefore, the recycling of CFs from the FRP composite waste is very crucial, and the utilization of recycled fibers is more useful for the global economy and environmental health. Annually, thousands of tonnes of thermoset composites are generated worldwide, as shown in Fig. 1b. GFs and CFs are effective reinforcement materials for many applications, although they become alarming to the ecology after EoL.<sup>29</sup> Toyota manufactured the hatch door frame using Mitsubishi Rayon's sheet moulding material, and the BMW Group used rCFs to strengthen the C-pillar with a sheet moulding compound.<sup>33–35</sup> In March 2025, the Syensqo and Vartega groups announced the development and promotion of the use of rCFs 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 rCFs.<sup>36</sup>

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 rCFs' 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 light weight components is exemplified by Airbus' ambitious target to recycle ~95% of its CFRP waste.<sup>37</sup> However, obtaining rCFs from 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 facing significant challenges. Firstly, the composite material comprises fibers and a polymer matrix, which has distinct chemical and physical properties, making separation challenging.<sup>33</sup> Secondly, obtaining high-performance fibers without compromising the mechanical properties is a challenging task. Third, reshaping and remoulding are almost impossible after the curing of the thermoset polymer matrix.<sup>38</sup> During the most efficient recycling process, solvolysis, it produces chemical wastes such as bases, acids, harmful gases, and solid wastes.<sup>29,39</sup> Therefore, it is highly essential to develop a feasible strategy that enables the recycling of high-performance fibers through a suitable pathway for an economical and sustainable society (Fig. 2).

## 3. Approaches to produce recyclable thermoset composites

In this section, the conventional and advanced recycling of fibers from thermoset composites is discussed in detail. A detailed discussion of the pros and cons of the approaches is also presented, as 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 they 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. If rCFs are not recycled, they are typically sent for disposal. 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



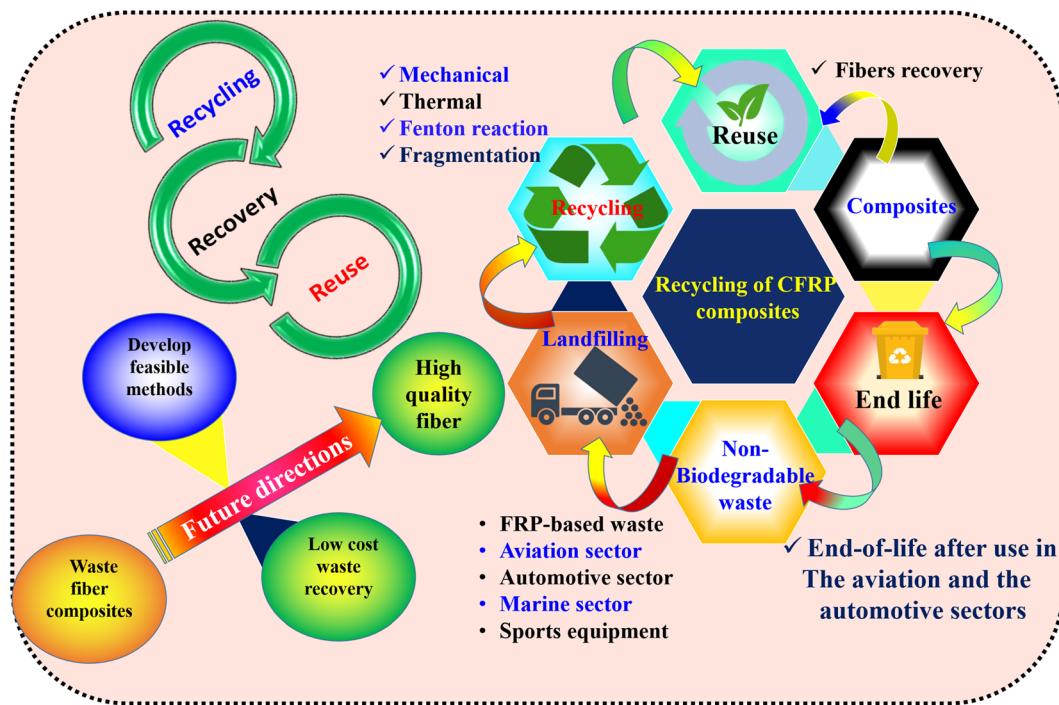


Fig. 2 Schematic representation of the recycling of high-performance fibers from the FRP composite specimens.

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

Recycling methods	Advantages	Disadvantages	Pristine CFs (GPa)	rCFs (GPa)	Points of attention	Ref.
Thermal recycling	High-performance fiber recovery	High energy consumption and risk of fiber damage	$\sigma = 3$ and $E = 210$	$\sigma = 2.89$ and $E = 225.5$	Fiber quality and safety concerns	40
Thermal recycling	Energy savings and performance retention	Aggressive thermal degradation	$\sigma = 3\text{--}5$ and $E = 210\text{--}250$	$\sigma = 2.8\text{--}4.2$ and $E = 180\text{--}240$	Post-recycling treatments	41
Chemical recycling	Retain stiffness (85–95%) and low energy consumption	rCFs lose 10–30% strength	$\sigma = 4.7$ and $E = 228$	$\sigma = 4.4$ and $E = 214$	Solvent selection and fiber quality control	42
Chemical recycling	Reducing the environmental impact	Limited industrial scalability and residue contamination	$\sigma = 4.8$ and $E = 241$	$\sigma = 4.31$ and $E = 221$	Scalability and practical implementation	43
Chemical recycling	Used biodegradable solvents	Incomplete resin removal	$\sigma = 4.48$ and $E = 200.56$	$\sigma = 4.07$ and $E = 190.52$	Lifecycle analysis and fiber quality control	44
Chemical recycling	Mild conditions and energy savings	Recovery cost	$\sigma = 3.49$	$\sigma = 3.34$	Environmental and safety risks	45
Catalyst-assisted solvolysis	Selective cleavage in epoxy bonds	Catalyst cost and slow reaction kinetics	—	—	Environmental and economic balance and surface integrity	46
Catalyst-assisted solvolysis	Mild solvolysis	Limited to a specific epoxy resin	—	—	Replace with a cheaper functional catalyst and monomer purification	47
Microwave-assisted pyrolysis	Selective heating and high-purity recovery	Incomplete polymer removal	$E = 71.12$	$E = 66.53$	Handling molten salts	48
Microwave-assisted pyrolysis	Efficient polymer removal and fast reaction rate	Fiber property degradation	—	—	Byproduct management and reusability in composites	49

(EU) Waste Management Directive ranks landfilling as the least preferred waste management alternative, despite its cost-effectiveness.<sup>50</sup> 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 facil-



ties.<sup>51</sup> The EU landfill directive and UK landfill fee attempt to prevent landfill utilization while encouraging sustainable disposal methods.<sup>52</sup> 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, landfilling costs for this waste have risen significantly. This highlights the necessity for innovative disposal techniques for FRP composite waste and will encourage the recycling of FRP composites.<sup>53,54</sup> 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.<sup>24,50,55</sup> 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 rCFs.<sup>56,57</sup> 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.<sup>58</sup> 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 compo-

site waste will encourage the recycling of FRP composites. Several reviews on the recycling of fibers from the waste FRP composite *via* thermal treatment have been reported.<sup>20,24,59,60</sup> These reviews discussed the thermal treatment process in detail and conducted a literature survey. Therefore, the 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  $\sim 350$ – $450$  °C to decompose the polymeric matrix.<sup>61,62</sup> Therefore, the recovery step for the waste composites was carried out above 800 °C. Generally, thermal treatment techniques are of various types, *i.e.*, aerobic (combustion), anaerobic (pyrolysis), fluidized bed process (FBP), and microwave-assisted thermal treatment (Fig. 3a–d).<sup>63</sup> During the combustion process, *i.e.*, in the presence of oxygen, the waste can be transformed into considerable heat and gases (volatile organic compounds, CO<sub>2</sub>, CO, water vapour, *etc.*), which are released from the combustion of the polymer matrix in the presence of oxygen and rCFs. The overall properties of rCFs were degraded due to the oxidation of the fibers. Therefore, the combustion method is not an efficient route for recycling high-performance fibers.<sup>64–66</sup> The advantages and disadvantages of the various recycling methods are summarized in Table 1. The pyrolysis method converts thermoset composites into useful

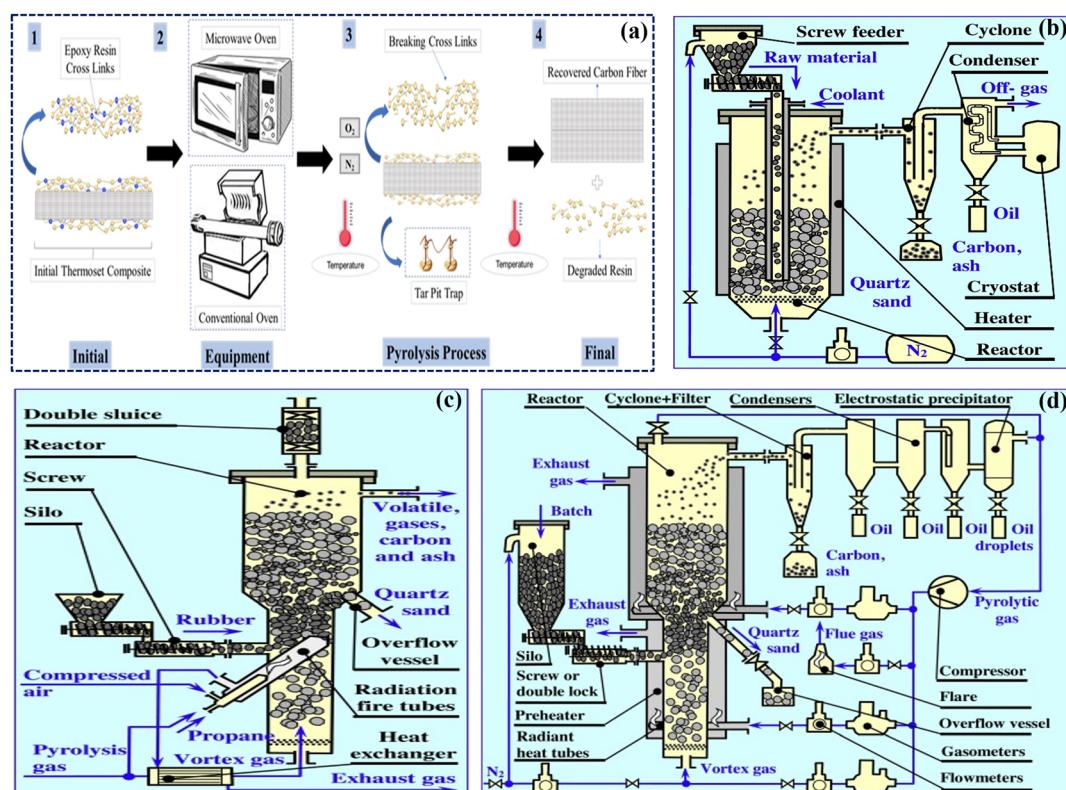


Fig. 3 (a) Pyrolysis system: (1) CF/epoxy resin laminates, (2) Microwave or conventional oven, (3) Breaking epoxy resin cross-links, and (4) rCFs. Reproduced with permission from ref. 63. (b) Laboratory fluidised bed reactor for polymer pyrolysis. Reproduced with permission from ref. 75. (c) Fluidised bed pyrolysis reactor<sup>76</sup> and (d) FBP plant. Reproduced with permission from ref. 77.



fuels, chemicals, and fibers. The pyrolysis was conducted under an inert atmosphere in the 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 for handling and recycling fibers. The retention of thermal and mechanical properties by the rCFs is ~85–90%. However, there are some challenges in recovering the high performance of pristine fibers. During pyrolysis, there is a chance of deposition of carbon on the fiber surface.<sup>64–68</sup> Kim and co-workers are trying to optimize the temperature conditions to recover high-quality fibers. They analyzed the thermal decomposition of CFRP composites, exhibiting two-stage degradation where aliphatic chains broke down at ~350 °C, followed by aromatic network disruption at >400 °C. This work quantified that pyrolysis under an N<sub>2</sub> atmosphere at 500 °C with a slow heating rate of 5 °C min<sup>-1</sup> resulted in near-complete resin removal (~99 wt%) while retaining approximately 92% of the original CF properties. In contrast, faster heating rates under 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.<sup>68</sup> 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 an internal heating element 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.<sup>69</sup> 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.<sup>70</sup> 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.<sup>52</sup> The microwave-assisted pyrolysis method was more environmentally friendly and cost-effective compared to other pyrolysis methods. This method releases 544 tons of CO<sub>2</sub> eq., while conventional pyrolysis emits 744 tons of CO<sub>2</sub> eq. It required low costs of EUR 5.60 per kg, compared to EUR 12.00 per kg for the conventional pyrolysis method.<sup>71–73</sup> However, scaling up the approach to an industrial scale has not yet been demonstrated. Fluidized bed pyrolysis (FBP) of 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.<sup>74</sup>

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 under an oxygen atmosphere, as shown in Fig. 3b–d.<sup>75–78</sup> The organic resin undergoes degradation, allowing the filler particles and fibers to be extracted as needed. Reported works on recycling of fibers using the FBP method showed that the tensile strength of the recycled fibers was ~75% of the virgin fibers.<sup>76,77,79</sup> 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.<sup>80</sup> 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 a filler or reinforcement in new composites following size reduction and powder generation.

In this process, FRP wastes are crushed, followed by grinding, milling, and sieving to obtain the final recycled products, which are mixtures of the ground powder and fiber.<sup>81</sup> This method is more cost-effective and sustainable than the thermal recycling procedures.<sup>82</sup> There are several reports on the recycling of fibers from FRP waste and their reuse in various applications.<sup>75,83,84</sup> 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 presence of residual polymer matrix on mechanically recycled fibers compromises their mechanical properties relative to pristine fibers.<sup>85</sup> Another limitation is filler loading – using ground fibers in epoxy composites. Exceeding 10 wt% reduced the mechanical properties due to agglomeration.<sup>86,87</sup> This recycling method is only useful for a large amount of EoL FRP composite waste to recover short fibers. However, only minimal amounts of the 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 suffer from low pro-



duction yield and high cost. Emerging methods, such as high-voltage fragmentation (HVF) and solvent-based chemical recycling, show promising results for long-term, cost-effective fiber recovery.<sup>88</sup> 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.<sup>89,90</sup> HVF was initially employed in rock mining in the 1960s to break down rocks and minerals.<sup>91</sup> The latest research has shown that pulsed high-voltage discharges in a water-filled chamber cause plasma-induced shockwaves predominantly spreading *via* the fiber–matrix interface owing to differences in their dielectric characteristics.<sup>92</sup> This method provides sustainable and precise degradation compared to the mechanical recycling process, successfully retaining the fiber length while minimizing damage to the fiber surfaces. Though this method holds promise, the industrial adoption of HVF faces significant challenges. A key disadvantage is its high energy utilization (sometimes hundreds of  $\text{kJ kg}^{-1}$ ), which remained a vital economic and ecological obstacle as opposed to the other conventional recycling methods.<sup>89</sup> Current research focuses on optimizing the 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 density, resulting in thermoset-like properties at operating temperatures, as well as thermoplastic-like reprocessability and recyclability when heated.<sup>93</sup> Comprehensive studies have previously discussed the fundamental chemistry of CANs elaborately, including transesterification, Diels–Alder/retro-DA chemistry, imine bonds, and disulfide metathesis.<sup>94–101</sup> The various types of CAN-based polymer mechanisms are illustrated in (Fig. 5a–f). However, this section will concisely highlight their utilization in the recycling of 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.

To develop high-performance composites with high thermal and mechanical stability, *catalyzed transesterification-based* vitrimers, typically catalyzed by Lewis acids like  $\text{Zn(II)}$  acetates, where ester bonds exchange with the adjacent hydroxyl groups, are often the leading materials (Fig. 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 ( $T_v$ ).<sup>95–97</sup> In contrast, dissociative systems, such as Diels–Alder or acetal linkages, can exhibit reduction in the 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.<sup>98</sup> 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, vitrimer composites offer a clear path to a sustainable economy for high-performance materials through molecular innovation.

## 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.<sup>87,88</sup> 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 the recycled fibers compared to virgin fibers.<sup>102</sup> The most common chemical recycling procedure is the oxidation method by using various oxidants such as nitric acid, hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), peracetic acid, *etc.* The rCFs obtained from this recycling procedure retains their 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 at higher ( $\geq 200\text{ }^\circ\text{C}$ ) or lower ( $\leq 200\text{ }^\circ\text{C}$ ) temperatures.<sup>103</sup> Water and co-solvents such as alcohol, phenol, and amine have been utilized



effectively in the solvolysis process.<sup>104</sup> Acidic or basic catalysts are used to promote the reaction, and it is essential when the epoxy is highly stable towards degradation.<sup>29,105</sup> Solvent-based methods, including subcritical and supercritical fluids, are considered effective methods for recycling fibers from FRP composite waste.<sup>106</sup> However, the energy consumption in this recycling is high compared to the other methods.<sup>107,108</sup> Another limitation of this method is controlling the reaction 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 a 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<sub>2</sub>) or nitrous oxide (N<sub>2</sub>O) gas. Zhang *et al.* recovered CFs from the CFRP composites *via* the acid digestion method, as shown in Fig. 4a.<sup>42</sup> In this method, the fabricated composites with dimensions of 50 × 10 × 2 mm<sup>3</sup> 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 (Fig. 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 Fig. 4c and d. The thermal properties of EP were affected under vigorous conditions. Therefore, the sol-

volysis in the presence of strong acids has a negative impact on both the environment and the overall properties of the fibers (Fig. 4e).<sup>43,109</sup> Additionally, the reaction at high temperature generates enormous heat as the reaction is exothermic, which poses a risk of safety issues. Therefore, 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 Fig. 6a.<sup>110</sup> After completion of the reaction, the fibers were separated out and can be used for further utilization in the preparation of composites. The depolarization mechanism of mCPBA with EP is illustrated in Fig. 6b. The mechanical properties of single rCFs and vCFs were investigated. The tensile strength of vCFs was ~4.70 GPa, while that of rCFs was 4.40 GPa (Fig. 6c). The Young's modulus was ~228 GPa for vCFs and 214 GPa for rCFs, as shown in Fig. 6d.

rCFs exhibited a minimal degradation rate of ~93.6% in comparison with vCFs and maintained mechanical qualities at a similar or higher level than that reported in earlier research, even after the recycling procedure. To investigate the interfacial bonding between the epoxy matrix, an rCF/EP composite was prepared, and contact angle and interfacial shear strength (IFSS) measurements were made. The results of contact angle

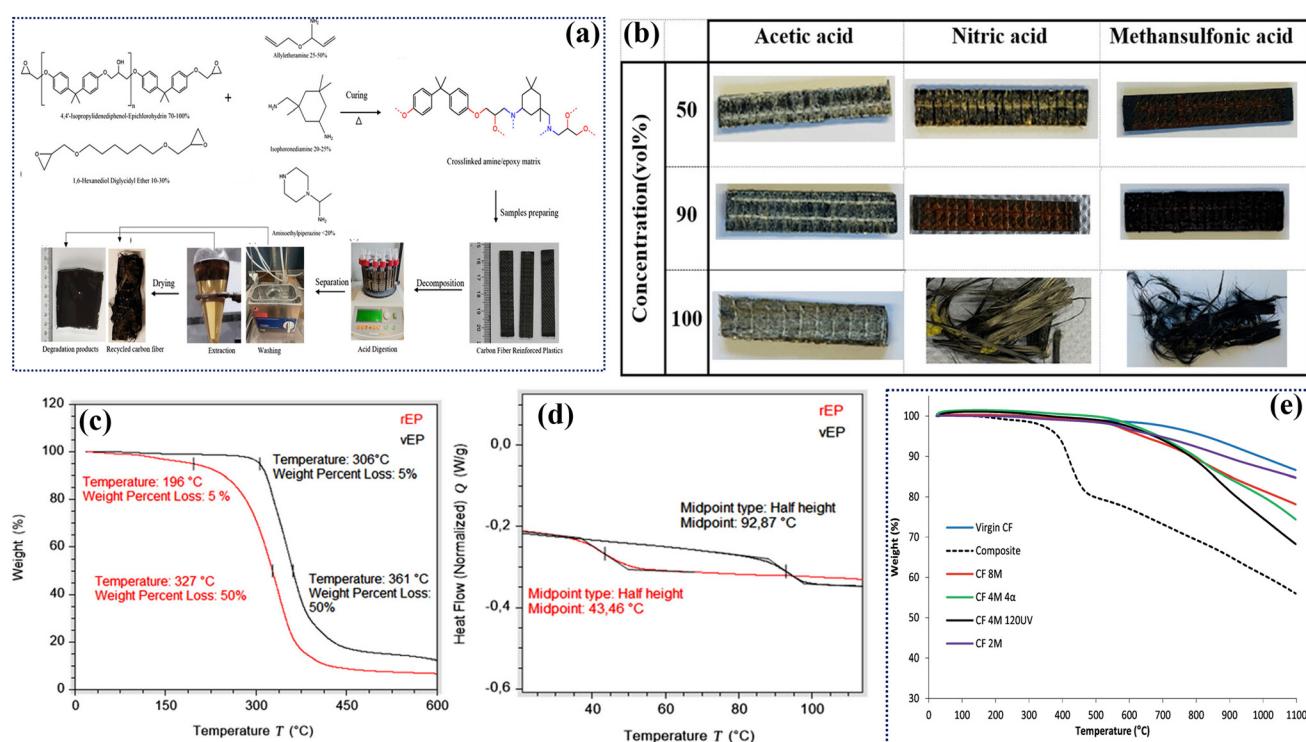
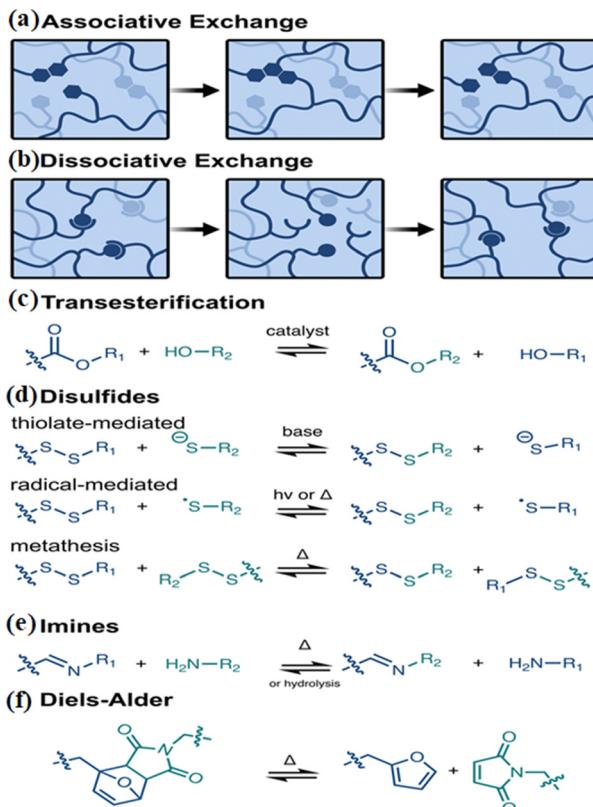


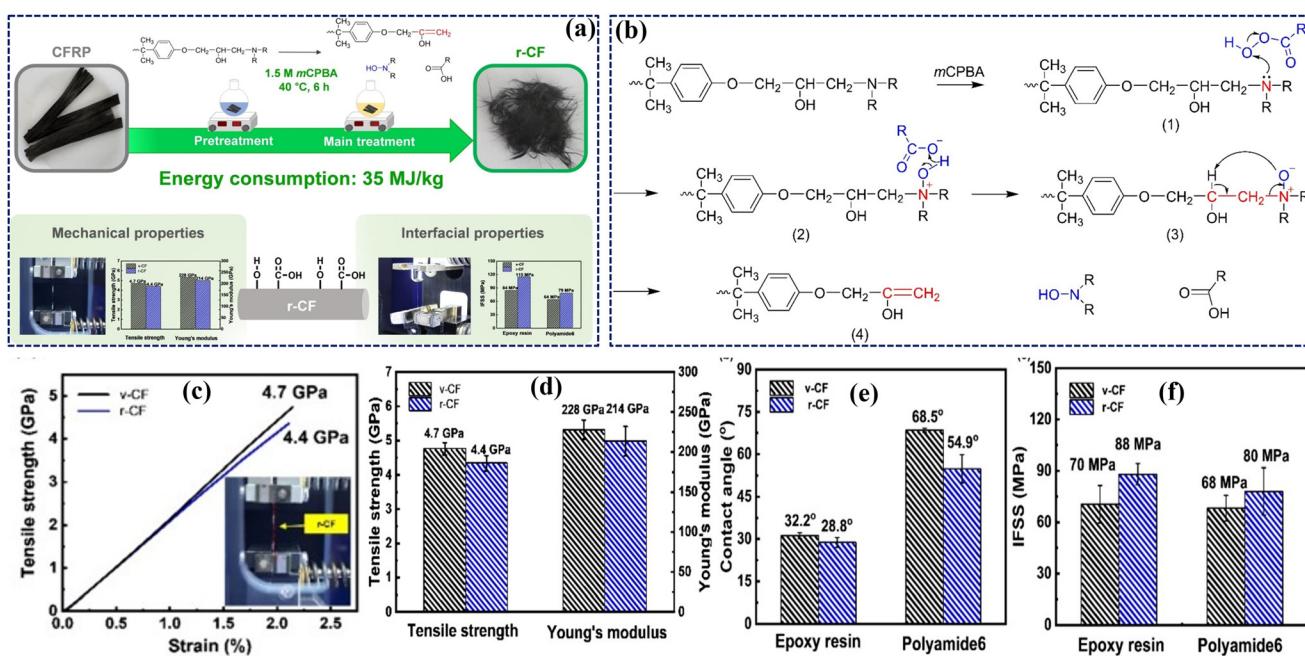
Fig. 4 (a) Schematic illustration of the recycling method, (b) acid-treated rCF samples at different acidic concentrations, (c) TGA, and (d) DSC analysis of rEP and vEP. Reproduced with permission from ref. 42. (e) TGA analysis of the recovered CFs. Reproduced with permission from ref. 109.





**Fig. 5** CAN based mechanism included (a) associative mechanism (vitrimers) or (b) dissociative mechanism. Examples of dynamic covalent chemistries: (c) transesterification, (d) disulfide exchange, (e) imine exchange, and (f) Diels–Alder chemistry. Reproduced with permission from ref. 94.

and IFSS measurements, as depicted in Fig. 6e and f, suggest that rCFs enhance the interfacial bonding between the fiber and matrix.<sup>42</sup> Other works emphasize the recovery of fibers from FRP composite waste using mild chemicals, such as acetic acid, tartaric acid (TA), and alcohol. Additionally, a few researchers tried to recycle fibers by using an alcohol/water mixture.<sup>109–113</sup> The recycled CF reinforced composite retained ~90% of the tensile strength and ~82% of the tensile modulus compared to a virgin CF reinforced composite.<sup>113</sup> Mild solvolysis is a promising recycling method for sustainable chemistry, but it faces challenges in speed, completeness, solvent management, and scalability.<sup>114</sup> Another limitation was the recovery of the matrix, which was dissolved in the solvent used. Under mild conditions, the 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 repolymerizable 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.<sup>97–101</sup> As part of these solvolysis processes, plasma-assisted solvolysis has emerged as a promising hybrid technique due to the fast reaction under mild conditions. It uti-



**Fig. 6** (a) Chemical recycling of CFRP and analysis of the interfacial shear strength on rCFs, (b) depolarization mechanism of EP using mCPBA, and (c–f) the mechanical properties of vCFs and rCFs. Reproduced with permission from ref. 110.

lizes 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.<sup>115,116</sup> When combined with a solvent such as nitric acid, this plasma generates a highly aggressive but regulated environment that breaks down the polymer network.

The plasma–solvent synergy greatly enhances epoxy matrix degradation, enabling faster reactions under milder chemical conditions and lower temperatures compared to 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 at elevated 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 the abundance of persistent carbon–carbon bonds in the viscous decomposed product.<sup>117</sup> 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.<sup>118–121</sup> Among these methods, metal-based catalytic solvolysis and the catalytic oxidation process (mainly Fenton's reaction) are more efficient than the bio/ionic liquid-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.<sup>122</sup> 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 Fig. 7a–d.<sup>46,123,124</sup> The most commonly used metal-based catalysts are  $ZnCl_2$ , Ru-based catalysts, and Fe-based catalysts, which are also known as Fenton catalysts. Liu *et al.* developed a unique recycling approach, using a mixture of deep eutectic solvents (DESSs) and metal salt catalysts (*e.g.*,  $ZnCl_2$ ,  $FeCl_2$ , and  $FeCl_3$ ), which has resulted in the successful recovery of both valuable long CFs and epoxy resin from CFRP. The reaction was completed under mild conditions. The decomposition of highly cross-linked epoxy moieties was facilitated *via* diffusion of  $Zn^{2+}$  into the polymer matrix to break the C–N and C–O–C

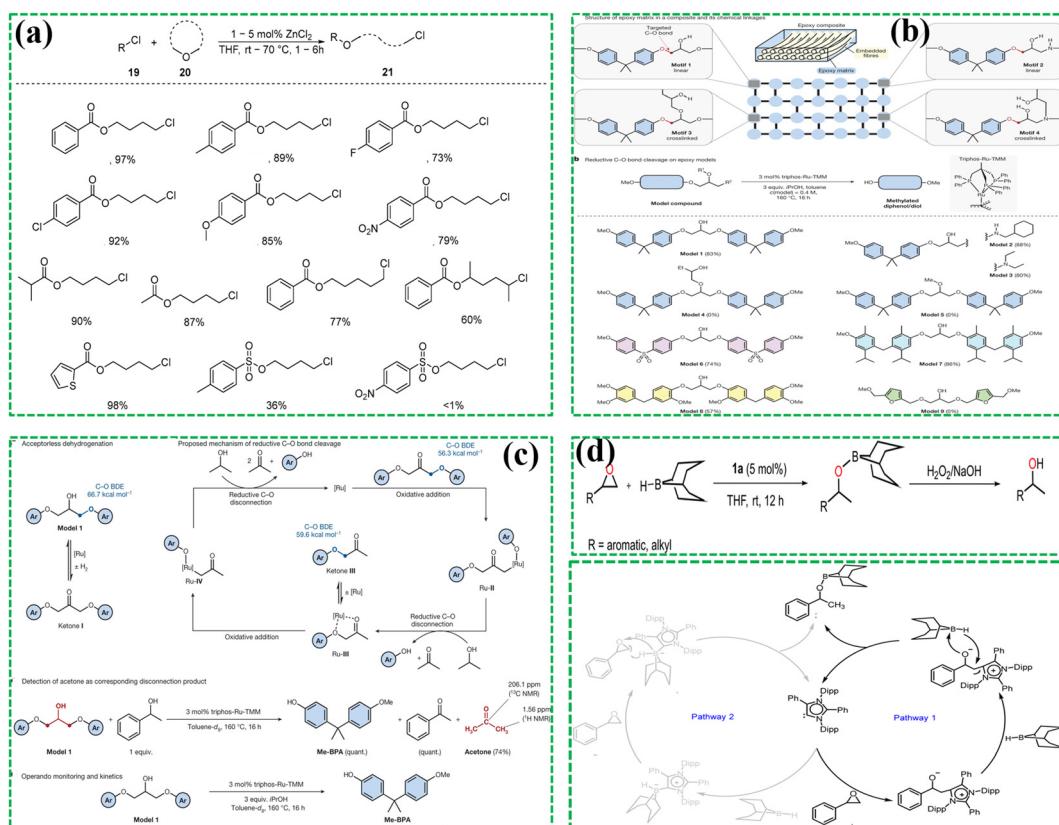


Fig. 7 (a)  $ZnCl_2$ -catalyzed ring opening of cyclic ethers. Reproduced with permission from ref. 123. (b and c) Mechanism of Ru-catalysed C–O bond disconnection. Reproduced with permission from ref. 46. (d) Plausible ring opening of the epoxy ring. Reproduced with permission from ref. 124.



bonds. The rCFs retained ~94.5% of the original properties.<sup>125</sup> The Fenton reaction was carried out to recycle the fibers from the composites. Wang *et al.* developed a novel method to recycle CFs from unsaturated polyester resin (UPR) composites without compromising the thermal and mechanical properties.<sup>117</sup> The mild nano-Fe<sup>0</sup> *in situ* formation technique significantly increased the degradation performance. During the recycling process, H<sub>2</sub>O<sub>2</sub> was added to accelerate the reaction rate to decompose the thermoset polymer to recover the fibers. The C=O in the hydrolysed resin was rapidly weakened by radicals compared to 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 CFs from composites without affecting the fibers' properties.<sup>126</sup> The Fenton reaction proceeds through radical formation (Fe<sup>2+</sup> + H<sub>2</sub>O<sub>2</sub> → Fe<sup>3+</sup> + 2'OH) to decompose the CFRP composite.<sup>126</sup> 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 product 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 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 (Fig. 8a and b). The obtained results suggest that chemical recycling using a catalyst can be successfully carried out under mild conditions (temperature less than 100 °C).

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 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<sub>3</sub>PO<sub>4</sub>) and potassium carbonate (K<sub>2</sub>CO<sub>3</sub>) in ethanol-based solvolysis.<sup>127</sup> These catalysts are highly soluble under elevated reaction conditions, resulting in high catalytic efficiency; however, they separate out of the solu-

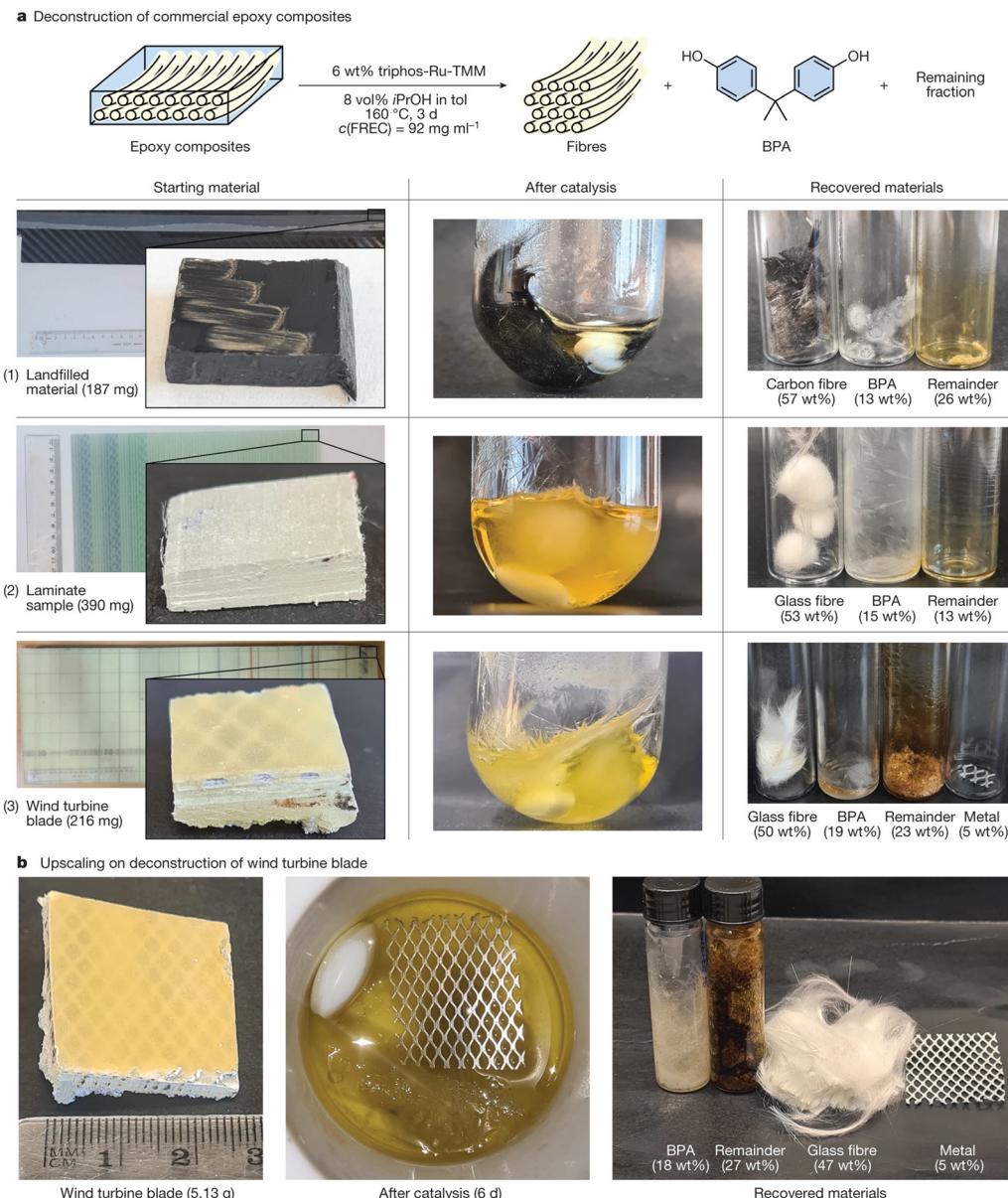
tion when cooled to room temperature, allowing for straightforward filtering and reuse in the next cycle. Developing self-separating, supported, and recyclable catalysts is crucial for bridging the gap between lab-scale advances and economically viable large-scale catalytic recycling.

#### 4.3. Microwave-assisted recycling

The microwave-assisted recycling method is gaining attention among researchers as an alternative pathway of thermal treatment/pyrolysis at high temperature to recover high-performance fibers. 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 sources, transmission lines, and applicators). Microwaves are generated by the source, sent to the applicator *via* transmission lines, and then transferred to the material that is being heated.<sup>127</sup> The microwave will heat the dielectric materials such as the epoxy matrix *via* the following mechanism steps: 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 reorientation of the molecules, generating friction in turn, the molecule becomes heated, and decomposition occurs.<sup>128</sup> Shu *et al.* recovered CFs *via* a molten salt pyrolysis-oxidation recycling method.<sup>48</sup>

The molten salt consisting of Na<sub>2</sub>CO<sub>3</sub>, K<sub>2</sub>CO<sub>3</sub>, and Li<sub>2</sub>CO<sub>3</sub> 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 Fig. 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 at different temperatures were investigated and are illustrated in Fig. 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 Fig. 9e. The mechanical properties of the rCFs gradually decreased with an increase in pyrolysis temperature. This investigation revealed 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 such as microwave-assisted recycling, followed by chemical methods and the design of large-scale reactors for industrial applications.





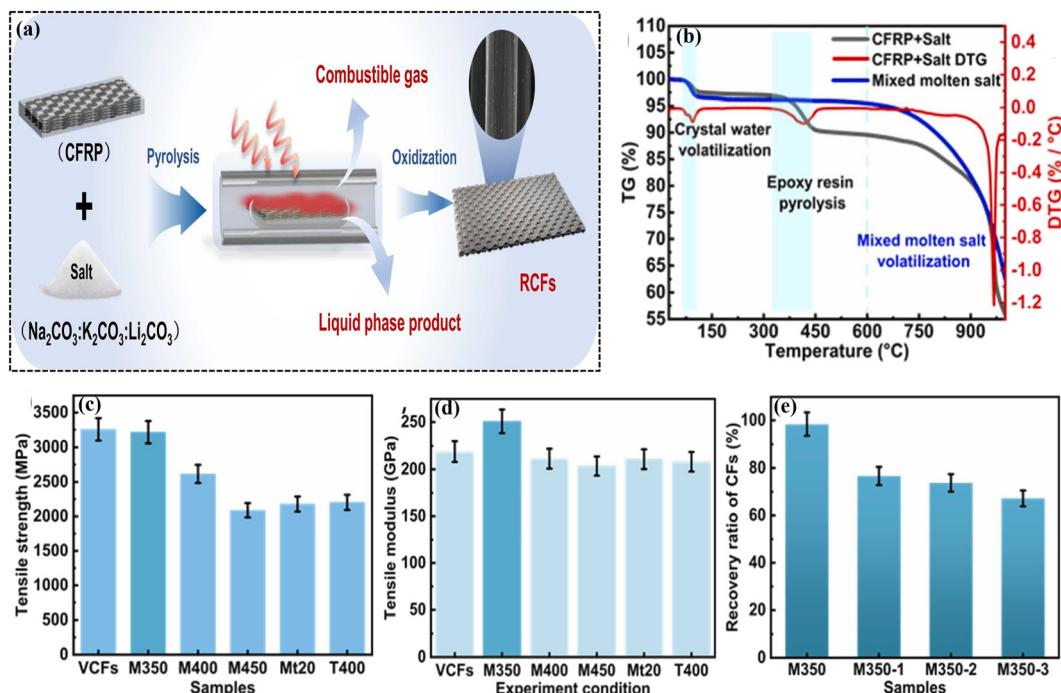
**Fig. 8** (a) The scope of the catalyzed composite samples. Composite pieces 1, 2, and 3 measured 1.0–1.5 cm in length and width. (b) Increased deconstruction circumstances on wind turbine blades. Reproduced with permission from ref. 46.

#### 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.<sup>129,130</sup> 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.<sup>131</sup> Using electrospinning/electrospraying, researchers are develop-

ing nano-fibrous biodegradable membranes using esterase and cellulase enzymes for a wide range of applications, including oil removal, water treatment, etc.<sup>132–136</sup> 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 °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.<sup>122</sup> Min *et al.* developed a green chemical recycling approach for anhydride-cured epoxy-based CFRPs using a  $\beta$ -phenylethanol/TBD catalytic system. The





**Fig. 9** (a) Recovery of CFs by microwave-molten salt pyrolysis and oxidation, (b) TG-DTG of CFRP/salt and mixed molten salt, (c and d) tensile strength and modulus of rCFs, and (e) recovery ratio of CFs of the composite molten salt reuse. Reproduced with permission from ref. 48.

process achieved over 99% resin degradation within 2 h under mild conditions, with rCFs retaining 93.2% of their original tensile strength. XPS and XRD analyses confirmed the retention of surface chemistry and graphitic structure, suggesting efficient closed-loop recyclability.<sup>137</sup> Deng *et al.* studied the biodegradation of the epoxy resin varnish coating in seawater influenced by *Bacillus flexus*. Electrochemical and spectroscopic analyses revealed a significant loss of corrosion resistance and structural integrity due to microbial activity.<sup>138</sup> Another bacterium, *Pseudomonas aeruginosa*, 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.<sup>139</sup> Mikel Dolz *et al.* used fungal *peroxygenses* to investigate the capability of degrading the epoxy resins. This approach offers a biotechnological route for recycling and upcycling of epoxy-based FRP composites.<sup>140</sup> 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 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.<sup>27</sup> 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 Fig. 10. In this section, the review discusses the utilization of rCFs in various fillers as reinforcing agents as well as fillers to develop advanced composites.

### 5.1. Automotive and aviation sectors

rCFs recovered from CFRP waste have emerged as an appealing alternative to pristine CFs, particularly in the automotive and aviation sectors, where light weight and environmental considerations drive the development of these materials.<sup>35,80</sup> 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 rCFs 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





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

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. Primarily, BMW and Airbus groups agreed to consider the reutilization of rCFs, and BMW started series production of i3 and i8 models in 2013.<sup>141</sup> BMW utilized rCFs in seat frames and C-pillars 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.<sup>35</sup> Additionally, Tesla is exploring the rCFs in the battery enclosure to improve the energy density and reduce weight.<sup>142</sup> Therefore, the utilization of rCFs as an alternative to pristine CFs opens up new opportunities for the automotive sector. In the aviation sector, rCFs are 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.<sup>143</sup> Recently, the utilization of rCFs in military drones has gained more attention due to a reduction in processing cost by ~40%.<sup>144</sup> Additionally, the recycled fibers are utilized for secondary aircraft structures, aligning with the circular economic goals.

### 5.2. Consumer goods and construction

rCFs are gaining popularity in consumer products and construction due to their light weight, strength, and economical benefits. It is impregnated in consumer items such as sports equipment (bike frames, bicycles, and tennis rackets), and electronic devices like laptops and smartphones, providing an excellent strength-to-weight ratio and superior aesthetics. The wide utilization of rCFs in different fields is presented in Table 2. Additionally, the overall price of the instruments was also reduced after the utilization of rCFs instead of costly pristine CFs.<sup>145–147</sup> In constructions, it can enhance the crack resistance, the durability of the concrete, and also be used for restoring aged structures with fibre covering.<sup>148,149</sup> Furthermore, rCFs are commonly used in architectural renovation, especially to improve the aging bridges, columns, and beams. Beyond its load-bearing applications, rCFs are currently being considered in 3D printed designs as reinforcing fillers in geopolymers, enabling complex, waste-minimized architectural designs.<sup>150–153</sup> The use of rCFs 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, rCFs are utilized in the energy industry, including wind energy, energy storage (batteries and supercapacitors), solar energy, grid infrastructure, geothermal energy, and marine energy. rCFs were 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 Fig. 11a.<sup>155–157</sup> Upadhyayula *et al.* investigated the life-cycle environmental sustainability of blades incorporating pristine CF and rCF

Table 2 Summarization of various applications of rCFs in a wide range of sectors

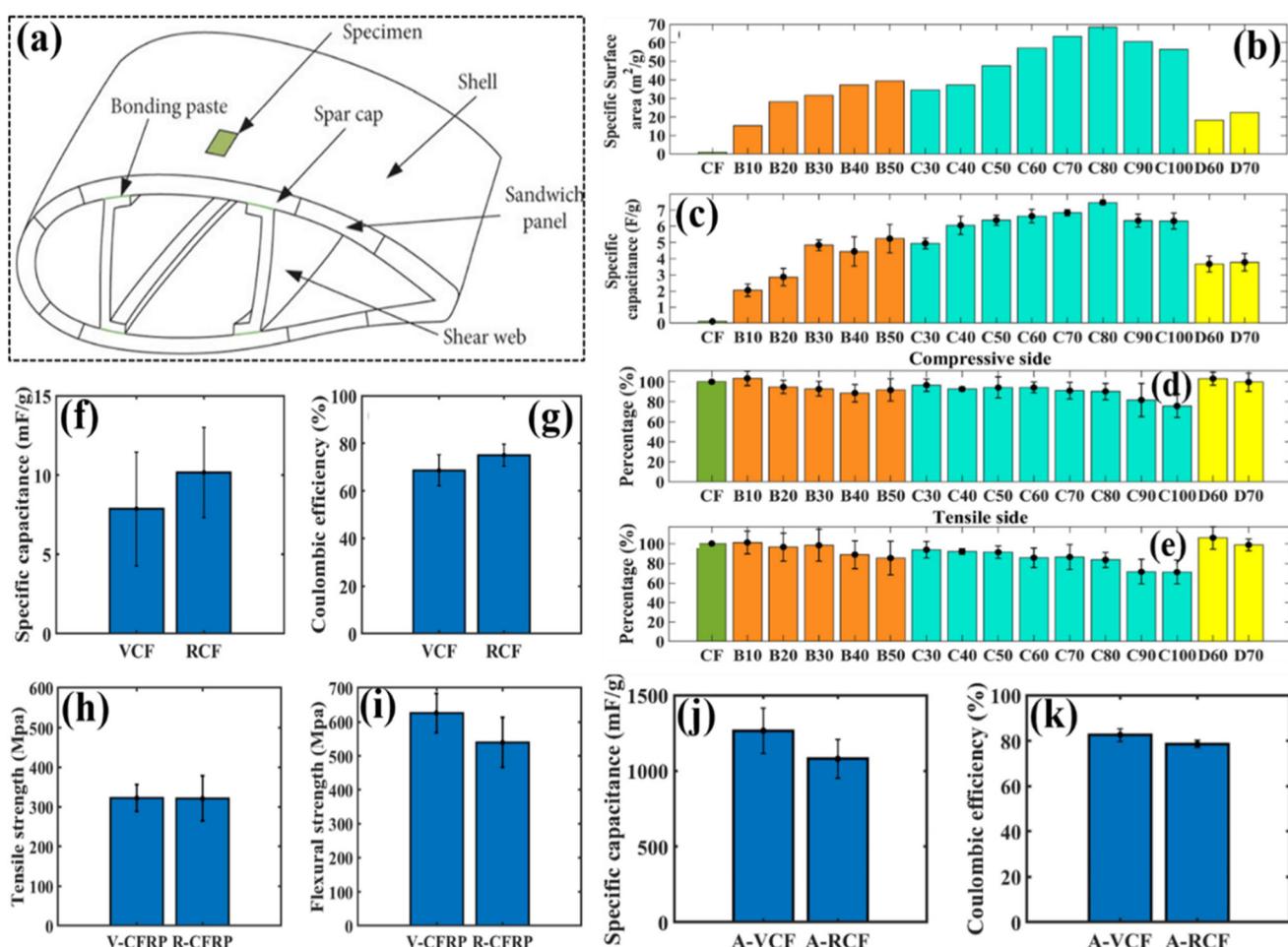
Sectors	Applications	Benefits	Ref.
Automotive	Engine covers, interior parts, structural components, and bumper beams	Weight reduction and cost savings	35
Aerospace	Fuselage, wings, tails, landing gears, seat frames, and interior panels	Light weight, reduced material costs, and environmental sustainability	141 and 154
Construction	Concrete reinforcement, bridges, and architectural panels	Improved durability, corrosion resistance, and 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 and lower production emissions	155–158
Electronics	Consumer electronics casings, heat sinks, and EMI shielding components	Thermal conductivity and electromagnetic protection	159



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.<sup>156</sup> The use of rCFs contributed to circular economy goals to circular economy goals by transforming the CFRP wastes into superior renewable energy products. rCFs have 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.*<sup>157,158</sup> used rCFs and activated them at  $\sim 700$  °C for  $\sim 80$  minutes, resulting in a specific surface area of  $68.39\text{ m}^2\text{ g}^{-1}$ .<sup>160</sup> This work reports an affordable method for recycling CFs and assembling them into energy storage devices, thereby increasing the reuse value. Mechanical and electrochemical analyses were conducted, and the obtained specific capacitance of the rCF-based device ( $7.87\text{ mF g}^{-1}$ ) is almost similar to that of virgin CFs ( $10.17\text{ mF g}^{-1}$ ). They also fabricated a unibody multifunctional energy storage composite (UBMES) and investigated the electrochemical and mechanical properties, as depicted in Fig. 11b–k.<sup>160</sup>

The results indicate that the utilization of rCFs by replacing pristine CFs retained both properties. This research opens up new avenues for utilizing recovered CFs in the energy storage industry. rCFs can be utilized as a reinforcing agent to fabricate liners that have improved burst pressure resistance in a Type IV hydrogen tank.<sup>160</sup>

However, the recycled and recovered fibres from the CFRP waste are widely used in other energy sectors as follows: rCFs replaced aluminum solar panels to reduce the weight and installation costs; rCF composites are utilized in geothermal reservoir liners and tidal turbine blades because of their saltwater resistant nature and in transformer and switchgear components due to their high dielectric constant and thermal stability.<sup>161–164</sup> rCFs can be transformed into fillers 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 materials were crucial.<sup>165–171</sup> This substitution promotes ecological viability by decreasing the dependency on virgin resources and minimizing carbon emissions.



**Fig. 11** (a) Components of the turbine blade. Reproduced with permission from ref. 157. (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. 160.



## 6. Life cycle assessment (LCA) and economic viability

To figure out the affordability and prospective market of rCFs, 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.<sup>20</sup> 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 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.<sup>172</sup> The different types of conventional and advanced recycling methods are discussed in detail. LCA studies suggest that conventional disposal methods (landfilling and 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.<sup>173</sup> 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.<sup>174</sup> Advanced recycling methods, such as catalytic solvolysis and microwave-assisted strategies, have shown 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. The global warming potential (GWP) impact results suggest that solvolysis and electrochemical techniques can reduce GHG emissions during the FRP life cycle.<sup>175</sup> 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 rCFs may exhibit reduced mechanical properties, it remains viable for low to medium-performance applications such as automotive interiors, panels, and construction boards. Although the recovered fibers and fillers exhibit 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.<sup>174-176</sup> 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.<sup>154,177</sup> 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 TRLs), but is primarily restricted to down-cycled items. Pyrolysis and solvolysis function at a medium TRL, demonstrated at the pilot scale. On the other hand, new technologies like vitrimer composites and enzymatic degradation are still at low TRLs 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.<sup>178,179</sup> This approach represents the frontier of materials design, creating truly adaptive structural components.

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 composites 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 evaluation protocols are necessary for rCFs to



**Table 3** Comparative analysis of CFRP recycling technologies

Recycling methods	TRL	Estimated energy consumption (MJ kg <sup>-1</sup> )	Fiber retention (%)	Qualitative cost analysis	Waste generation	Ref.
Mechanical recycling	9	5–15	60–80	Low	Dust and short fibers	180
Conventional pyrolysis	7–8	40–80	80–90	Medium-high	VOCs, char, and bio-oil	181
Microwave-assisted pyrolysis	5–6	20–40	85–95	Medium	VOCs	182
Solvolytic	6–7	25–50	90–98	Medium-high	Chemical solvents and wastewater	183–185
Catalytic solvolytic	4–5	20–35	92–98	High	Catalyst residues and solvents	185
Biological recycling	2–3	5–15	95–99	Low (potential)	Biomass and nutrients	186
Vitrimer composites	3–4	15–30	98–100	Medium-high	Minimal	115, 116, 187 and 188

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 rCFs 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 rCFs. 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 the 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

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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