A comprehensive overview of the potential of recycled carbon fiber from composite waste: reclamation, remanufacturing, and performance

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A B S T R A C T

The widespread adoption of carbon fiber–reinforced polymers (CFRPs) across high-performance sectors such as aerospace, automotive, wind energy, and construction has significantly increased the global demand for carbon fibers (CFs). However, the energy-intensive production process and growing volume of end-of-life (EoL) CFRP waste present significant environmental and economic challenges. This review offers a comprehensive analysis of the state of the art in carbon fiber recycling, focusing on the reclamation, remanufacturing, and reuse of recycled carbon fibers (rCFs) to support a sustainable circular economy. These waste streams are projected to grow substantially, driven by the decommissioning of wind turbines and aircraft. The valuable fibers are lost in traditional waste management practices, such as landfilling and incineration. Landfilling is also detrimental to the environment and unsustainable. Hence, recovering CFs through recycling is essential for minimizing environmental impacts and preserving material value.

This review presents a comprehensive assessment of recycling technologies, including mechanical, thermal, chemical, and emerging methods. Each technique is assessed based on quantified fiber retention, energy efficiency, scalability, and technological readiness. The study further explores remanufacturing technologies for rCFs, detailing their transformation into intermediate forms suitable for reuse. The alignment of discontinuous fibers is critical for maximizing mechanical performance. Analytical and numerical modeling tools applied to predict fiber orientation, alignment efficiency, and composite behavior are included. In addition to technical insights, the article integrates economic viability, quality assurance, and life cycle assessment (LCA) to evaluate environmental performance, supporting market acceptance and regulatory compliance by quantifying the sustainability advantages of rCFs.

1. Introduction

High-performance carbon fiber–reinforced polymer matrix composites (CFRP) are replacing traditional structural materials in various engineering fields, gaining prominence in the aerospace, automotive, marine, energy, construction, sport and leisure, and medical industries. The increasing popularity of CFRP can be attributed to its low density, superior specific mechanical properties, outstanding fatigue performance, thermal and electrical conductivity, and design freedom. Since the early development of carbon fibers (CF), the utilization of CFRPs has increased markedly, resulting in a global demand for CFRPs of around 181 kt per annum. The current compound annual growth rate (CAGR) of

the CF composite market has been approximately 12.5% over the last two decades (Zhang et al., 2023), and trends indicate that demand for CFRPs will continue to grow. CFRPs are crucial in meeting more stringent global greenhouse gas emission (GHG) standards, carbon dioxide (CO_2) neutrality legislation, and mitigation measures. Lightweight composites offer advantages in renewable energy sectors like wind, solar, and hydrogen. To exploit the sustainability benefits of carbon fiber composites, we need to manage the waste generated after production and at the end of life (EoL) of components. As the first generation of mass-produced CFRP structures reach the end of service, developing efficient recovery and recycling solutions has become a critical priority for the composites industry.

CFRP composites represent high technical value because the production of CF is an energy- and cost-intensive process requiring 198–704 MJ/kg (Zhang et al., 2023; Meng et al., 2018). Recovering used CF can significantly reduce the potential environmental impact and help meet the growing demand for CF, as recycled carbon fiber (rCF) re-enters the value chain as a potential reinforcing material. However, managing waste containing CFRP is a complex issue that poses numerous engineering challenges. During waste management, numerous input and output parameters influence recycling, complicating circular material use in the composite industry. Technical challenges arise due to the complex composition of CFRPs, consisting of a combination of reinforcing fibers, matrix materials, fillers, inserts, additives, and coatings, making effective separation and recovery challenging (Pakdel et al., 2021b). Thermoset matrices, such as epoxy resins, further complicate recycling, as their cross-linked structure prevents remelting and requires chemical or thermal degradation to recover the fibers. However, remelting can be achieved by applying thermoplastic matrices (Bernatas et al., 2021; Pegoretti, 2021). Although recycling is expected to lower energy consumption relative to the production of virgin carbon fiber (vCF), many current recycling technologies remain energy-intensive, which undermines their economic viability (Meng et al., 2018; Pakdel et al., 2021b; Yang et al., 2012, p. 20). Additionally, the absence of sorting mechanisms for composite waste leads to substandard quality, significant variations in recovered fiber properties, and poor reproducibility, resulting in inferior mechanical performance compared to virgin materials and consequently limiting the application of recycled CFRP products primarily to non-structural components (Bernatas et al., 2021; Pakdel et al., 2021b). Moreover, the absence of standardized recycling processes and quality control measures leads to variability in material properties, creating variability in their performance (Yang et al., 2012). Logistical challenges arise since CFRP waste is dispersed and its volume is relatively low compared to metals and non-reinforced polymers; this makes collection and recycling difficult and increases costs (Bernatas et al., 2021). Addressing these challenges requires improved and more efficient recycling technologies as well as enhanced material quality, which would, in turn, improve the market acceptance of recycled CFRPs.

The increasing volume of CFRP waste is generated from two primary sources: production waste and EoL components, such as decommissioned aircraft parts, wind turbine (WT) blades, and automotive structures, and manufacturing waste, which includes excess material and defective products discarded during production (Borjan et al., 2021). Landfilling occupies valuable space, resulting in a loss of high-performance material that could be recovered and reused. Incineration, while reducing waste volume, may lead to the release of GHG and potentially toxic byproducts, exacerbating environmental pollution. Many studies report waste generation in terms of CFRP mass, including fibers and matrix, rather than CF mass alone. Since CFRPs typically contain 55–65 wt% carbon fiber in structural applications, a conversion factor must be applied to estimate the fiber-only quantities. Throughout this review, we explicitly distinguish between CFRP and CF masses, converting to fiber-only values when reporting materials balances. Based on recent reviews and stock-flow projections (Borjan et al., 2021; Danish et al., 2022; Heidarian et al., 2024; Isa et al., 2022; Khurshid, et al., 2019; Lefeuvre et al., 2019, 2017; Zhang et al., 2020), the global quantity of CF waste in 2024 is estimated at around 50 kt/year, with a plausible range of 35–65 kt/year. This arises from manufacturing scrap (25–45 kt/year) which is commonly cited 30–40% waste fraction during production (Borjan et al., 2021; Isa et al., 2022; Zhang et al., 2020), and EoL waste (10–20 kt/year). Thus, while manufacturing scrap remains the dominant source of rCF feedstock today, EoL volumes are entering the waste stream at a scale that will reshape recycling priorities in the upcoming years. This increase is driven by the anticipated decommissioning of 6,000 to 8,000 commercial aircraft by 2030, each contributing over 20 tons of CFRP waste (Longana et al., 2016; Ribeiro and Gomes, 2015; Zhang et al., 2020). Cumulative waste arising from

the wind energy and aerospace sectors alone is predicted to reach 983 kt of CFRP waste by 2050. Assuming a conservative mass fraction of 60 wt %, this corresponds to 590 kt of carbon fibers, underscoring the magnitude of future recycling demand.

Given that the global demand for CFRP reached 199,000 tons in 2022, the current production capacity of rCF addresses only a small fraction of the total composite waste generated (P.-Y. Chen et al., 2023). The current global recycling capacity of CFRP is approximately 6,120 tons per year. Key companies like Carbon Conversions Inc. and Gen2-Carbon Ltd. (former ELG Carbon Fibre) produce 2,000 tons/year each, followed by CFK Valley Stade Recycling (1,000 tons/year), V Carbon (1100 tons/year), Thermolysis Co., Ltd. (700 tons/year), Alpha Recyclage Composites (300 tons/year), and Curti SpA (120 tons/year). This underscores the need for a substantial expansion of recycling capacity to manage the increasing volumes of CFRP waste projected in the coming decades. Despite challenges in quality consistency and processing efficiency, CFRP recycling offers substantial environmental and economic benefits, reducing lifecycle emissions and enabling circular economy solutions (Naqvi et al., 2018). Recently, several initiatives and collaborative projects have started to develop and scale up CFRP recycling to an industrial scale. Key developments include efforts by organizations such as the Aircraft Fleet Recycling Association (AFRA) (McConnell, 2010), PAMELA (Ribeiro and Gomes, 2015), or the CleanSky2 to establish best practices for aircraft disposal and recycling, as well as technological advancements by Boeing and Airbus to improve the eco-efficiency of the production of aircraft materials (Job, 2013).

Integrating recycling considerations into the design phase of CFRP products leads to minimizing material and energy consumption while addressing EoL challenges. A synergistic collaboration and knowledge transfer between designers and recyclers enables the industry to cope with the economic and environmental challenges posed by CFRP recycling (Dauguet et al., 2015; Pompidou et al., 2013). There is a need to develop a robust recycling network to facilitate circular material flow, improve product lifecycle management, and expand market opportunities for recycled CFRP (rCFRP) (Hagnell and Åkermo, 2019). However, quality assurance remains a challenge due to the variability in the properties of recycled fiber. Therefore, standardized testing protocols and enhanced communication are needed between industry stakeholders. A more interconnected lifecycle approach will be essential for improving sustainability in CFRC applications (Pompidou et al., 2013). Another strategy for boosting sustainability in the CFRP industry is extending the lifespan of structures using self-monitoring and self-healing mechanisms (Cohades et al., 2018). These enable CFRP components to repair damage autonomously or semi-autonomously, reducing maintenance costs, enhancing reliability, and minimizing material waste. Valuable tools such as life cycle assessment (LCA) can contribute to the broader use of rCF by quantifying its environmental and economic benefits, including reduced energy consumption and CO_2 footprint compared to vCF (Bianchi et al., 2023, 2021; Giorgini et al., 2020; He et al., 2023). The results of LCA underscore the environmental and economic benefits of rCF and, therefore, support its market acceptance. Additionally, LCA optimizes manufacturing and recycling processes by identifying energy and emissions hotspots, improving efficiency, and enhancing material performance. Informing decision makers and promoting standardization enhances the market value of rCF, hence circular material use in the composite industry.

Recently, several review articles have been published on CFRP recycling (Asmatulu et al., 2014; Barnett and Ghossein, 2021; Borjan et al., 2021; Gagliardi et al., 2021; Heidarian et al., 2024; Khurshid, et al., 2019; Li et al., 2024; May et al., 2021; Oliveux et al., 2015; Pakdel et al., 2021b; Pimenta and Pinho, 2011; Singh et al., 2017; Utekar et al., 2021; Wang et al., 2019a; Yazdanbakhsh and Bank, 2014; Zhang et al., 2020), reflecting the growing interest in sustainable composite waste management. These reviews (Asmatulu et al., 2014; Barnett and Ghossein, 2021; Borjan et al., 2021; Gagliardi et al., 2021; Heidarian et al., 2024; Khurshid, et al., 2019; May et al., 2021; Oliveux et al., 2015;

Pakdel et al., 2021b; Pimenta and Pinho, 2011; Singh et al., 2017; Utekar et al., 2021; Wang et al., 2019b; Yazdanbakhsh and Bank, 2014; Zhang et al., 2020) cover various fiber reclamation and remanufacturing methods, highlighting their advantages, challenges, and potential applications. A recurring theme is the need for optimized recovery techniques that preserve fiber integrity while ensuring economic feasibility. Additionally, many reviews emphasize the role of circular economy principles in integrating rCF into new composite products. The literature also identifies gaps in scaling up recycling technologies, standardizing material characterization, and developing industry-wide regulations to support the commercialization of rCF.

While previous reviews have largely catalogued reclamation and remanufacturing methods, this present study provides a more integrated, system-level perspective on how rCFs can achieve high-performance composite applications. CFRP recycling is an emerging and rapidly evolving field, and each new scientific result contributes to widening the collective understanding of the complete value chain, from waste generation to reclaimed fiber quality, remanufacturing efficiency, and final composite performance. We focus on these aspects because progress remains fragmented: even when high-quality fibers are recovered, remanufacturing limitations often prevent their full mechanical potential from being realised. This review therefore (i) systematically compares recent advancement in fiber-reclamation technologies using quantitative metrics such as retained single fiber properties, energy efficiency and scalability; (ii) evaluates remanufacturing routes that govern fiber alignment, hybridization and achievable fiber volume fractions; (iii) examines analytical and numerical modelling approaches that provide predictive insight into rCFRP behavior; and (iv) surveys emerging application domains and industrial capabilities. These combined elements provide a more comprehensive and actionable synthesis and clarify how each stage of the recycling chain influences the final performance of rCFRPs. Importantly, by consolidating quantitative performance data across the value chain, this review establishes a reference benchmark that enables future studies to position new results relative to previous efforts. Together, these elements build a coherent understanding of the entire rCF value chain, identify key technical bottlenecks limiting structural performance, and outline future research needs such as tighter reclamation process protocol, standardized testing protocols, and integration of life cycle analysis (LCA) with predictive modelling. Ultimately, the goal is to clarify how rCF can transition from low-value, down-cycled uses toward reliable, high-performance applications within a circular composites economy.

2. Recycling technologies and properties of reclaimed carbon fibers

Conventional end-of-life approaches such as landfilling and incineration of carbon-fiber-reinforced polymer (CFRP) waste are becoming increasingly unsustainable from both economic and environmental perspectives. Landfilling results in the permanent loss of valuable carbon fibers (CFs) and poses potential leaching risks to soil and groundwater. Although it can temporarily store CFRP waste, available capacity is limited. Several countries, such as the UK and Germany, have already banned this option in line with EU directives promoting the waste hierarchy of prevention, reuse, recycling, recovery, and disposal ("End of Life and Recycling | Composites UK," 2025; "Guidance on the interpretation of key provisions of Directive 2008/98/EC on waste," 2012). High landfill taxes (≈130–140 GBP/t in the UK) further discourage disposal. Incineration enables partial energy recovery through matrix combustion, yet it typically destroys the fibers and releases greenhouse gases and toxic ash (Oliveux et al., 2015). These regulatory and environmental pressures have collectively accelerated the search for viable recycling pathways.

Waste from composite production and different applications is a diverse mix of CFRP materials. For efficient reprocessing, adequate categorization and sorting are needed for various types of CFRP waste.

CFRP waste can be classified according to different criteria, which can help determine the most suitable recycling methods and potential applications for the reclaimed carbon fibers (rCFs). Critical elements of classification include the type of CF used in the reinforcement (intermediate modulus-IM, high modulus-HM, ultra-high modulus-UHM, low modulus-LM, high strength-HS, super high tensile-SHT); the embedding thermoset or thermoplastic polymer matrix materials; and the source of waste based on application.

According to previous studies (Abdkader et al., 2017; Bernatas et al., 2021; Hagnell and Åkermo, 2019), the waste generated can be classified into three main groups. Group 1: Dry fiber waste consists of unused CFs from textile cutoffs and unused bobbins not impregnated with the polymer matrix. Group 2: prepreg waste is off-cuts from pre-impregnated CF textiles or expired prepreg rolls, where the CF reinforcement is impregnated with the resin, but curing is incomplete. Prepregs also typically include other polymers, such as backing and release films. Group 3: crosslinked CFRP waste consisting of cured and consolidated parts, which include EoL parts, trimmings, and other scraps. However, other authors emphasize factors such as value-chain position or geometry (Utekar et al., 2021). The diversity of these schemes illustrates a lack of standardization. While Hagnell and Åkermo (Hagnell and Åkermo, 2019) stress geometrical form as the decisive recycling determinant, Morin et al. (Morin et al., 2012) categorize waste by output quality, distinguishing primary, secondary, and tertiary recycling. This contrast highlights an unresolved tension between input-based and performance-based classification approaches, representing a crucial methodological gap in achieving harmonized waste management. Comparative analyses show that post-industrial waste is far easier to recycle than post-consumer waste. Its known fiber origin and low contamination enable near-closed-loop processing, whereas EoL products contain multiple materials, embedded metal inserts, or core structures that hinder fiber recovery (Asmatulu et al., 2014; Pimenta and Pinho, 2011; Utekar et al., 2021). Utekar et al. (Utekar et al., 2021) emphasize logistical barriers such as collection and sorting inefficiencies, while Asmatulu et al. (Asmatulu et al., 2014) focus on the design-for-disassembly challenge, arguing that poor integration decisions made during product design largely determine recyclability. Together, these perspectives reveal that CFRP waste management issues are as much systemic, rooted in supply chain and design practices, as they are technical. A consistent conclusion across studies is that the cross-linked thermoset matrix remains the primary barrier to efficient recycling (Utekar et al., 2021; Asmatulu et al., 2014; Pimenta and Pinho, 2011; Zhang et al., 2020; Oliveux et al., 2015). While Oliveux et al. (Oliveux et al., 2015) and Zhang et al. (Zhang et al., 2020) emphasize the chemical stability that prevents matrix reprocessing, Pimenta and Pinho (Pimenta and Pinho, 2011) quantify how this intractability compromises fiber strength recovery.

State-of-the-art CF reclamation technologies are categorized into mechanical, thermal, chemical, and other processes (Fig. 1, Table 1). Previous reviews have comprehensively covered these methods' technical, economic, and environmental aspects. The present study compares the retained mechanical properties of single fibers after reclamation (Table 1, Fig. 2, Fig. 3).

2.1. Mechanical recycling

Mechanical recycling relies on size reduction through shredding, crushing, grinding, or milling to produce reusable CFRP fragments (Pakdel et al., 2021b). The resulting particle size distribution depends on process parameters such as crushing-disc distance, rotor speed, and sieve-grate size, all of which control fiber length and shape. In thermoplastic systems, these chips can be directly remolded by injection or compression molding after plasticization, providing a comparatively simple, solvent-free pathway for material reuse.

Early work by Schinner et al. (Schinner et al., 1996) demonstrated that grinding CF-PEEK composites could enhance the properties of bulk
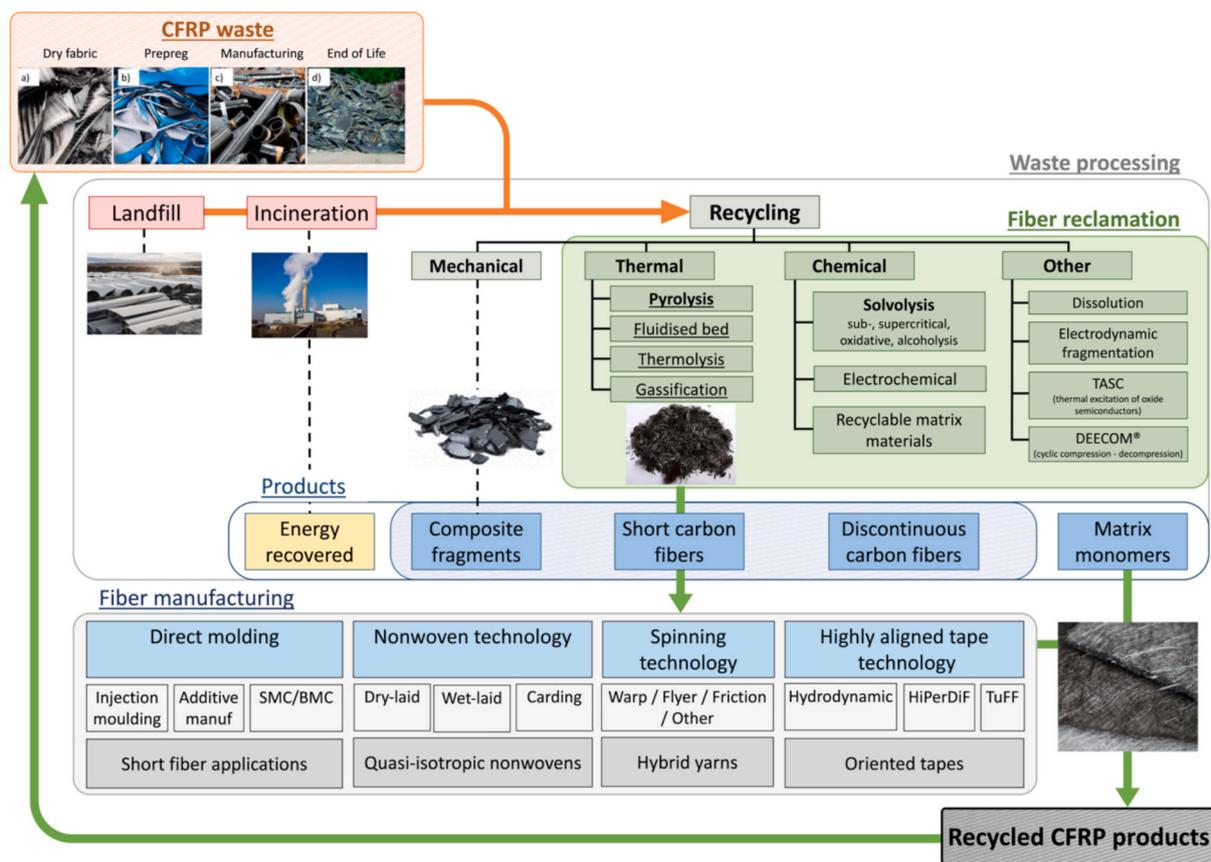
Fig. 1. Carbon fiber reinforced polymer composite (CFRP) waste management framework: waste sources, reclamation processes, recycled products, remanufacturing pathways, closing the material loop.

and sheet molding compounds (BMC/SMC). Subsequent studies highlighted the limits of such gains. Okayasu et al. (Okayasu et al., 2013) reported that adding milled rCF to ABS improved tensile and fatigue strength only up to a threshold, beyond which fiber agglomeration reduced strass-transfer efficiency. Evens et al. (Evens et al., 2019) demonstrated that repeated mechanical recycling reduces fiber length bellow a critical threshold (Lc), leading to stiffness and strength losses dominated by fiber pull-out. These studies indicate that short-fiber systems can exploit rCF reinforcement only while sufficient fiber length is retained.

Energetically, mechanical recycling is favorable: milling requires only 0.21–2.03 MJ/kg (Howarth et al., 2014), far less than thermal or chemical routes. This benefit is offset by substantial fiber shortening and morphology variability, creating a trade-off between low energy use and reclaimed fiber quality. Colucci et al. (Colucci et al., 2015) further showed that matrix durability for PA66-based CFRP, such as UV aging, can influence performance losses as much as milling itself. Economic assessments echo these limitations. While mechanical recycling is cost-effective and scalable (Li et al., 2016), it rarely produces fibers suitable for high-value applications and is therefore mainly used as a pre-processing step before higher-quality reclamation methods.

2.2. Thermal methods

Thermal reclamation processes decompose the CFRP polymer matrix at elevated temperatures and are particularly effective for thermosetting composites (Karuppannan Gopalraj and Kärki, 2020; Oliveux et al., 2015; Pimenta and Pinho, 2011; Zhang et al., 2020). These methods are commonly classified into pyrolysis, pyrolysis-based thermal oxidative processes, fluidized bed, and gasification methods (Hecker et al., 2023b).

Pyrolysis is a thermal decomposition treatment (TDT) carried out in an inert atmosphere, during which the matrix breaks down into smaller molecules, char, condensable oil and tar, and non-condensable volatiles (Ge et al., 2023; Hecker et al., 2023b; Meyer et al., 2009). Although literature reports temperatures between 300–800 °C, this broad range reflects experimental exploration rather than practical operation (Hecker et al., 2023b; Pickering, 2006; Zhang et al., 2020). Bellow 400–450 °C decomposition is incomplete, while the effective temperature window lies around 450–600 °C, for epoxy and polyester-based CFRPs, 500–550 °C is widely reported as optimal, yielding 70–95% strength retention and clean fiber surface. Above 600–650 °C oxidation accelerates and causes fiber thinning, pitting, and severe strength loss, with values falling below 50% at 700–800 °C. fiber quality is highly sensitive to heating rate, dwell time and post treatments (Nahil and Williams, 2011). Reported modulus retention ranges from 75 to 105%, while strength varies between 25–110% due to process-dependent scatter (Table 1, Fig. 2). Residual char and removal of original sizing can reduce interfacial shear strength (IFSS), so most studies employ controlled oxidative post-treatments to achieve clean fiber surfaces (Hecker et al., 2023b; Kim and Kim, 2023; López et al., 2013; Mazzocchetti et al., 2018; Meyer et al., 2009; Pimenta and Pinho, 2012).

Nahil et al. (Nahil and Williams, 2011) showed that increasing pyrolysis temperature from 350 to 700 °C improves resin decomposition but progressively degrades the fibers, defining the narrow operating window later confirmed by Manis et al. (Manis et al., 2015). Matsuda et al. (Matsuda et al., 2022) modelled the retained strength distributions, while Guo et al. (Guo et al., 2022) and Mazzocchetti et al. (Mazzocchetti et al., 2018) demonstrated that two-step pyrolysis-oxidation and pyro-gassification can achieve up to 90% strength retention and improved IFFS through controlled secondary oxidation. Process-optimization studies, such as the machine-learning approach of

Table 1

Comparing technical benchmarks of carbon fiber reinforced plastic composite (CFRP) reclamation technologies in terms of process conditions, retained single fiber properties, primer energy demand (PED), technological readiness (TRL), estimated costs and technical maturity. References: (Ballout et al., 2022; Branfoot et al., 2023; P.-Y. Chen et al., 2023; Chin et al., 2024; Colombo et al., 2021; Deng et al., 2019; Hecker et al., 2023b; Heidarian et al., 2024; Isa et al., 2022; Kooduvalli et al., 2022; Lefeuvre et al., 2019, 2017; Lester et al., 2004; Ma et al., 2025; Meng et al., 2017b; Meng et al., 2018; Oliveux et al., 2015; Pakdel et al., 2021b; Pickering, 2006; Pimenta and Pinho, 2011; Qazi et al., 2021; Ren et al., 2022; Sun et al., 2015; Teltschik et al., 2024; Wu et al., 2023; Zhang et al., 2024).

	Conditions	Retained strength of single CF (mean value %)	Retained modulus of single CF (mean value %)	Primary energy demand - PED (MJ/kg)	Technological readiness level TRL (median value)	Estimated cost range (€/kg)	Comments
CF production	-	100	100	120–250	1–9 scale	18–60	PAN and pitch based continuous CF production
Waste processing							
Landfill	Many countries ban landfilling of untreated/combustible fractions, so even if the per-kg price looks low somewhere, access to landfill may be restricted in practice (forcing incineration or recycling).	-	-	1.1	1–9 scale	0.10–0.15	Gate fee + landfill tax
Incineration	Incineration taxes: A growing number of countries apply incineration taxes (often €5–€80/t) to push waste up the hierarchy	-	-	1.7	1–9 scale	0.09–0.13	Gate fee + incineration levy
Recycling — Mechanical	Size reduction of CFRP waste into smaller particles through shredding, crushing, milling, or grinding, followed by fiber–resin separation and reclassification. Pre-treatment CFRP scrap is often cleaned and cut into manageable sizes (10–50 mm pieces). Metallic inserts or contaminants are removed magnetically or manually. Hammer or cutting mills: rotor speeds of 1000–3000 rpm, producing coarse flakes (~1–5 mm). Ball or impact milling: used for finer powders and short-fiber recovery (fiber lengths 0.1–2 mm). Cryogenic milling (liquid nitrogen) is occasionally employed to reduce resin embrittlement and minimize fiber length degradation.	-	-	1.0–5.0	1–9 scale	1.0–3.0	Industrially mature, low energy, short fiber yield
Recycling — Thermal — Pyrolysis	Temperature range 450–600 °C, with an optimal window 500–550 °C for epoxy- and polyester-based CFRPs. Below 450 °C - incomplete resin decomposition and residual char. Above 600–650 °C - oxidative degradation of fibers, diameter reduction, and strength losses. Dwell time typically 30–120 min depending on reactor design, laminate thickness, and oxygen control. Shorter times (≤60 min) are preferred to limit fiber damage. Extended dwell times (>90 min) can accelerate surface pitting and tensile strength reduction. Conducted in an inert or low-oxygen atmosphere (N₂, Ar, or vacuum). Some semi-oxidative setups intentionally introduce small O₂ concentrations (<1–3%) to assist resin burnout post-pyrolysis. Heating rate commonly 5–20 °C/min, slower rates favor uniform resin decomposition and minimize thermal gradients.	76.93	92.78	37.4–115.9	1–9 scale	5.0–12.0	Commercially deployed rCF cost range
Recycling — Thermal — Fluidized bed	Temperature range 450–550 °C, with 500 °C as the most commonly cited. Below 450 °C incomplete matrix removal and fiber contamination. Above 550–600 °C onset of carbon fiber oxidation and strength loss. Air or controlled oxidative gas stream (partial oxidation) fluidizing a silica sand bed. Silica sand (particle size 200–600 μm) fluidized by air or N₂ at 0.4–0.6 m/s superficial velocity. The bed provides efficient heat transfer and abrasion of resin residues. Processing time generally 2–10 minutes for chopped composites or 10–20 minutes for larger pieces. Post treatment: acid washing or mild oxidation to remove inorganic residues and restore surface functionality. Tensile strength retention depends on oxygen concentration and dwell time. Some reports note surface roughening due to particle collisions in the bed, improving IFSS in new composites.	76.59	98.47	6.0–10.3	1–9 scale	6.0–10.0	Pilot/semi-industrial scale, moderate cost
Recycling — Thermal — Gassification	Temperature range 700 - 900 °C, with 800 °C being the most common compromise. Below 700 °C, incomplete resin burnout occurs; above 900 °C, oxidation severely degrades the fibers. Controlled partial oxidation or steam/air mixture to sustain endothermic gasification and produce CO + H₂-rich syngas. Operation is under sub-stoichiometric oxygen conditions (λ ≈ 0.2–0.4) to prevent complete combustion. Process time 5–20 min depending on particle size and gas velocity. Shorter residence times can leave residual matrix; longer times risk fiber thinning due to oxidation. Post-treatment acid washing (e.g., HCl, HNO₃) or mild oxidation (450–500 °C) is applied to remove ash and restore surface chemistry.	74.86	104.42	6.0–20.0	1–9 scale	5.0–9.0	Early scale, efficiency potential, fiber damage trade-off
Recycling — Thermal — Microwave assisted pyrolysis	Temperature range between 450–600 °C, with 500–550 °C identified as optimal for epoxy-based CFRPs. Microwave irradiation provides volumetric heating via interaction of the electromagnetic field with conductive CFRP and susceptor materials (e.g., SiC, graphite). Heating rates typically 50–100 °C min⁻¹, far exceeding conventional furnace rates. Reaction times are 10–30 min, often followed by post-oxidation at 450–550 °C for 10–30 min in air to remove residual char. Conducted under inert N₂ or Ar atmosphere during microwave heating to prevent oxidation, with optional secondary oxidation step for surface cleaning. Lower total energy input and shorter processing time compared with conventional pyrolysis. Reduced fiber damage and enhanced surface quality. Particularly effective for thick or complex CFRP components where uniform heating is critical.	69.72	108.46	10–30 (typically 30-50% less than pyrolysis)	1–9 scale	4.0–10.0	Pilot/early stage, energy savings compared to conventional pyrolysis
Recycling — Chemical — Solvolysis	Temperature commonly in the range 200–300 °C, sometimes up to 350–400 °C, depending on solvent and pressure. Lower temperatures favor milder chemical attack and limit fiber degradation. High pressure (often 5–20 MPa or higher) to keep the solvent in liquid or supercritical state (e.g. water, alcohols) for efficient polymer dissolution. Sometimes alkaline, acidic, or catalytic additives are used to enhance resin cleavage. Process time typically 1–4 hours, depending on resin type, temperature, and solvent. Common solvents: supercritical water (hydrothermal), sub-/supercritical alcohols (e.g. ethanol, methanol), glycol mixtures, or ionic liquids. Solvent-to-CFRP mass ratios often range from 5:1 to 20:1 to ensure sufficient penetration and resin dissolution. After solvolysis, the dissolved resin or monomers are separated, and recovered fibers are washed, dried, and sometimes mildly oxidized or plasma cleaned to remove residual organics.	90.99	95.09	21–250	1–9 scale	10.0–25.0	High-pressure / solvent costs, but high-quality fiber
Recycling — Hybrid — Thermolysis	Typically uses a mild oxidative environment (3–7% O₂) rather than a fully inert atmosphere; the low oxygen helps decompose resin while minimizing CF oxidation. Resin decomposition begins around 230 °C; major matrix degradation occurs in 350–550 °C; CFs start oxidizing above 550 °C. Dwell time of 30 min is used as optimal for epoxy removal without over-oxidation. In thermolysis under oxygen, 11% mass loss begins at 230 °C, 38% between 350–550 °C (resin degradation), and carbon fiber oxidation starts above 550 °C (1.1% residual mass) in experiments.	81.77	92.62	0.8–7.9	1–9 scale	4.0–8.0	Mostly lab scale
Recycling — Other — Electrodynamic fragmentation	Submerging CFRP waste in a water bath between electrodes and applying pulsed high voltage (on the order of 50–200 kV) with fast rise times (<5 microseconds) to generate electrical discharges (plasma channels) within the material. The discharge deposits high energy density (~10–100 J/cm³) locally, creating shock waves, rapid heating (up to ~10,000 °C) and extremely high pressures (10⁴ MPa) that exceed the matrix strength, thus fracturing the composite along interfaces. Because the matrix and fiber dielectric breakdown differ, EDF preferentially fragments along resin–fiber interfaces, delaminating the composite structure with limited dust or fine particle generation. In a demonstration by Roux et al. (cited in the draft), helicopter door hinge components (CF-PEEK) were fragmented via EDF over six cycles with 60% of the original mass converted into usable fragments, and the recovered parts retained ~83% of original mechanical properties.	62.87	-	0.7–8.0	1–9 scale	>20	Very early stage, high electricity load

Chen et al. (S. Chen et al., 2023), highlight the sensitivity of rCF quality to temperature and dwell time. Energy analyses o pyrolysis remains debated: Giorgini et al. (Giorgini et al., 2015) reported that pyrolysis by-products can cover up to 75% of energy demand, whereas Friederici et al. (Friederici et al., 2024) identified additional volatile fractions suitable for polymer synthesis, suggesting untapped potential for by-product valorization. Engineered recyclable resins (e.g., Elium®) allow nearly full fiber property retention (Bel Haj Frej et al., 2021). Cost analyses by Hagnell and Åkermo (Hagnell and Åkermo, 2019) estimated

pyrolysis at €10–23 kg⁻¹, with microwave-assisted variants (Lester et al., 2004; Ren et al., 2022; Salas et al., 2023) offering lower energy use and improved fiber quality, though scalability remains limited. Overall, studies converge on the importance of temperature control and oxidation management, yet differ in conclusions regarding energy self-sufficiency and optimal fiber treatment, underscoring the need for standardized benchmarking across pyrolytic routes.

Thermolysis operates in a low-oxygen atmosphere (3–7% O₂ in nitrogen) at temperatures around 600 °C, where controlled oxidation
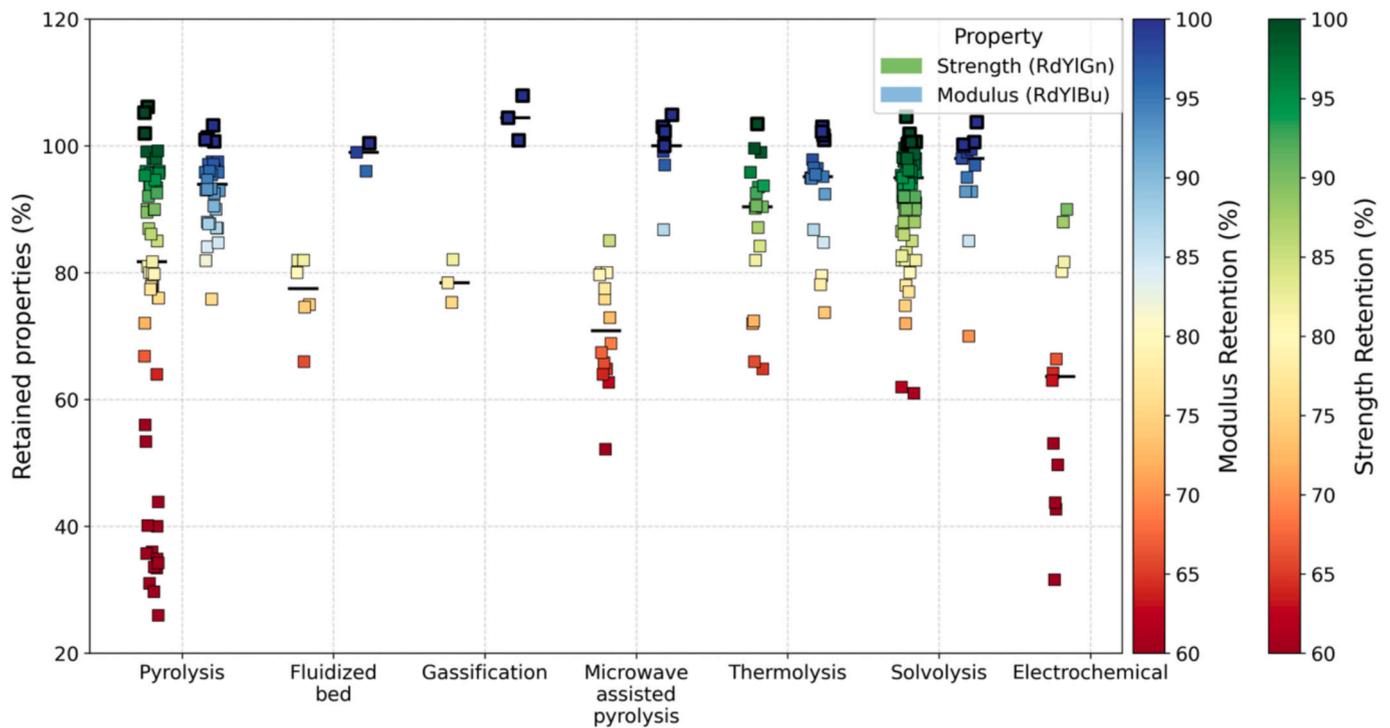
Fig. 2. Retained tensile strength and modulus of recycled carbon fibers (rCFs) compared to virgin carbon fibers (vCF, 100% benchmark), based on single-fiber tensile testing (SFTT) data reported in the literature. Variations reflect differences in process temperature, atmosphere, dwell time, and post-treatment conditions across studies. Cases reporting > 100% retained properties are indicated, corresponding to Weibull size effects arising from the removal of the outer fiber skin and associated thinning during reclamation. References: (Akonda et al., 2012; Branfoot et al., 2023; Cheng et al., 2020, 2019; Deitzel et al., 2019; Feng et al., 2023; Gagliardi et al., 2021; Gebhardt et al., 2021; Guo et al., 2022; Hecker et al., 2023b; Isa et al., 2022; Karuppannan Gopalraj and Kärki, 2020; Kim and Kim, 2023; Knappich et al., 2019; Lester et al., 2004; López et al., 2013; Manis et al., 2015; Matsuda et al., 2022; Nahil and Williams, 2011; Oliveux et al., 2015; Ozdemir et al., 2024; Pakdel et al., 2021b; Pimenta and Pinho, 2012; Ren et al., 2022; Salas et al., 2023; Sun et al., 2015; Tian et al., 2022; van de Werken et al., 2019; Verma et al., 2018; Wang et al., 2019b; Wei and Hadigheh, 2023; Yuan et al., 2017b; Zhang et al., 2020).

assists matrix decomposition. Reported retention levels range from 80 to 90% in modulus and 47–82% in tensile strength (López et al., 2013; Qazi et al., 2021). Gassification methods, which use higher temperatures and strongly oxidizing conditions, typically yield 75–82% strength retention with little change in modulus. Palola et al. (Palola et al., 2022) suggest that carefully tuned oxidative environments can preserve rCF properties well enough for reuse in thermoplastic composites. Hecker et al. (Hecker et al., 2023b) also reviewed superheated-steam variants used in gasification-type processes, highlighting their fiber quality, environmental performance, and economic potential. The fluidized-bed process combines convective heat transfer with abrasive resin removal using hot air and fluidized sand. Its energy demand is up to 75% lower than conventional pyrolysis (Meng et al., 2018; Hecker et al., 2023b; Pickering, 2006; Pickering et al., 2000). CFRP waste is shredded to < 20 mm chips and fed into a reactor containing fine silica sand, fluidized at 450–550 °C and 0.1–0.25 bar pressure to decompose the thermoset matrix without significant fiber degradation. Released rCFs are separates in a cyclone, while combusted off-gases recover heat for incoming air. Reclaimed fibers typically measure 5–10 mm in length.

2.3. Chemical reclamation

Chemical reclamation encompasses a broad set of processes that employ reactive solvents to depolymerize crosslinked matrices and recover clean carbon fibers. Solvolysis is the most versatile of these approaches, capable of selectively cleaving polymer networks under subcritical or supercritical conditions using water, alcohols, organic acids, or tailored reagent systems (Branfoot et al., 2023; Morin et al., 2012; Oliveux et al., 2015; Piñero-Hernanz et al., 2008; Tian et al., 2022; Zhao et al., 2023). Branfoot et al. (Branfoot et al., 2023) provide a

comprehensive overview of solvolytic chemistries for epoxies, polyesters, phenolics, and thermoplastic matrices. The breadth of oxidative, reductive, catalytic, and dynamic-covalent systems (Branfoot et al., 2023; Kuang et al., 2018; Rahman et al., 2023; Tian et al., 2022; Toldy et al., 2025; Wang et al., 2019a; Wang et al., 2019b; Zhang et al., 2021a; Zhao et al., 2023) has produced a wide range of outcomes for both fiber and polymer recovery (Li and Wang, 2025).

Supercritical water and alcohol solvolysis can recover fibers up to 99% strength retention (Table 1, Fig. 2), though this performance requires high temperature, high pressure, and complex solvent handling. Milder solvolysis routes (Ballout et al., 2022) reduce operational severity but typically cause partial property loss. Catalyst-assisted methods, such as the Ni–Pd/CeO₂ system of Huang et al. (Huang et al., 2025), demonstrate selective depolymerization at far lower temperatures (180 °C and 1 bar H₂), achieving near-complete resin removal and high monomer recovery.

Studies involving recycled CFRP show that solvolysis typically alters the fiber surface by removing sizing and changing functionality, which affects downstream interfacial performance. Dauguet et al. (Dauguet et al., 2015) and Ballout et al. (Ballout et al., 2022) documented such effects, reporting modest reductions in inter laminar shear stress (ILSS) and compression strength following supercritical and mild solvolysis, respectively. Research on recyclable matrices, including vitrimers and dynamic covalent bond networks, shows that these systems enable near-close-loop recovery with minimal fiber degradation (Feng et al., 2023; Gebhardt et al., 2021; Yu et al., 2016; Yuan et al., 2017a), in contrast to conventional epoxies requiring aggressive supercritical conditions. Hybrid thermo-solvolytic routes (Wei and Hadigheh, 2023) further illustrate how combining controlled pyrolysis with targeted solvolysis can achieve > 90% strength retention while reducing overall energy
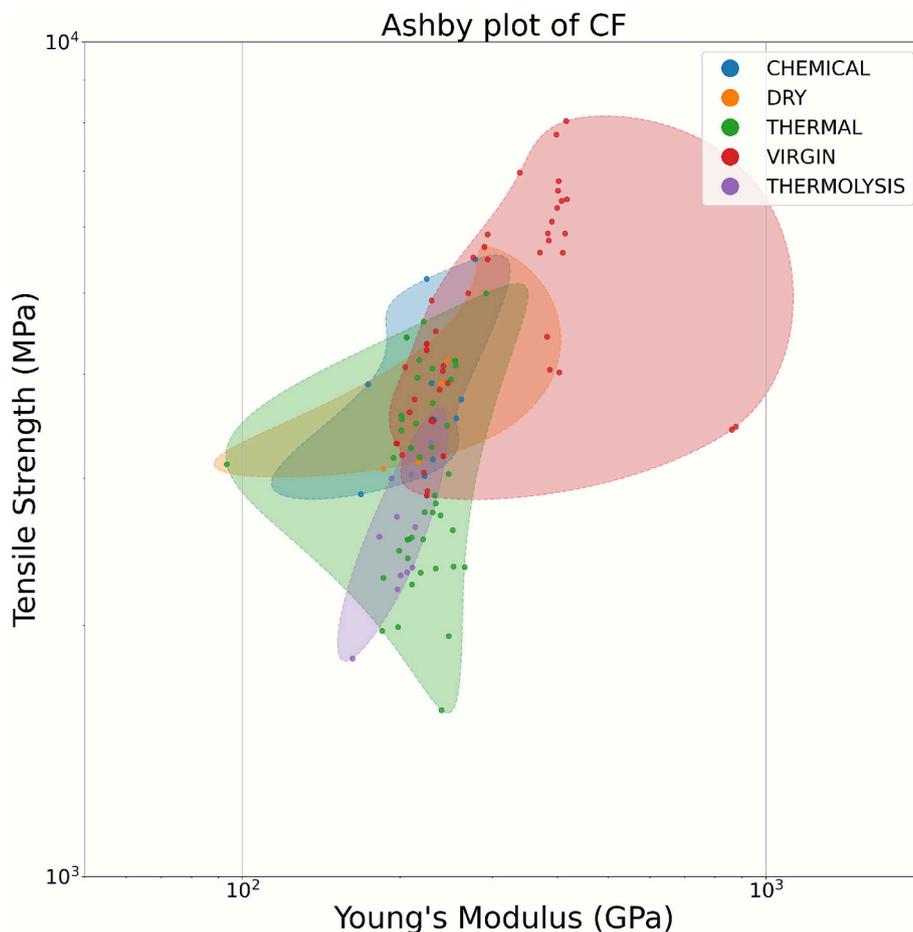
Fig. 3. Performance envelopes (strength vs. modulus) of reclaimed carbon fibers (rCF) produced by thermal, chemical, and thermolysis methods compared to benchmark virgin carbon fiber (vCF) based on single-fiber tensile testing (SFTT). Colored fields represent literature ranges; symbols indicate study-level reported properties. References: (Akonda et al., 2017, 2014, 2012; Aravindan et al., 2020; Barnett et al., 2022; Barnett et al., 2021a; Barnett et al., 2021a, 2021c; Cheng et al., 2022, 2020, 2019; Colombo et al., 2023; Deitzel et al., 2019; Feng et al., 2023; Finley et al., 2018; Gebhardt et al., 2021; Guo et al., 2022; Hasan et al., 2019; Hecker et al., 2023b; Hengstermann et al., 2020; Isa et al., 2022; Khurshid et al., 2020; Kim and Kim, 2023; Knappich et al., 2019; Kong et al., 2024; Lester et al., 2004; Liu et al., 2021; Longana et al., 2018, 2017, 2016; López et al., 2013; Manis et al., 2015; Matsuda et al., 2022; Mesquita et al., 2021; Nahil and Williams, 2011; Oliveux et al., 2015; Overberg et al., 2023; Ozdemir et al., 2024; Pakdel et al., 2021b; Pimenta and Pinho, 2012; Ren et al., 2022; Salas et al., 2023; Sun et al., 2015; Tian et al., 2022; Wang et al., 2019a; Wei and Hadigheh, 2023; Yu et al., 2015a, 2014; Yuan et al., 2017a; Zhang et al., 2020).

demand.

Electrochemical methods use an electric current and an electrolyte solution to depolymerize the resin matrix, which only applies to CFRPs due to their conductivity. The current and the concentration of the electrolyte significantly affect reclamation time and efficiency.

Sun et al. (Sun et al., 2015) demonstrated strength retention of 80% under optimized current and sodium chloride (NaCl) concentrations. Oshima et al. (Oshima et al., 2020) showed that high-voltage electrochemical treatment produces resin peeling in UD laminates via electrolysis-driven gas evolution, although excessive voltages can damage fibers. Matsuda et al. (Matsuda et al., 2024) found that combining electric pre-treatment with subsequent thermal decomposition enhances resin removal by promoting O_2 diffusion, but overstressing the fibers beyond 0.5 h of treatment leads to mechanical degradation.

2.4. Other fiber reclamation methods

Dissolution-based recycling uses selective solvents to physically separate polymers and fibers without altering their chemical structure. Unlike solvolysis, it preserves the molecular integrity of the matrix and operates under comparatively mild conditions. Knappich et al. (Knappich et al., 2019) demonstrated this using the CreaSolv® process,

successfully recovering both fibers and thermoplastic matrices (PA6, polyurethane, epoxy), highlighting potential for closed-loop recycling. However, reliance on proprietary solvents and extensive purification limits scalability. More recently, Sakai et al. (Sakai et al., 2024) introduced a nitric acid–hydrogen peroxide dissolution route that removes epoxy under aqueous, more environmentally benign conditions.

Beyond solvent-driven methods, several non-conventional physical and photonic processes aim to achieve rapid matrix removal. Electrodynamic fragmentation (Leißner et al., 2018; Roux et al., 2017) uses high-voltage plasma discharges to disintegrate composites, preserving fiber morphology but causing up to 17% mechanical loss. UV-assisted decomposition using CeO_2 semiconductors (Böhnke et al., 2020) enables localized resin removal within seconds at low energy input. Thermal excitation of oxide semiconductors (TASC) decomposes polymers via radical-driven oxidation at 350–500 °C, achieving 87–97% strength retention (Cheng et al., 2022, 2020, 2019; Mizuguchi et al., 2015), though precise radical control remains a challenge. Electrostatic shockwave and Joule-heating approaches (Tian et al., 2023) show rapid delamination capabilities but require further validation in terms of reproducibility and energy efficiency. The DEECOM® process (Hecker et al., 2023a; Norris et al., 2004), based on cyclic compression–decompression of superheated steam, has demonstrated effective resin removal, though broader industrial verification is still

needed.

2.5. Critical assessment of reclamation technologies

Rybicka et al. (Rybicka et al., 2016) evaluated the technological readiness levels (TRLs) of CF reclamation processes however, these assessments are now outdated, as the past decade has seen major technological advances. Currently, mechanical recycling is the most mature technology at the median value of TRL 8 (Gagliardi et al., 2021). Pyrolysis is also a well-established process at TRL 7–8 (Hecker et al., 2023b), and it has also been successfully used at an industrial scale worldwide. Other technologies, such as fluidized bed and microwave-assisted pyrolysis (Isa et al., 2022), are advancing toward commercial viability. However, they are still in the process of being fully optimized and validated for various applications, resulting in TRL 6–7 (Hecker et al., 2023b). Chemical processes, including solvolysis, are still developing and range between TRL 4–7 (Branfoot et al., 2023). Other emerging technologies like electrochemical recycling, high-voltage fragmentation, and cyclic compression-decompression are primarily at the research stage at TRL 3–4 (Pakdel et al., 2021b).

In addition to academic research, CFRP recycling is also receiving increasing attention in industrial practice. This is reflected in the increasing number of patents published on the subject. Colombo et al. (Colombo et al., 2021) provide a comprehensive patent technology roadmap for reclamation technologies. Their analysis shows that the industry experienced rapid expansion in the previous decade and is expected to continue growing until approximately 2040–2050. According to their technology maturity level (TML) assessment, mechanical recycling was the most mature route (61.51%), whereas thermal and chemical recycling were still in active growth phase (36.54% and 30.96%, respectively). It should be noted that these results reflect the status as of 2021, to date no subsequent studies have re-evaluated TML with comparable methodological depth, despite significant technological progress and new industrial entrants emerging since then. The findings highlight the need for further development of thermal and chemical technologies, particularly because most current reclamation routes operate in batch mode, limiting throughput and industrial integration. Advancing continuous or semi-continuous processes is essential for achieving the high processing volumes required by major sectors. However, technological advancement alone is insufficient. For recycling to deliver meaningful impact, the recyclates must be effectively reintegrated into the market, supported by consistent quality, certification pathways, and reliable supply chains. Thus, future progress depends not only on refining the recycling processes themselves, but also on ensuring that recycled materials can re-enter value chains at scale and with predictable performance.

Building on the broader trends identified above, the mechanical performance of reclaimed single fibers can be examined in more detail through the data compiled in Table 1, Fig. 2 and Fig. 3. Fig. 2 shows that most reclamation routes recover between roughly 70–95% of the vCF tensile strength and 80–100% of the tensile modulus at the single-fiber level, but with substantial scatter between individual studies. Thermal processes that operate within narrow temperature window and carefully controlled oxidation typically lie at the upper end of this band, whereas overly aggressive pyrolysis, gassification or long dwell time cause strength to fall below 60%. Chemical and hybrid thermo-solvolytic processes cluster in the high-retention regime, confirming that milder, more selective matrix removal is beneficial for preserving fiber integrity. A smaller group of data points exceeds the nominal 100% benchmark, which we attribute to the fiber-diameter paradox reported by Matsuda et al. (Matsuda et al., 2022). Removal of the outer, defect-rich skin reduces fiber diameter resulting in statistically higher strength and modulus. Performance envelopes for optimized thermal and chemical processes shown in the Ashby plot (Fig. 3) exhibit a substantial overlap with those of standard PAN-based vCFs, whereas mechanically degraded or over-oxidized fibers populate a distinct lower-left region with both

reduced single-fiber strength and stiffness. This separation allows a first-order classification of reclamation technologies according to the quality of the recovered reinforcement: processes whose envelopes lie closer to the virgin band can feed high-value structural applications, while those confined to the lower-performance region are more appropriate for non-structural uses. Importantly, the width of each envelope also reflects process robustness, as narrow fields indicate reproducible fiber quality, while broad fields suggest sensitivity to operating conditions. Fig. 3 contains fewer datapoints because many studies report only the retained percentage of the tensile strength and modulus after reclamation, without providing absolute single-fiber values. This highlights a persistent limitation in the literature, the lack of standardized reporting of qualified single-fiber properties, which restricts cross-study comparison and comprehensive benchmarking of rCF quality. Reclaimed CFs typically have inert surfaces that do not bond effectively with matrix materials, leading to weak IFSS and suboptimal composite performance. Surface treatments improve fiber–matrix adhesion by modifying fiber surfaces; Tiwari et al. (Tiwari and Bijwe, 2014) review methods like oxidation, plasma treatment, and gamma irradiation to enhance interfacial properties of rCFs. Subsequent studies have shown that the effectiveness and applicability of these techniques strongly depend on both the rCF reclamation route and the downstream remanufacturing architecture. Pyrolyzed rCFs are typically recovered without sizing and may carry residual char or surface defects; consequently, mild oxidation or plasma treatments are often used to clean and activate the surface, although excessive oxidation can lead to fiber strength degradation (He et al., 2020b). In contrast, solvolyzed rCFs are generally recovered with cleaner and more polar surfaces, making them better suited for matrix-specific re-sizing or grafting strategies rather than aggressive oxidative treatments (Burn et al., 2016). The choice of surface modification is also closely linked to the remanufacturing route: nonwoven rCF preforms require scalable, area-uniform treatments compatible with high-throughput web processing, whereas highly aligned tapes and oriented discontinuous fiber architectures are more sensitive to over-treatment due to their higher fiber volume fractions and load-transfer efficiency (Li et al., 2024). Recent work further highlights the potential of integrated recycling–surface-modification routes, where chemical recycling is combined with controlled surface functionalization to restore interfacial performance while preserving intrinsic fiber properties, offering promising pathways toward higher-performance rCFRPs (Li and Wang, 2025; Semitekolos et al., 2025).

Life cycle assessments (LCA) consistently indicate that recycling CFRP offers substantial environmental advantages over vCF production, though the magnitude of benefit depends strongly on the recycling route and methodological assumptions. Mechanical recycling generally exhibits the lowest process energy demand but suffers from product downcycling and limited substitution potential for high-grade applications (Witik et al., 2013). Pyrolysis demonstrates significant global warming potential (GWP) and energy reductions, typically 30–50% relative to virgin fiber production, when off-gases are utilized for heat or power recovery and oxidation steps are optimized (He et al., 2020a). Solvolysis can achieve comparable or even greater benefits provided that solvent recovery rates are high and utilities derive from low-carbon energy sources (La Rosa et al., 2021; Meng et al., 2018). Reported primary energy savings of 395–520 MJ/kg and GWP reductions of 19–27 kg CO_2-eq/kg are highly sensitive to assumptions about process yields and substitution ratios.

Cross-study comparability remains limited due to inconsistent definitions of the functional unit, boundary conditions (cradle-to-gate vs. cradle-to-grave), and allocation or avoided-burden approaches (Tapper et al., 2020). Many published LCAs rely on pilot-scale data (Kawajiri and Kobayashi, 2022; Tapper et al., 2020; Vo Dong et al., 2018) that may underestimate industrial efficiencies and rarely include sensitivity or uncertainty analysis for solvent recovery or off-gas utilization. End-of-life assumptions, particularly credits for avoided virgin CF production or energy recovery, can invert the relative ranking of recycling routes.

Future CFRP recycling development will focus on improving the efficiency and consistency of emerging reclamation technologies. A clear R&D trend is to move toward more advanced processes, particularly hybrid routes that combine thermal pretreatment with solvolysis, to achieve higher rCF quality and meet the needs of high-value industrial applications. While pyrolysis remains the most mature and widely adopted technology, solvolysis and hybrid methods are expected to become competitive as their operational demands are optimized. To support reliable technology selection, future LCAs must provide clearer scenario ranges, uncertainty analyses, and transparent reporting of energy use, solvent recovery, and performance assumptions to ensure environmental benefits are maintained at industrial scale.

3. Remanufacturing technologies of reinforcements

After fiber reclamation, the recycled carbon fiber (rCFs) must be remanufactured into intermediate forms berofr reuse in new composite products. While the intrinsic quality of rCFs is determined during reclamation (Section 2), the remanufacturing route largely governs the final performance of recycled composites (rCFRPs). This section reviews the major remanufacturing technologies, key process parameters, and the requirements for achieving high-quality intermediates and preforms.

Discontinuous fiber composites (DFCs) offer notable advantages—high productivity, excellent formability, compatibility with complex geometries, and opportunities for fiber hybridization—making them suitable for both high-volume components and low-volume, high-value parts. Such et al. (Such et al., 2014) emphasized that aligned DFCs can approach the performance of continuous fiber composites (CFCs) while retaining superior formability, and highlighted the need for further development in alignment technologies.

The fiber length (L_f) of rCFs remains a major determinant of reuse potential. Long fibers enable higher structural performance, whereas severely shortened fibers restrict applications to fillers or low-performance parts. Melendi-Espina et al. (Melendi-Espina et al., 2016) showed that commercial value increases with retained strength and modulus; conversely, low-value rCFs often result from short L_f and degraded properties. Hagnell et al. (Hagnell and Åkermo, 2019) demonstrated that repeated recycling shortens rCFs to the point where their stiffness contribution becomes negligible. Contamination issues, such as incidental glass fiber (GF), were investigated by. Wei et al. (Wei et al., 2019), who found that small amounts of contamination do not significantly compromise rCFRP properties. Nakagawa et al. (Nakagawa et al., 2022) showed that although aged prepreg waste increases viscosity and void content in molded DFCs, mechanical properties remain largely unaffected, supporting the viability of repurposing prepreg scrap. Overall, the main parameters affecting rCFRP quality are the retained properties of rCF, fiber length distribution (FLD), fiber orientation distribution (FOD), and interfacial properties (IFSS). Depending on output requirements and economic constraints, these parameters will determine the remanufacturing pathway for rCFs.

Since rCF feedstock inherently consists of discontinuous fibers with broad FLDs, established textile processes are well suited to
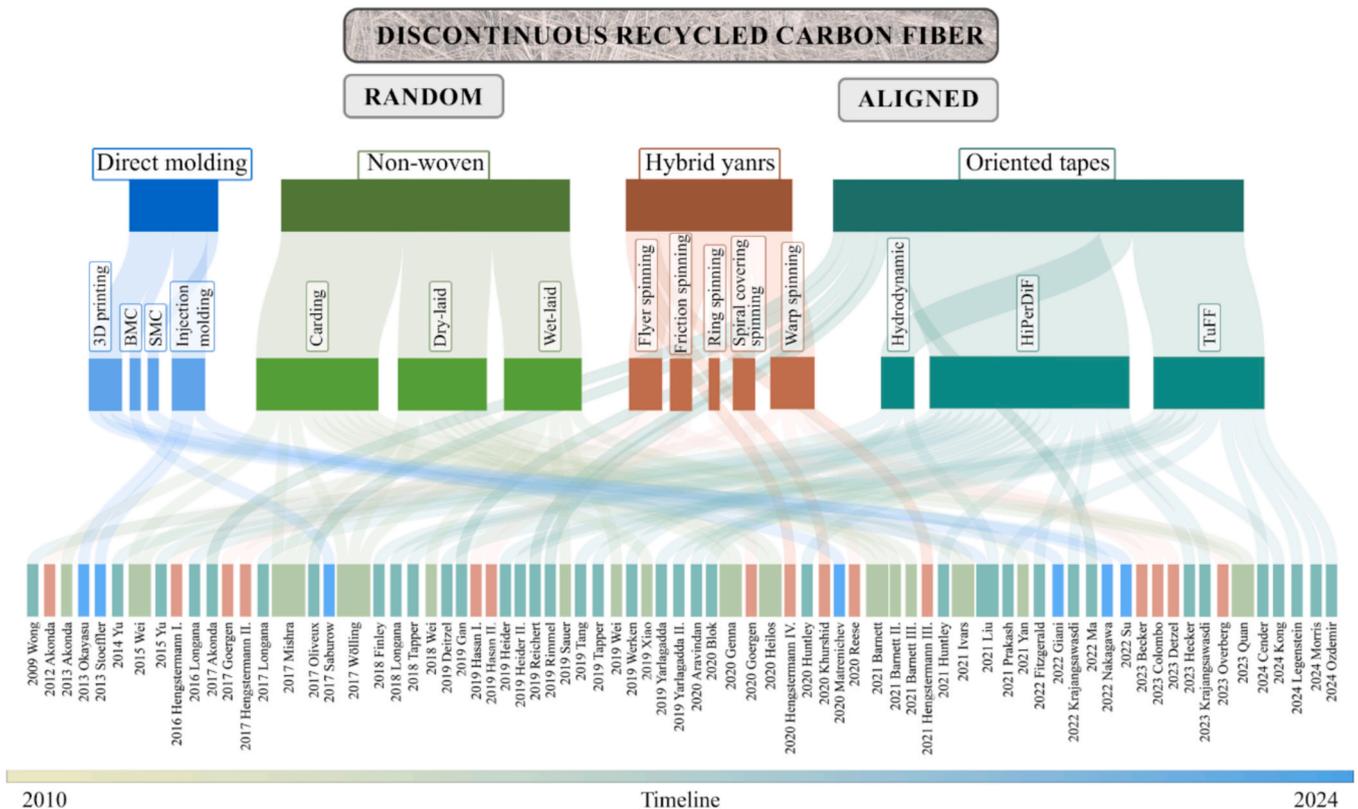

Fig. 4. Sankey plot of recycled carbon fiber remanufacturing technologies development timeline, key processes, and categorization reported in the literature. References: (Akonda et al., 2017, 2014, 2012; Aravindan et al., 2020; Badrul Hasan et al., 2019; Barnett et al., 2021a; Barnett et al., 2021a; Becker et al., 2023; Blok et al., 2020; Cender et al., 2024; Colombo et al., 2023; Deitzel et al., 2019; Detzel et al., 2023; Finley et al., 2018; Fitzgerald et al., 2022; Gan et al., 2019; Genna et al., 2020; Giani et al., 2022; Goergen et al., 2020, 2017; Hasan et al., 2019; Hecker et al., 2023a; Heider et al., 2019a, 2019b; Heilos et al., 2020; Hengstermann et al., 2021, 2020, 2017, 2016; Huntley et al., 2021, 2020; Ivars and Labanieh, 2021; Khurshid et al., 2020; Kong et al., 2024; Krajangsawasdi et al., 2023b, 2022; Legenstein et al., 2024; Z. Liu et al., 2021; Longana et al., 2018, 2017, 2016; Ma et al., 2022; Matrenichev et al., 2020; Mishra and Loganathan, 2017; Morris et al., 2025; Nakagawa et al., 2022; Okayasu et al., 2013; Oliveux et al., 2017; Overberg et al., 2023; Ozdemir et al., 2024; Prakash et al., 2022; Quan et al., 2023; Reese et al., 2020; Reichert et al., 2019; Rimmel et al., 2019; Saburow et al., 2017; Sauer et al., 2019; Stoeffler et al., 2013; Su et al., 2022; Tang et al., 2019; Tapper et al., 2019, 2018; van de Werken et al., 2019; Wei et al., 2019, 2018, 2015; Wölling et al., 2017; Wong et al., 2009; Xiao et al., 2019; Yan et al., 2021; Yarlagadda et al., 2019b, 2019a; Yu et al., 2015a, 2015b, 2014).

remanufacture them into functional intermediates. Remanufacturing methods are presented here according to increasing levels of fiber orientation, progressing from random networks to highly aligned architectures. Previous reviews have examined these technologies in detail (Pakdel et al., 2021b; Khurshid, et al., 2019; Heidarian et al., 2024; May et al., 2021; Barnett and Ghossein, 2021). Pakdel et al. (Pakdel et al., 2021b) focus on dry-fiber wastes, Khurshid et al. (Khurshid, et al., 2019) and Heidarian et al. (Heidarian et al., 2024) summarize recent advances for thermoplastic matrices, while May et al. (May et al., 2021) and Barnett et al. (Barnett and Ghossein, 2021) highlight the role of textile processing in achieving high alignment and fiber continuity.

Fig. 4 summarizes the development and interconnection of rCF remanufacturing technologies in a Sankey-diagram linking time, process categories and alignment levels. Early work is dominated by direct molding of mechanically recycled compounds and quasi-random non-wovens, which offer high throughput but are constrained to modest fiber volume fractions and limited structural performance. Over time, research has diversified toward dry-laid and wet-laid nonwovens, hybrid yarn spinning, and, most recently, highly aligned discontinuous fiber composites (ADFRCs). The increasing flow of publications and patents toward the right-hand branches of the diagram reflects a clear strategic shift from down-cycling to performance-oriented remanufacturing. Fig. 5 shows that composite performance is driven far more by remanufacturing quality than by the rCFs themselves. Randomly oriented, short-fiber molding compounds lie in the low performance region, while dry- and wet-laid nonwovens form an intermediate band limited by fiber

orientation and moderate fiber volume fractions. In contrast, hybrid yarn laminates and oriented tapes approach the continuous-fiber envelope. When orientation, FLD, and Vf are effectively controlled, rCFRPs can achieve performance levels suitable for structural applications traditionally reserved for virgin continuous-fiber materials.

3.1. Direct molding

Direct molding with mechanically recycled carbon fiber composites (rCFRPs) is among the most industrially accessible remanufacturing routes due to its compatibility with existing thermoplastic compounding and molding infrastructure. Because mechanical recycling does not separate fiber and matrix, the resulting recyclates contain residual resin that aids dispersion during compounding but limits fiber purity. All CFRP waste types (I–III, Fig. 1) can be processed via this route, offering high feedstock flexibility. During twin-screw extrusion, however, the combined shear and thermal exposure significantly shortens fibers, from millimeter lengths to sub-millimeter scales (Stoeffler et al., 2013). These compounds are therefore well suited for injection molding or pelletized feedstock but exhibit limited tensile efficiency due to reduced fiber aspect ratio.

When recovered fibers remain above the millimeter scale, compression molding routes such as BMC and SMC enable improved load transfer and moderately enhanced orientation (Knobelsdorf et al., 2016; Nakagawa et al., 2022; Saburow et al., 2017). Mechanical performance in SMC-type rCFRPs is governed primarily by fiber length and
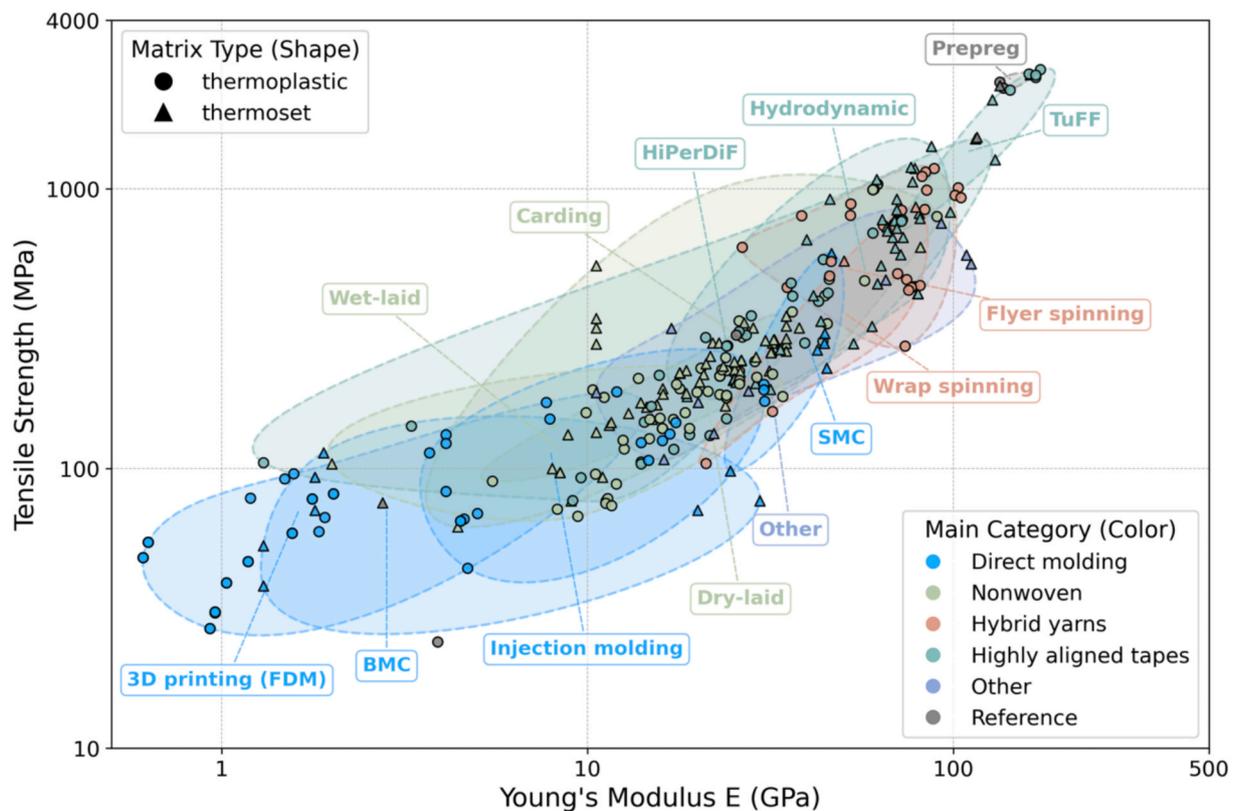

Fig. 5. Ashby plot of tensile strength versus modulus for remanufactured recycled carbon fiber (rCF) composites and benchmark virgin carbon fiber (vCF) composites, including both thermoset (CFRP) and thermoplastic (CFRTP) matrices, as reported in the literature. The performance envelopes highlight the wide range of achievable properties, from short-fiber, randomly oriented rCFRPs with reduced stiffness to highly aligned systems approaching vCF laminate (prepreg UD) benchmarks. References: (Akonda et al., 2017, 2012; Aravindan et al., 2020; Barnett et al., 2021a; Barnett et al., 2021a; Becker et al., 2023; Bel Haj Frej et al., 2021; Blok et al., 2020; Detzel et al., 2023; Evens et al., 2019; Gan et al., 2019; Genna et al., 2020; Giani et al., 2022; Giorgini et al., 2015; Goergen et al., 2020, 2017; Hasan et al., 2019; Hecker et al., 2023a; Heider et al., 2019a; Heilos et al., 2020; Hengstermann et al., 2021, 2020, 2017, 2016; Ivars and Labanieh, 2021; Krajangsawasdi et al., 2023a; W. Liu et al., 2021; Z. Liu et al., 2021; Longana et al., 2017, 2016; Matrenichev et al., 2020; Nakagawa et al., 2022; Okayasu et al., 2013; Oliveux et al., 2017; Overberg et al., 2023; Ozdemir et al., 2024; Pimenta et al., 2010; Pimenta and Pinho, 2012; Quan et al., 2023; Rimmel et al., 2019; Saburow et al., 2017; Sauer et al., 2019; Stoeffler et al., 2013; Su et al., 2022; Tang et al., 2019; Tapper et al., 2019, 2018; van de Werken et al., 2019; Wei et al., 2015; Wölling et al., 2017; Wong et al., 2009; Xiao et al., 2019; Yan et al., 2021; Yarlagadda et al., 2019b; Yu et al., 2015a, 2014).

orientation rather than the specific molding process. Type I dry waste, which retains factory sizing, often provides acceptable interfacial shear strength, whereas Types II and III typically require surface oxidation or re-sizing to restore consistent bonding (Khurshid, et al., 2019). Fiber volume fractions of 20–40% generally provide the optimum stiffness–toughness balance (Table 2), whereas fractions below 10% behave more like filled polymers with minimal reinforcement. Below the critical fiber length (L_c), load transfer is inefficient (Matrenichev et al., 2020; Okayasu et al., 2013; Stoeffler et al., 2013), though even short fibers can enhance wear and tribological performance (Ahsan et al., 2016; Latiff et al., 2016).

Recent developments extend direct molding concepts into additive manufacturing (AM). Extrusion-based AM processes reintroduce localized fiber alignment, albeit at low levels. Ateeq et al. (Ateeq et al., 2023) and Liu et al. (W. Liu et al., 2021) showed that even modest alignment (3%) in printed rCF–PEEK improves tensile and flexural properties. Su et al. (Su et al., 2022) quantified the FLD and FOD in printed rCF–PA and demonstrated mechanical gains up to 40 wt% fiber content. Giani et al. (Giani et al., 2022) reported enhanced thermomechanical behavior in rCF–PLA, though tensile properties remained below those of virgin long-fiber CFRTPs. AM offers a scalable route for geometry-specific, semi-structural rCFRP components, but performance remains limited by fiber shortening, flow-induced orientation, and interfacial bonding.

3.2. Non-woven technologies

Discontinuous rCFs are commonly remanufactured into textile

Table 2
Maximum achieved tensile modulus and strength and corresponding fiber volume fraction of remanufactured recycled fiber reinforced composites (rCFRP) reported in the literature, sorted by remanufacturing method. References: (Akonda et al., 2017, 2012; Aravindan et al., 2020; Barnett et al., 2021a; Barnett et al., 2021d; Becker et al., 2023; Bel Haj Frej et al., 2021; Blok et al., 2020; Detzel et al., 2023; Evens et al., 2019; Gan et al., 2019; Genna et al., 2020; Giani et al., 2022; Giorgini et al., 2015; Goergen et al., 2020, 2017; Hasan et al., 2019; Hecker et al., 2023a; Heider et al., 2019a; Heilos et al., 2020; Hengstermann et al., 2021, 2020, 2017, 2016; Ivars and Labanieh, 2021; Krajangsawasdi et al., 2023a; W. Liu et al., 2021; Z. Liu et al., 2021; Longana et al., 2017, 2016; Matrenichev et al., 2020; Nakagawa et al., 2022; Okayasu et al., 2013; Oliveux et al., 2017; Overberg et al., 2023; Ozdemir et al., 2024; Pimenta et al., 2010; Pimenta and Pinho, 2012; Quan et al., 2023; Rimmel et al., 2019; Saburow et al., 2017; Sauer et al., 2019; Stoeffler et al., 2013; Su et al., 2022; Tang et al., 2019; Tapper et al., 2019, 2018; van de Werken et al., 2019; Wei et al., 2015; Wölling et al., 2017; Wong et al., 2009; Xiao et al., 2019; Yan et al., 2021; Yarlagadda et al., 2019b; Yu et al., 2015a, 2014).

Remanufacturing method	Fiber volume fraction v_f [%] at Max modulus (At Max strength if different)	Maximum tensile modulus [GPa]	Maximum tensile strength [MPa]
Prepreg UD – virgin benchmark	57.3	162	2558
Injection molding	32.7	30.5	200
BMC	53.2	29.6	114
SMC	58.2	46.4	587.1
3D printing (FDM)	30.7	12.1	187.9
Wet-laid	42.2 (30)	32	231.9
Dry-laid (nonwoven)	34.6 (37)	37.9	351.1
Wrap spinning	47.1 (37)	81.1	861.5
Flyer spinning	50	88.6	1182.4
Spiral covering spinning	45.0 (52.3)	52.3	805
Friction spinning	54.2 (52.8)	105	1010
Oriented tapes by carding	62	90.1	1038.4
Hydrodynamic	46.0 (42)	98	1417
HiPerDiF	55	115	1509
TuFF	63	173	2668
Other	55.6 (57.9)	111.7	752.5

intermediates to enable efficient handling and consolidation. Nonwoven preforms offer production rates an order of magnitude higher than woven fabrics (Mishra and Loganathan, 2017), making them attractive for both high-volume and cost-sensitive applications. Their degree of anisotropy depends on the layup method (Fig. 4, Fig. 5). Wet-laid and dry-laid techniques typically produce quasi-isotropic in-plane architectures—well suited for thin shell structures loaded primarily in-plane—while three-dimensional isotropy can be advantageous for thicker components subjected to transverse loading.

3.2.1. Wet-laid

Wet-laid nonwovens are produced using a modified papermaking process in which fibers are dispersed in water, deposited as a slurry onto a forming belt, and subsequently dried. This route enables isotropic fiber orientation, accommodates a wide range of areal densities (5–50 g/m²), and can process both long and short rCFs (Barnett and Ghossein, 2021; May et al., 2021; Wölling et al., 2017). Production rates can exceed 1000 m/min (Mishra and Loganathan, 2017). Depending on slurry formulation and deposition control, both quasi-isotropic and mildly anisotropic in-plane orientations are achievable (Yu et al., 2016). Wet-laid mats reinforced with thermoplastic fibers provide ideal preforms for subsequent compression molding. To improve handleability and consolidate high-density webs, secondary bonding is required. Techniques include needle punching, hydroentanglement, cellulose or latex binders, thermal bonding, and other chemical bonding routes procedures (S.J. Russell, 2007). Because fiber orientation is random, fiber volume fractions are typically limited to 30–40% (Table 2).

Several studies quantify mechanical behavior and process–structure relationships in wet-laid rCF composites. Wei et al. (Wei et al., 2018) used the modified rule of mixtures to analyze PA6 composites reinforced with mixed T300/T800 rCFs, achieving 23% V_f. In a later study, Wei et al. (Wei et al., 2019) showed that up to 5 wt% glass fiber contamination significantly reduces mechanical performance. Sauer et al. (Sauer et al., 2019) studied rCF/GF mixtures in PA matrices and observed quasi-linear improvements in tensile and bending stiffness with increasing rCF content. Yan et al. (Yan et al., 2021) optimized compression molding of rCF–PP sheets, identifying 30 wt% fiber, 190 °C, 2 MPa, and 10 min as conditions minimizing voids (0.9%); 6 mm fibers provided the best performance (59 MPa tensile, 146 MPa flexural).

Microstructural investigations by Pimenta et al. (Pimenta et al., 2010) linked wet-laid rCF failure mechanisms to fiber clustering and heterogeneity: tensile failure propagated along pre-existing microcracks, while compression failure involved shear banding within bundles. Their follow-up work (Pimenta and Pinho, 2014) showed that preserving fiber-bundle integrity during recycling or preform manufacturing can improve toughness by more than an order of magnitude. Recent work has examined processing optimization and hybridization strategies: Barnett et al. (Barnett et al., 2022) studied thermoplastic infiltration kinetics in wet-laid organosheets; Yaw Attahu et al. (Yaw Attahu et al., 2022) and Koçoğlu et al. (Koçoğlu et al., 2022) evaluated hybrid CF/aramid and CF/glass laminates, reporting tensile and flexural improvements up to 30% and 60%, respectively. Gao et al. (Gao et al., 2024) developed a Monte Carlo model to predict tensile behavior in hybrid CF/PA6 mats, demonstrating that stochastic FOD significantly influences property variability. Wet-laying processes are versatile methods to remanufacture rCF non-wovens, with the possibility for either anisotropic or isotropic properties and high throughput.

3.2.2. Dry-laid

Dry-laid nonwovens are produced by dispersing fibers in an airstream and depositing them onto a porous screen or conveyor, forming quasi-isotropic webs that become three-dimensional at areal densities above 50 g/m² (Barnett and Ghossein, 2021; Russell, 2007). The quality of air-laid mats depends strongly on the fiber-feeding method, free fall, compressed air, suction, or closed-loop systems, since fiber opening, airflow uniformity, and entanglement directly

influence web evenness and defect formation. Advantages include intrinsic isotropy, compatibility with diverse fiber types, and the ability to achieve high areal densities (200–5000 g/m²) (May et al., 2021). Limitations include relatively short processed fiber lengths (typically 1–4 mm) and lower production rates (20 m/min) than wet-laid processes. Comparative studies highlight the structural and mechanical distinctions between dry-laid and wet-laid routes. Wei et al. (Wei et al., 2015) systematically compared the two approaches for thermoplastic-matrix rCF composites, showing that carding yields higher alignment but lower productivity. Wölling et al. (Wölling et al., 2017) compared dry- and wet-laying routes, demonstrating that optimized processing parameters are required to maximize rCF mechanical performance (Table 2).

Anisotropic dry-laid textiles are produced by carding, which aligns fibers along the machine direction. Carding typically operates at areal weights of 20–200 g/m² (Barnett and Ghossein, 2021; May et al., 2021) and can reduce fiber length by up to 50% due to the high shear imparted by sawtooth rollers. Cross-lapping is used to increase areal density by depositing successive layers perpendicular to the carding direction, which simultaneously introduces transverse orientation. As with wet-laid materials, secondary bonding, most commonly needle punching is required to stabilize the web (Pimenta and Pinho, 2011; Rawal et al., 2025). Standard characterization methods for carded nonwovens include in-plane tensile testing, through-thickness compression, and permeability measurements (Amiot et al., 2014). Ivars et al. (Ivars and Labanieh, 2021) quantified the anisotropy in carded rCF textiles, showing pronounced differences between machine direction (MD) and cross direction (CD), which significantly affect compaction and forming.

Heilos et al. (Heilos et al., 2020) observed that rCF composites produced by dry-laying exhibited up to 60% higher tensile properties in the CD than the MD, consistent with anisotropic fiber alignment. Genna et al. (Genna et al., 2020) investigated resin-infused carded rCF textiles, demonstrating anisotropic behavior in low-velocity impact and indentation tests and showing higher impact resistance for $[0/90]_{2s}$ layups. Barnett et al. (Barnett et al., 2021a) compared PPS organosheets reinforced with virgin wet-laid and rCF carded nonwovens, finding higher anisotropy in the carded materials but limited influence of void content. Follow-up work (Barnett et al., 2021d) showed that annealing rCF–PPS organosheets increased crystallinity and improved strength, modulus, and thermal stability, particularly at 210 °C.

Recent developments focus on enhancing alignment, interfacial performance, and fracture resistance. Xiao et al. (Xiao et al., 2019) modified carding with roller-based stretching to increase fiber alignment and achieve V_f up to 43%, quantified via a defined stretch ratio. Quan et al. (Quan et al., 2022) demonstrated that UV treatment of rCF/PPS carded mats enhances intralaminar fracture resistance via improved fiber–matrix adhesion, while noting reduced interlaminar fracture energy due to diminished fiber-bridging. Their subsequent study Quan et al. (Quan et al., 2023) confirmed fiber pullout as the dominant mechanism in interlaminar fracture of commingled rCF/PPS dry-laid mats. Akonda et al. (Akonda et al., 2014) developed non-crimp fabrics from T700 staple fibers and PET via carding, partial thermal consolidation, and stitch bonding, demonstrating improved mixing, alignment, and drapability relative to conventional dry-laid preforms. Overall, dry-laid routes, including air-laying, carding, and cross-lapping provide flexible, scalable pathways for remanufacturing rCF into nonwovens with tunable alignment, although fiber shortening, anisotropy, and web uniformity remain key challenges influencing composite performance.

3.3. Hybrid yarn spinning

Hybrid yarn spinning offers one of the most effective routes for improving fiber alignment in discontinuous rCF systems, enabling the production of highly oriented textile intermediates with significantly enhanced composite performance (Table 2, Fig. 4, Fig. 5). In these processes, a carded web of rCFs and thermoplastic fibers (PE, PP, PA6,

PA66, PET, PPS, and PEEK most commonly) is drawn and drafted into a sliver, which is then consolidated, either left unspun to form unidirectional tapes (Akonda et al., 2014) or spun into yarns where twist provides cohesion and a round cross-section (Abdkader et al., 2023; Barnett and Ghossein, 2021). The final alignment and yarn quality depend on fiber length (typically $\geq$ 10–20 mm for stable spinning), fiber diameter distribution, mixing ratio, and the chosen spinning method (warp, flyer, ring, friction). Longer fibers (>25 mm) consistently yield stronger yarns due to improved inter-fiber friction and load transfer (Hengstermann et al., 2017, 2016).

Process optimization plays a central role in minimizing fiber breakage and mass irregularities. Hengstermann et al. (Hengstermann et al., 2020) identified critical breakage points within the carding line and optimized roller spacing and drafting settings, enabling more precise control of the FLD. Khurshid et al. (Khurshid et al., 2020) applied auto-leveling strategies to stabilize hybrid sliver mass and reduce fiber damage, improving the quality of UD tapes and yarn feedstock. The interaction of sizing with fiber blending and bundle behavior was examined by Hengstermann et al. (Hengstermann et al., 2021), highlighting that sizing formulations optimal for textile processing are not necessarily ideal for the final composite matrix.

3.3.1. Wrap-spinning

Akonda et al. (Akonda et al., 2012) used a modified carding and wrap spinning process for rCF/PP thermoplastic composites to align staple rCFs. They manufactured unidirectional CFRTP plates using winding and compression molding; the 30:70 and 50:50 wt ratios used for staple fiber blends resulted in volume fractions of 15% and 27.7%, respectively, and achieved more than 90% alignment in the yarn direction. Reese et al. (Reese et al., 2020) used wrap-spun yarns of rCF and PA6 fibers to create woven fabrics with different patterns. The electrical conductivity and Joule heating of rCFs were used to consolidate composites under pressure; volumetric heating resulted in low cycle times, improved energy efficiency, and low volume fractions. Detzel et al. (Detzel et al., 2023) describe a novel process where wrap-spun staple fiber yarns from rCF and PA6 were subjected to a modified impregnation and calendaring process. Stretching applied during heated impregnation increased orientation from 66.3% to 91.9% within $\pm$ 10° and from 39.1% to 71.6% within $\pm$ 5°, resulting in a 15.2% increase in tensile modulus and a 14.5% increase in flexural modulus. Becker et al. (Becker et al., 2023) compared rCF and PA6 hybrid yarns in composites with an epoxy and thermoplastic matrix and monitored damage behavior using in-situ X-ray microscopy and acoustic emission. In-situ test results indicated different failure modes for rCF composites compared to conventional UD in transverse tension due to the inhomogeneity of staple rCF fibers and cracks initiated inside the clustered rCF inside a roving instead of matrix transverse cracks.

3.3.2. Flyer spinning

Hengstermann et al. (Hengstermann et al., 2016) investigated the remanufacturing of hybrid yarns from rCFs and PA6 fibers of defined lengths using carding, drawing, and flyer spinning, focusing on fiber breakage during processing. They found that longer fibers enhanced fiber–fiber cohesion and significantly improved the mechanical properties of the yarns, especially with higher twist levels and carbon fiber content. In a related study, Hengstermann et al. (Hengstermann et al., 2017) examined how fiber length and twist affect the tensile properties of rCF/PA6 thermoplastic composites, reporting tensile strengths of 771 MPa for 40 mm virgin CF, 838 MPa for 60 mm virgin CF, and 801 MPa for rCF at 50% fiber volume content. Overberg et al. (Overberg et al., 2023) presented a micro-scale hybridized multi-material flyer-spun hybrid yarn structure utilizing rCF, aramid, and PA6 fibers to enhance impact strength. Incorporating 24 v% aramid fibers improved ductility for rCFRTP composites; impact strength increased by 70%, while tensile strength decreased by 25% compared to solely rCF samples. However, hybridization significantly increases elongation break, by 62.5%,

underlining the effectiveness of fiber hybridization for improved toughness of rCFRTP.

3.3.3. Spiral covering spinning

Goergen et al. (Goergen et al., 2017) produced non-crimp fabrics from 400 and 800 tex rCF/PA6 hybrid staple fiber yarns in weft and warp directions. Fiber length was reduced to 21–25 mm during carding and spiral covering spinning, and rCF v_f was set to 55%. The tensile strength of UD rCFRTP plates was 77% of that of T300/epoxy UD composites. They also investigated the plastic deformation of organic sheets at elevated temperatures, which showed excellent thermoforming capabilities due to the inter-fiber sliding of discontinuous rCFs. Goergen et al. (Goergen et al., 2020) comprehensively characterized the deep-drawing of rCF/PA6 non-crimp fabric. Results showed an average plastic deformation of up to 50% during thermoforming, and the authors developed and validated a finite element model for the simulation of the deep-drawing behavior of rCF organic sheets.

3.3.4. Friction spinning

Hasan et al. (Hasan et al., 2019) developed novel multi-material hybrid yarns with friction spinning. The core-sheath structure of the yarns consisted of waste CF, GF, and PA6 fibers for the core and PA6 for the sheath. Different mixtures were tensile and impact tested, and results showed a 50.5% increase in impact strength with the incorporation of 6 v% GF, although tensile strength was compromised. Friction spinning proved an efficient method (Badrul Hasan et al., 2019) for producing thermoplastic hybrid yarns from waste CFs; it produces reproducible quality, which depends on parameters like air suction pressure, spinning drum speed, core-to-sheath ratio, and input CF length.

3.3.5. Ring spinning

Colombo et al. (Colombo et al., 2023) used ring spinning to produce rCF thermoplastic hybrid yarns with polyester and PA6 fibers and varying blending ratios. Their results showed that fiber orientation plays a pivotal role during the carding process and a lower fraction of rCFs results in better alignment; however, increasing rCF content results in higher tenacity for hybrid yarns and improved tensile strength for rCFRTP.

These results demonstrate that rCF-based composites can provide cost-effective solutions for a wide variety of non-structural applications, while also delivering notable environmental benefits and broadening the usable range of composite materials. Hybrid yarn spinning significantly improves fiber alignment and thereby enhances mechanical performance; however, the achievable orientation remains inherently limited. Misalignment primarily originates from the short and heterogeneous fiber lengths typical of rCF, their irregular morphology, and the interaction with thermoplastic matrix fibers during blending and spinning. Additional deviations arise from suboptimal spinning parameters, fiber entanglement, and equipment constraints. Nonetheless, careful process optimization and appropriate fiber pre-treatments can mitigate these effects and markedly improve alignment consistency.

3.4. Highly oriented tapes

To fully exploit the economic and functional value of rCFs, they must be remanufactured into high-performance structural composites. Achieving this requires strong fiber alignment, which enables dense packing, high fiber volume fractions, and maximized mechanical efficiency (Table 2). Aligned discontinuous fiber composites (ADFRCs) therefore represent a major opportunity for value-added reuse: by orienting rCFs to near-unidirectional layouts, their performance can approach that of continuous virgin composites (Fig. 5). Recent advances in highly aligned tape technologies, spanning modified carding, convergent-flow alignment, HiPerDiF, and TuFF, have dramatically improved stiffness and strength of rCFRPs and demonstrate that alignment-driven remanufacturing is central to unlocking structural-grade recycled composites.

3.4.1. Oriented tapes by carding

As discussed earlier, carding provides high fiber alignment and productivity, enabling the manufacture of ADFRCs as well as hybrid yarns. Akonda et al. (Akonda et al., 2017) demonstrated a modified carding route in which rCF/PET slivers were partially consolidated at 240 °C to form 0.5 mm thick tapes, later slit into 20 mm widths for cross-ply and woven architectures. Cross-ply laminates showed superior tensile, flexural, compression, and impact properties compared to woven versions. Reichert et al. (Reichert et al., 2019) produced similar rCF/PA6 tapes (2000 tex), though quality assessments revealed irregular edges and thickness variations, with fiber orientation not quantified. Rimmel et al. (Rimmel et al., 2019) used copolyamide binder tapes to create UD laminates via automated fiber placement, achieving a tensile strength of 618 MPa for thermoset binder-tape composites. Despite these advances, both hybrid yarn and carding-based tape routes remain limited for high-end structural applications due to non-uniform bundle packing and insufficiently controlled alignment.

3.4.2. Convergent flow alignment

Convergent-flow alignment techniques use a carrier fluid to orient fibers through flow contraction or momentum change (Such et al., 2014, p. 20). Wong et al. (Wong et al., 2009) reviewed hydrodynamic alignment approaches and their applicability to rCF. Early work by Explosive Research and Development Establishment (ERDE) introduced three patented ADFRC alignment concepts based on extrusion, filtration, and centrifugal deposition (Bagg, 1977, 1971; Bagg et al., 1969; Parratt, 1968) noting that alignment depends primarily on fiber length, while sufficiently high viscosity is needed for stable dispersion.

More recently, van de Werken et al. (van de Werken et al., 2019) aligned chemically reclaimed T800 fibers using a glycerol–water suspension and a convergent nozzle feeding a centrifugal collector. About 70% of 1.5 mm fibers aligned within ± 15°, doubling normalized tensile strength (266 MPa) and increasing modulus by 137% (33.7 GPa). Liu et al. (Z. Liu et al., 2021) further optimized this centrifugal process, achieving very high alignment, up to 92% within ± 10° (3 mm fibers), and producing laminates with 98 GPa modulus and 826 MPa tensile strength at 46% V_f. Their results agreed well with modified rule-of-mixtures predictions incorporating FOD and FLD effects.

3.4.3. HiPerDiF (momentum change alignment)

The High-Performance Discontinuous Fibre (HiPerDiF) technology is an advanced manufacturing process developed by Yu et al. (Yu et al., 2014) at the University of Bristol. It aligns discontinuous fibers into highly aligned, unidirectional preforms via the momentum change of fiber suspension jets directed onto orientation plates. The process is independent of fiber type; it can efficiently align CF, GF, thermoplastic, and natural fibers. Longana et al. (Longana et al., 2016) explored the effect of multiple closed-loop recycling of HiPerDiF composites, proving the method's potential for material circularity. However, after the second recycling cycle, specimens showed reduced stiffness, strength, and strain due to fiber shortening and residual matrix accumulation, this shows the need for optimized fiber recovery to maintain performance. Aravindan et al. (Aravindan et al., 2020) remanufactured waste CFs from dry fiber cutoffs into highly aligned preforms via the HiPerDiF process. Preforms with different FLD were tested; tensile tests on laminated specimens showed a stiffness of 70–81 GPa, a strength of 706–841 MPa, and failure strains of 0.97%–1.19%, with longer fibers yielding better mechanical performance (Table 2).

Hydrodynamic optimization has been advanced through smoothed-particle modeling. Huntley et al. (Huntley et al., 2021, 2020) validated models showing that nozzle angle, plate spacing, and fiber length strongly influence the fraction of fibers aligned within a few degrees of the machine direction. Surface-modified rCFs further improve dispersion and reduce flocculation, as demonstrated by Kong et al. (Kong et al.,

2024), enhancing the stability of fiber suspensions essential for high-quality preforms.

Discontinuous rCFs produce pseudo-ductile behavior in hybrid composites (Yu et al., 2015b; Longana et al., 2017, 2018; Yu et al., 2018). Longana et al. (Longana et al., 2017) demonstrated the potential of HiPerDiF-aligned reclaimed/virgin CF composites and developed a quality control method for rCFs (Longana et al., 2018). Yu et al. (Yu et al., 2018) confirmed the effectiveness of HiPerDiF in producing optimized pseudo-ductile hybrid composites and applied a modified analytical model for design optimization. Finley et al. (Finley et al., 2018) demonstrated that isolating fiber types in HiPerDiF-manufactured hybrid composites increases strength by 27% and pseudo-ductility by 44%, with their modified process and virtual testing framework providing key insights into fracture mechanisms in discontinuous hybrids.

The HiPerDiF method can also be applied to thermoplastics by aligning short recycled fibers within a thermoplastic matrix, improving both mechanical performance and recyclability. Tapper et al. (Tapper et al., 2018) demonstrated a closed-loop process for CF–PP composites in which dissolution/precipitation reclamation combined with HiPerDiF remanufacturing yielded highly aligned preforms and improved tensile stiffness, strength, and strain across multiple recycling cycles, with only minor shear-strength reductions from PP chain scission. A follow-up study on CF–PA6 Tapper et al. (Tapper et al., 2019) showed that fiber misalignment and residual matrix accumulation gradually impair tensile properties over two cycles, consistent with SEM and FTIR evidence of structural and chemical changes. Complementing these findings, Tang et al. (Tang et al., 2019) produced hybrid composites of aligned discontinuous CFs and self-reinforced PP, achieving high stiffness (10 GPa) and > 10% pseudo-ductile strain, where controlled debonding and fiber pull-out mitigated brittleness and enhanced damage tolerance.

Thermoplastic ADFRC tapes can also serve as precursors for high-performance 3D-printing filaments, offering properties approaching those of continuous-fiber composites while reducing defects such as wrinkling and bridging. Blok et al. (Blok et al., 2020) demonstrated that tapes with 12.5% V_f using ABS, PLA, Nylon, or PETG achieve stiffness up to 30 GPa and strengths of 400 MPa, underscoring the viability of discontinuous fiber filaments. Krajangsawasdi et al. (Krajangsawasdi et al., 2023a, 2023b, 2022) further showed that aligned-fiber filaments outperform conventional PLA composites and that 3D printing enables fiber steering to tailor stress distribution. Tensile, short-beam shear, and open-hole tests confirmed that multilayer printed ADFRC parts can deliver stiffness and strength sufficient for structural applications.

Hecker et al. (Hecker et al., 2023b) demonstrated a circular CFRP recycling pathway by combining DEECOM® superheated-steam fiber reclamation with HiPerDiF realignment, achieving high property retention and validating the concept through yacht-sail demonstrators. Complementing this, Fitzgerald et al. (Fitzgerald et al., 2022) assessed the environmental footprint of HiPerDiF via LCA, identifying electricity use and water consumption as key impact drivers and recommending energy-efficient vacuum systems and water recirculation, as well as renewable energy sourcing and optimized logistics to enhance the technology's circular-economy performance. Since its origin, the patented HiPerDiF (Yu and Potter, 2017) method has gone through several development stages and has been scaled up to an industrial scale. Currently, Lineat Co. commercializes the HiPerDiF technology and the highly aligned preforms.

3.4.4. TuFF (momentum change alignment)

The Tailorable Universal Feedstock for Forming (TuFF) process is a major advancement in manufacturing high-performance discontinuous-fiber composites, producing mechanical properties comparable to continuous-fiber systems (Fig. 5). Its patented alignment and preforming mechanism (Tierney et al., 2021) generates highly regulated micro-structures with exceptional fiber orientation, up to 95% within $\pm$ 5°, using controlled fiber cutting (1–7 mm), fluid-based dispersion to

prevent agglomeration, and wet-laid laminar-flow deposition with slanted alignment plates and vacuum filtration (Heider et al., 2019b; Yarlagadda et al., 2019b). The scalable multilayer deposition system enables thin plies (70 g/m^2) and high fiber-volume fractions (up to 63%), delivering composites with > 40% biaxial strain capacity and tensile strengths equivalent to continuous-fiber laminates (Table 2).

Subsequent studies confirmed TuFF's durability and versatility. Prakash et al. (Prakash et al., 2022) demonstrated excellent fatigue resistance in thermoplastic TuFF laminates, while Heider et al. (Heider et al., 2019a) and Ozdemir et al. (Ozdemir et al., 2024) showed that recycled CFs can be reoriented to achieve mechanical properties comparable to virgin composites. Deitzel et al. (Deitzel et al., 2019) further enabled low-cost rCF integration through ozone-based IFSS enhancement, increasing interfacial strength from 10 to 40 MPa. Analytical and forming studies expanded TuFF's design space: Cender et al. (Cender et al., 2024) modeled strain-softening via fiber-spacing and overlap variability; Morris et al. (Morris et al., 2025) established forming-limit diagrams capturing TuFF's exceptional biaxial extensibility; and Legenstein et al. (Legenstein et al., 2024) demonstrated 60% stretch-steering during AFP, offering drastically improved drapability relative to continuous-fiber tapes.

TuFF technology offers a cost-effective approach for producing high-performance composites with superior formability, mechanical integrity, and high-value recyclability. It is the most effective process for remanufacturing discontinuous rCF into highly aligned composites competitive with continuous vCF composites, making it a compelling alternative for aerospace, automotive, and structural applications.

3.5. Other methods

Apart from the previously mentioned alignment processes, there are some unique approaches for improving the alignment of discontinuous rCFs. Gan et al. (Gan et al., 2019) presented a dry alignment technique using a vibration-assisted process to align 12 mm long rCF tows within hybrid composites. Stiffness increased by up to 24.4%, and strength improved by up to 59.9% compared to non-aligned hybrids. The improved fiber alignment also produced a pseudo-ductile failure response. The patented process (Mantaux et al., 2014) developed by Oliveux et al. (Oliveux et al., 2017) at the University of Bordeaux is an innovative method for separating and realigning rCFs from fabric cuttings. This process utilizes a comb-assisted unraveling step and an oscillating vibration module, producing a fiber alignment of approximately 90% within $\pm$ 10° of the loading axis. Ma et al. (Ma et al., 2022) introduced a novel electric field–induced manipulation approach for recycling short chopped CFs, which uses electrostatic induction and dielectric polarization for the precise dispersion, collection, and controlled alignment of rCFs, thereby enhancing the recovery process and enabling the fabrication of function-enhanced resin-based composites.

3.6. Critical assessment of remanufacturing technologies

Remanufacturing technologies for rCFs exhibit distinct trade-offs between mechanical performance, processing speed, and scalability. Wet-laid nonwovens deliver the highest throughput (up to 1000 m/min) and excellent formability, making them attractive for semi-structural applications. However, their random fiber orientation limits fiber volume fraction, stiffness, and tensile strength, confining them mainly to secondary components. HiPerDiF achieves exceptional alignment precision and near-virgin fiber performance, with tensile strengths surpassing 1000 MPa in some cases, and industrial upscaling is almost complete. But it is evident that TuFF has advanced further by combining highly controlled fiber alignment with continuous tape manufacturing. This process yields structural-grade laminates with reproducible quality and offers a viable pathway for scaling ADFRCs. However, it remains constrained by its reliance on short, precisely controlled fiber lengths,

stringent feedstock quality requirements, high capital and operational costs, and moderate throughput. Moreover, its incomplete qualification and certification status currently limit full industrial adoption. Future progress will depend on simplifying the process chain and demonstrating consistent large-scale mechanical performance under certified production conditions.

Hybrid yarn technologies also warrant particular attention as a mature, high-throughput route for rCF remanufacturing. By co-mingling rCFs with thermoplastic filaments, these yarns improve handling, fiber cohesion, and matrix distribution during textile processing and consolidation. However, because the polymer filaments act as binders and matrix precursors, hybrid yarn systems are inherently limited to thermoplastic composites, restricting direct applicability to thermoset systems.

4. Modeling – multiscale modeling and homogenization

The modeling of recycled carbon fiber (rCF) reinforcement structures and composites (rCFRPs) can significantly contribute to the widespread application of these materials by providing insights into their mechanical performance, manufacturability, and potential for cost reduction. By accurately simulating the behavior of rCFRPs using analytical and numerical models, researchers can optimize design parameters, predict failure modes, improve reliability, and enhance the overall performance of the composites. This is particularly important as rCFs often exhibit variability (Finley et al., 2020; Harper et al., 2017; Henry and Pimenta, 2017; Lang et al., 2023; Lewis et al., 2024; Luchoo et al., 2011; Nakagawa et al., 2024; Selezneva and Lessard, 2016) in properties due to the reclamation and remanufacturing processes. Including these materials in finite element analysis (FEA) allows for a more comprehensive understanding of their behavior under various loading conditions, ultimately facilitating their adoption in multiple industries. Some of the methods discussed were originally developed for discontinuous or chopped virgin fibers (vCF) but are directly transferable to rCF systems, while others were explicitly formulated to model rCFs and their unique variability.

Belnoue and Hallett (Belnoue and Hallett, 2024) highlight the role of process models in Composites 4.0, emphasizing faster, stochastic models to improve design efficiency and reduce reliance on physical testing. The authors stress the need for robust optimization and real-time integration to support digital twins and minimize variability. They also address the challenges of transitioning to sustainable materials, advocating for process models to enhance efficiency and accelerate the adoption of rCF. Advances in short-fiber composite modeling are therefore highly relevant to rCF systems, as recycled carbon fiber composites are commonly based on stochastic short- and discontinuous-fiber reinforcements with broad length and orientation distributions.

Recently, Lewis et al. (Lewis et al., 2024) gave a comprehensive overview of current approaches to modeling the behavior of aligned discontinuous fiber composites (ADFRCs) during alignment, forming, and mechanical loading, providing a route to design optimization. Fig. 6 shows that the performance of ADFRCs is influenced by various micro, meso, and macro factors. The reclamation process exerts the most significant influence on the microscale fiber, matrix, and interfacial properties. In contrast, remanufacturing can affect mesoscale properties on a ply level, while the macroscale determines the structural response of the rCFRP laminate.

Additionally, fiber–matrix interfacial effects and impregnation quality significantly impact composite strength. Multiscale modeling approaches can be employed to capture the interactions across different scales, from the microstructural level to the macro-level performance of the composite (Lewis et al., 2024; Pimenta et al., 2010; Zweifel et al., 2023; Nachtane et al., 2022; Pal and Kumar, 2016). These approaches allow for a more comprehensive understanding of how microstructural variations influence overall composite behavior, which is significant for rCFs with considerable variability.

Conventional models assume uniform fiber and matrix properties, overlooking the variability in rCF. Refinements must consider variations in the length (L_f), diameter (d_f), and mechanical properties of fibers due to recycling, and stochastic modeling must be required for accurate representation. Fiber length, crucial to tensile performance, has been extensively studied (Harper et al., 2006, 2010; Pimenta et al., 2010; Pinho et al., 2012; Okayasu et al., 2013; Pal and Kumar, 2016; Selezneva and Lessard, 2016; Henry and Pimenta, 2017; Harper et al., 2017; Yu et al., 2018; Finley et al., 2018, 2020; Tapper et al., 2019; Huang et al., 2023; Zweifel et al., 2023; Nakagawa et al., 2024; Cender et al., 2024; Lewis et al., 2024). A high fiber aspect ratio enhances load transfer, reducing fiber/matrix interfacial failure, especially with uniform fiber length (FLD) and orientation distribution (FOD). However, excessively long fibers increase flocculation and misalignment. Numerical process simulation helps assess this trade-off (Ghossein et al., 2018; Gramsch et al., 2016), though achieving perfect alignment remains challenging.

Micromechanical modeling of rCFRPs aims to predict stiffness, strength, and failure by linking microstructural features such as FLD, FOD, and interfacial shear strength IFSS, to macroscopic behavior. Analytical approaches remain widely used for their computational efficiency but rely on simplifying assumptions that limit accuracy for heterogeneous recycled systems. The Mori–Tanaka method (Mori and Tanaka, 1973), derived from Eshelby's inclusion theory (Eshelby and Peierls, 1957), provides reasonable stiffness estimates at moderate fiber contents but assumes uniform fiber orientation and perfect bonding. The Halpin–Tsai equations (Affdl and Kardos, 1976) offer empirical stiffness predictions yet lose validity with high aspect ratios and fiber waviness common in rCFRPs. The Cox shear-lag model (Cox, 1952) incorporates fiber length and IFSS, improving predictions for short-fiber composites but still neglecting interfacial debonding and nonlinear effects (Li et al.,
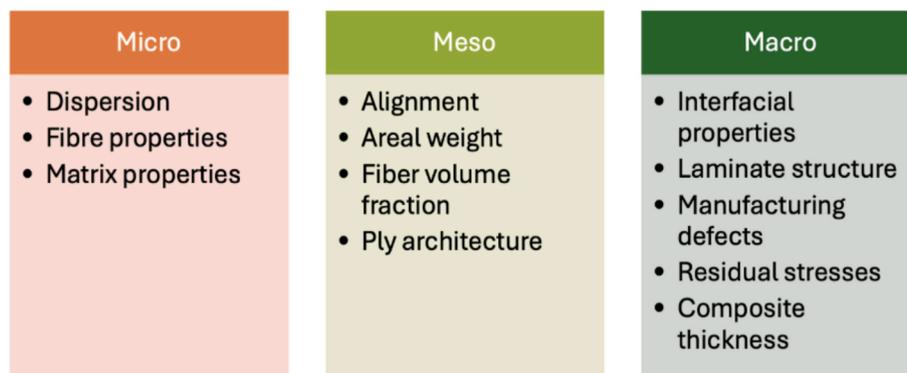
Micro	Meso	Macro
• Dispersion • Fibre properties • Matrix properties	• Alignment • Areal weight • Fiber volume fraction • Ply architecture	• Interfacial properties • Laminate structure • Manufacturing defects • Residual stresses • Composite thickness

Fig. 6. Hierarchical modeling of rCF composites, physical properties, and model parameters at micro, meso, and macro scale, .
Reproduced from Lewis et al. (Lewis et al., 2024)

2021). Overall, while analytical models are valuable for screening and sensitivity studies, they cannot capture the stochastic FOD, clustering, and progressive damage typical of recycled composites. Consequently, numerical approaches such as representative volume element (RVE) or Monte Carlo–based modeling are increasingly preferred for realistic prediction of rCFRP behavior.

Numerical micromechanical modeling provides detailed and physically grounded predictions of rCFRPs by explicitly representing their heterogeneous microstructures. Finite element based approaches are particularly suited for rCFRPs, where irregular fiber lengths, random orientations, and imperfect fiber–matrix interfaces critically influence mechanical behavior. An RVE (Bargmann et al., 2018) is typically used to statistically capture the composite microstructure while maintaining computational feasibility. RVE generation commonly relies on Monte Carlo random placement of fibers (Gao et al., 2024; Fukuda and Chou, 1982; Hine et al., 2002; Lusti et al., 2002; Barnett et al., 2021c) or micro-CT–based reconstruction scans (Alves et al., 2023; Cai et al., 2021; Fliegener et al., 2014; Sasagawa et al., 2020; Stelzer et al., 2020), which provides realistic fiber topology. Sequential absorption algorithms further ensure non-overlapping placement, essential for modeling entangled rCFs (Babu et al., 2018; Harper et al., 2012a, 2012b; Lang et al., 2023; Liu et al., 2016; Pan et al., 2008a, 2008b; Yan et al., 2023).

FE-based RVEs can accurately capture local stress gradients, debonding, and progressive damage, but their computational demand is substantial. To improve efficiency, Generalized Method of Cells (GMC) models (Pahr and Arnold, 2002) subdivide the RVE into cuboidal sub-cells, while High-Fidelity GMC (HFGMC) (ABOUDI, 2004; Aboudi et al., 2001; Arnold et al., 1999) extends this framework to nonlinear and interfacial effects. The Finite Volume Direct Averaging Method (FVDAM) (Cai et al., 2022, 2020) offers another compromise between computational cost and accuracy by averaging stress across finite volumes. Boundary Element Methods (BEM) (Gun and Kose, 2014) achieve high efficiency by discretizing only boundaries but lose precision for dense or irregular fiber networks (Lewis et al., 2024). Emerging Peridynamic (PD) approaches (Hu et al., 2022; Qu et al., 2018; Zhang et al., 2021b) represent composites as interacting particles rather than a continuum, allowing explicit simulation of complex damage modes such as fiber–matrix debonding and crack coalescence. However, PD models remain computationally intensive and struggle to represent realistic fiber geometry.

Fiber alignment and length effects remain central predictors of performance. Van de Werken et al. (van de Werken et al., 2019) demonstrated a nonlinear relationship between alignment and modulus for rCFRPs, requiring a fiber orientation factor above 0.7 for optimal stiffness and fiber lengths exceeding 5 mm for high modulus. Harper et al. (Harper et al., 2010, 2006) found that finer filamentization of tows in conventional ADFRCs improved stiffness and strength by up to 44%, while FLD strongly affected coverage and load transfer. Wan and Takahashi (Wan and Takahashi, 2020) further advanced orientation quantification through structure tensor analysis of vCF sheet molding compounds, correlating molding pressure with fiber alignment and internal morphology. Auenhammer et al. (Auenhammer et al., 2024) developed an X-ray scattering tensor tomography–based finite element modeling framework that enables direct 3D mapping of fiber orientation and anisotropy in heterogeneous short fiber composites. This approach bridges experimental tomography with micromechanical simulation, providing unprecedented accuracy in predicting local stiffness and damage evolution in fiber-reinforced composites.

Numerical and stochastic modeling approaches have increasingly captured rCFRP heterogeneity. Harper et al. (Harper et al., 2017) developed 3D geometric RVEs that predicted tensile behavior of discontinuous vCF within 5% error to experiments, while Gao et al. (Gao et al., 2024) and Barnett et al. (Barnett et al., 2021a) used Monte Carlo–based simulations to integrate experimental variability and reproduce tensile responses of vCF and rCF nonwovens with under 10% error, respectively. Lang et al. (Lang et al., 2023) introduced a domain superposition technique for rCF hybrid yarn composites, achieving accurate predictions for fibers > 50 mm. Semi-analytical frameworks by Henry and Pimenta (Henry and Pimenta, 2017) and Negi and Picu (Negi and Picu, 2019) incorporated stochastic fiber strength of rCFs, plasticity, adhesion, and friction, offering efficient yet physically grounded descriptions of failure.

Multiscale and hybrid models connect these micromechanical insights to laminate-level predictions. Yu et al. (Yu et al., 2018) and Finley et al. (Finley et al., 2020, 2018) modeled aligned discontinuous and hybrid vCF composites produced by HiPerDiF, revealing how fiber intermingling delays fracture and enhances pseudo-ductility—consistent with experimental pseudo-yield trends. Gopalraj and Kärki (Karuppannan Gopalraj and Kärki, 2021) extended FEA to rCF/GF–epoxy systems, validating elastoplastic behavior and ductile damage models. Zweifel et al. (Zweifel et al., 2023) combined tomography, image analysis, and mechanical testing to quantitatively link FOD and tortuosity to mechanical anisotropy of rCFs.

Overall, multiscale and Monte Carlo–based models currently offer the most realistic representation of rCFRP behavior, bridging microscale variability and macroscopic mechanical predictions. Hybrid analytical–numerical methods (Visweswaraiah et al., 2018) and emerging machine-learning–assisted frameworks further enhance predictive accuracy and computational efficiency. However, a primary limitation to the broader adoption of stochastic modeling approaches lies not in the models themselves, but in the current lack of statistically robust, process-resolved microstructural data, particularly regarding fiber length and orientation distributions, retained fiber strength and stiffness, fiber volume fraction, interfacial properties, and their evolution during reclamation and remanufacturing.

Despite these advances, key challenges remain, including defining representative RVE sizes that capture FLD, FOD, and clustering variability (Harper et al., 2012b), modeling high fiber-volume fractions with overlapping fibers (Babu et al., 2018), and building standardized experimental databases for model calibration. Progress in parallel computing, data fusion from multimodal imaging, and adaptive learning or multiresolution modeling will be essential to deliver robust, design-level predictive tools capable of supporting structural-grade application and certification of rCFRPs.

5. Reuse and applications of recycled carbon fiber

As previously mentioned, recycled carbon fiber composites (rCFRPs) are becoming increasingly popular across various industries as they can enhance sustainability, maintain high performance, and are cost-effective. They are particularly valued for their lightweight, which is essential for modern energy and mobility applications. The energy-intensive production of virgin carbon fibers (vCFs) and high waste rates from traditional manufacturing methods underscore the need to effectively reuse recyclates in many industries, including the automotive, aerospace, energy, sport and leisure, and construction industries. The cost-efficiency of recycled carbon fibers (rCFs) (Table 1) is unlocking new possibilities where the high price of vCF previously limited its use. This broader application spectrum fosters further innovation and contributes to the circular economy by repurposing high-performance materials across industries.

Recent research demonstrates rCFRPs can deliver competitive mechanical performance while substantially improving economic and environmental sustainability. Hagnell and Åkermo (Hagnell and Åkermo, 2019) quantified this potential through a recyclate value model, showing that structural use of rCFs can reduce material costs by up to 50% without significant performance losses. This finding emphasizes the importance of advancing recycling and sorting technologies to preserve fiber quality and maximize lifecycle value. Similarly, Palmer et al. (Palmer et al., 2010) demonstrated that integrating coarse rCF into SMC formulations allows mechanical properties comparable to conventional grades when well-controlled fiber distribution offers a

pathway to scalable, cost-efficient structural composites.

Process innovation further enhances the performance potential of rCF materials. Kiss et al. (Kiss et al., 2020) introduced an in-house recycling and co-molding technique, using shredded rCF waste as core layers between continuous-fiber skins to create high-performance laminates with near-virgin properties. Legenstein et al. (Legenstein et al., 2024) extended this concept to automated fiber placement (AFP), showing that aligned IM7 rCFs in a PEI matrix enable defect-free deposition on tight radii and dramatically improve steerability—expanding design freedom for aerospace-grade structures. Beyond polymer matrices, Kessel et al. (Kessel et al., 2021) demonstrated that wet-laid nonwoven processing of hybrid ceramic matrix composites (CMCs) offers precise microstructural control and reduced production costs, while Bianchi et al. (Bianchi et al., 2023) confirmed via LCA that rCF-based CMC brakes outperform cast iron alternatives over long service life due to reduced environmental burdens. Geier et al. (Geier et al., 2022a, 2022b) showed that rCFRPs exhibit slightly higher thrust and torque during drilling but reduced burr formation and negligible microstructural damage, confirming their industrial machinability and processing robustness.

5.1. Aerospace industry

The aviation sector faces growing pressure to integrate rCF into its supply chain as part of broader decarbonization and circular-economy goals. As Vieira et al. (Vieira et al., 2017) note, next-generation aircraft such as the Airbus A350 (53% CFRP by weight) and Boeing 787 (50%) will generate substantial end-of-life (EoL) waste, estimated at 3,000 tonnes of CFRP annually by 2030. Yet, market development for rCFRP in aerospace is hindered less by mechanical limitations than by certification, traceability, and standardization barriers. At present, the use of rCFRP in aerospace applications remains largely confined to secondary structures, driven mainly by certification-related challenges rather than intrinsic material limitations. Key barriers include batch-to-batch variability in fiber length, surface condition, and mechanical properties arising from heterogeneous feedstock and recycling processes, which complicates the establishment of statistically robust design allowables and knock-down factors. In addition, the availability of long-term durability data, particularly for fatigue, creep, environmental aging, multiple recycling, and damage tolerance under aerospace-relevant service conditions, remains limited. A further challenge is the absence of non-destructive inspection (NDI) standards and acceptance criteria tailored to discontinuous and stochastic rCF architectures, which differ fundamentally from conventional continuous-fiber laminates. Additional barriers include limited traceability of recycled feedstock, insufficiently standardized qualification protocols, and challenges in defining representative material allowables for highly heterogeneous microstructures. These issues collectively hinder compliance with conservative aerospace certification frameworks. Addressing these issues will require improved process control, standardized qualification protocols, and certification frameworks adapted to the specific characteristics of rCF-based composite systems.

Lifecycle and process-level studies reinforce the economic and environmental potential of circular aviation. Ribeiro and Gomes (Ribeiro and Gomes, 2015) demonstrated, via the PAMELA project, that 85% of an aircraft's mass can be recovered through systematic dismantling and recycling, while Meng et al. (Meng et al., 2020) found that substituting rCF for GFRP in aircraft interiors can reduce environmental impacts by 4–31% and costs by up to 31%. Translating such benefits to primary aerospace structures requires industry-wide data sharing and pre-competitive round-robin testing to establish consensus mechanical allowables and fatigue/durability baselines.

Industrial initiatives show steady progress. Boeing's ecoDemonstrator program ("Boeing ecoDemonstrator," 2025) (2019–2024) has incorporated rCF-based lavatory floors and interior panels, cutting cabin weight and improving durability, while Airbus's Aircraft Dismantling

and Recycling Project in China (2025) ("HRC, Airbus LSC launch aircraft dismantling, recycling project," 2025), and Thermoplastic Fuselage Demonstrator under Clean Sky 2 2 ("Fantastic thermoplastics | Airbus," 2024) highlight the move toward recyclable thermoplastic composites. The V-Carbon LIFE Project ("V-Carbon LIFE Project," 2025) further advances a low-energy solvolysis route targeting 2,000 tonnes of CFRP recycling per year across multiple sectors, supporting a closed-loop material supply chain.

5.2. Automotive industry

The automotive sector has emerged as the most dynamic adopter of rCF materials, driven by cost, lower certification barriers, sustainability, and lightweighting imperatives. Industrial pioneers such as McLaren Racing have showcased the potential of rCF in high-performance applications ("McLaren Racing pioneers use of sustainable materials with innovative recycled carbon fibre trial," 2025), demonstrating up to 90% life-cycle emission reductions through V-Carbon's reclaimed fibers integrated into Formula 1 cockpit panels. Similarly, the BMW Group, through its joint venture with Boeing and SGL Automotive Carbon Fibers ("BMW Group und Boeing vereinbaren Zusammenarbeit beim Recycling von Carbonfasern," 2025), has achieved large-scale implementation of rCFRP in vehicles like the i3 and i8, where recycled fibers are blended into non-woven and structural components such as the C-pillar shell—delivering both cost and performance benefits. Parallel developments by Toyota using Mitsubishi Rayon's SMC technology and non-woven exterior materials illustrate how process adaptability expands rCF applications across diverse thermoset and thermoplastic platforms components ("Toyota Industries Corporation Wins JEC Composites Innovation Awards for CFRP Recycling Technology and Recycling System | Toyota Industries Corporation," 2025). Ishikawa et al. (Ishikawa et al., 2018) and Wan et al. (Wan and Takahashi, 2021) highlight advancements in CFRTP in Japan, introducing predictive methods supporting the use of rCF to improve the weight reduction of parts, cost-effectiveness. Recently, Lotus has unveiled the Theory 1 supercar concept ("https://www.lotuscars.com/en/theory1," 2025), which incorporates extensive carbon and recyclable materials for a lightweight structure.

At the materials supply level, Mitsubishi Chemicals ("Recycled Carbon Fiber," 2025), Asahi Kasei ("Recycling technology for inexpensive, high-quality carbon fiber - Asahi Kasei Automotive Europe," 2023), and Angeloni Group ("Angeloni Group and Herambiente," 2025), alongside certified recyclers such as CFK Valley Stade Recycling, establish industrial ecosystems capable of processing thousands of tonnes of CFRP waste annually. Technologies like carboNXT, which thermally reclaims pure CFs (80–500 μm) from composite scrap, and low-energy solvolysis systems under development by Asahi Kasei, exemplify scalable, high-yield recovery models that balance fiber integrity with environmental efficiency.

Academic and industrial research underscores that mechanical performance and sustainability gains are not mutually exclusive. Feraboli et al. (Feraboli et al., 2012) showed that long entangled fibers recovered via chemical reclamation can achieve up to 33% fiber volume fractions while maintaining reusability in standard molding operations. Stelzer et al. (Stelzer et al., 2022) validated this with a one-shot SMC process combining virgin and recycled fibers, producing mechanical properties comparable to conventional materials with reduced life-cycle impacts. He et al. (He et al., 2023) demonstrated that preserving woven fiber architecture during recycling enhances flexural strength fourfold and reduces GHG emissions by 11–23%, depending on powertrain type. Barnett et al. (Barnett et al., 2023; Barnett et al., 2021b) further confirmed that rCFRPs exhibit crash energy absorption comparable to virgin laminates, making them viable for automotive safety structures.

From a systems perspective, Iyer et al. (Iyer et al., 2024) introduced multi-objective optimization to minimize life-cycle cost (LCC) and cumulative energy demand (CED), while Meng et al. (Meng et al., 2017)

show that rCF in automotive applications reduces environmental impacts, including greenhouse gas emissions and primarily energy demand, compared to other structural materials. Hecker et al. (Hecker et al., 2023a) emphasized the role of end-of-life integration and fiber realignment (HiPerDiF) in closing material loops across automotive and marine sectors.

5.3. Wind energy sector

The use of CFRPs in wind turbine (WT) blades remains concentrated in high-performance designs where stiffness-to-weight optimization is critical. While most commercial blades rely on glass fiber composites, CFRP is increasingly applied in spar caps and critical load-bearing zones, constituting 5–20% of large offshore blades ($\geq$70 m) and reaching over 60% CFRP content in specific designs. Projections indicate that by 2028, 70% of new blades may incorporate CFRP spar caps, reflecting their importance for next-generation, long-span rotors (Lefeuvre et al., 2019). However, this growth amplifies EoL waste challenges, 225,000 tons of rotor blade material will require recycling annually by 2034 (Chen et al., 2019; Cherrington et al., 2012; Liu and Barlow, 2017; Rani et al., 2021). The heterogeneous composition of WT blades, combining CFs and GFs, thermoset or thermoplastic matrices, core foams, coatings, and adhesives, complicates recycling and material recovery. Current EoL practices still rely on landfilling and incineration, both of which are restricted under EU legislation, pushing the industry toward recycling and energy recovery. Cherrington et al. (Cherrington et al., 2012) and Liu and Barlow (Liu and Barlow, 2017) converge on the need for extended producer responsibility, design-for-recyclability, and market incentives for secondary raw materials. They argue that economic viability depends as much on regulatory pressure as on technical feasibility, particularly in developing reliable routes for high-value reuse of recovered fibers.

Recent reviews by Rani et al. (Rani et al., 2021) and Khalid et al. (Yasir Khalid et al., 2023) classify mechanical, thermal, chemical, and hybrid recycling processes for WT composites, underscoring that chemical and hybrid routes yield the highest fiber quality but remain cost- and energy-intensive. Khalid et al. (Yasir Khalid et al., 2023) highlight emerging reuse pathways for recovered rCF, including concrete reinforcement, 3D printing feedstock, and lightweight structural elements, marking a transition toward circular material loops. Chen et al. (Chen et al., 2019) further emphasize innovations in reprocessable thermoset systems with active covalent bonds that could enable reshaping and reprocessing, though these remain in early development.

Several pilot projects have successfully incorporated rCF into WT blade designs, showcasing its recyclability, sustainability, and performance capabilities. Siemens Gamesa's 2020 recyclable blade ("Siemens Gamesa RecyclableBlade," 2025) features a resin system allowing rCF to be recovered and reused. Vestas partnered with Carbon Clean Solutions to upcycle rCFs from decommissioned blades, reducing reliance on vCF while maintaining high-quality standards ("Vestas unveils circularity solution to end landfill for turbine blades," 2025). GE Renewable Energy's Haliade-X turbine, launched in 2019 ("GE Haliade-X 12 MW turbine blade delivered for testing," 2025), uses rCF and bio-based resins to reduce the environmental impacts of manufacturing. LM Wind Power and Tencate are developing a pilot production line to integrate rCF into a new generation of blades ("LM Wind Power readies first recyclable wind turbine blade prototype under ZEBRA project | LM Wind Power," 2025), improving sustainability and reducing costs. These projects showcase significant progress in making wind turbine blades more sustainable through the integration of rCF.

5.4. Construction industry

Yazdanbakhsh and Bank (Yazdanbakhsh and Bank, 2014) and Li et al. (Li et al., 2024) reviewed the reuse of FRP waste as aggregate replacement for cementitious materials, noting benefits for sustainability but variable effects on concrete strength due to poor interfacial bonding. More recent studies highlight advances in performance optimization: Wang et al. (Wang et al., 2023) demonstrated that rCFs can enhance compressive and flexural strength, though improvements depend strongly on fiber aspect ratio, volume fraction, and surface treatment. Li et al. (Li et al., 2023) achieved further gains through hydrogen peroxide modification, improving fiber–matrix adhesion and mechanical properties. Similarly, Belli et al. (Belli et al., 2023) showed that rCFs, when combined with industrial by-products such as foundry sand or gasification char, not only reinforce mortars but also enhance durability and piezoresistive sensing.

5.5. Multifunctional rCFRPs

Recycled CFs are increasingly recognized enablers of multifunctional performance in advanced composites. May et al. (May et al., 2021) emphasize that rCFs retain distinctive attributes, quasi-plastic deformation, fiber steerability, deep-draw formability, and high energy absorption, that enhance processability and crashworthiness. Their inherent electrical conductivity enables integration into smart, functional materials such as electromagnetic interference (EMI) shields, sensors, and heating elements. Meredith et al. (Meredith et al., 2012) demonstrated that rCFs retain 65% to 94% of the mechanical properties of vCFs, such as compressive strength and energy absorption capacity. Similarly, Quan et al. (Quan et al., 2023, 2022) demonstrated that incorporating rCF or rCF/PPS mats can increase interlaminar fracture toughness by up to 220%, underscoring their potential in high-integrity structural laminates.

High-performance thermoplastics and tribomaterials further benefit from rCF integration. Lin et al. (Lin et al., 2022) found that rCF/PEEK composites outperform commercial tribological materials, offering superior friction and wear resistance irrespective of recycling history. Novel surface treatments also expand rCF functionality. Pakdel et al. (Pakdel et al., 2021c) developed superhydrophobic rCF nonwovens with PDMS/ZIF-8 coatings, achieving a 153.5° contact angle and > 99% oil–water separation, suggesting potential for filtration and environmental remediation.

The electrical conductivity of rCF enables additional multifunctional uses. Pang et al. (Pang et al., 2013) produced wet-laid rCF sheets with 2.8×10^3 S/m conductivity, capable of stable Joule heating over 3,000 cycles. Reese et al. (Reese et al., 2020) demonstrated rCF-based hybrid yarns for thermoplastic composites that heat uniformly within 15 s, maintaining low void content and high flexural strength. Building on these capabilities, Duan et al. (Duan et al., 2023) created rCF@PPy/MXene EMI-shielding composites, achieving 162.9 S/m conductivity, 60 dB shielding, and 186 °C heating at 3.4 V, while Pakdel et al. (Pakdel et al., 2021a) achieved up to 85 dB EMI shielding in CF/PA6 hybrid nonwovens. Similarly, Hu et al. (Hu et al., 2023, p. 20) produced conductive rCF felts via eco-friendly papermaking, yielding 66 dB EMI performance, and Wang et al. (Wang et al., 2024) used two-step pyrolysis to preserve fiber integrity, achieving 70.5 dB shielding and excellent recyclability over ten reuse cycles.

Beyond EMI applications, surface-engineered rCFs enable next-generation energy devices. Zhao et al. (Zhao et al., 2022) enhanced the electrochemical capacitance to 122.2F/g with 100% stability over 30,000 cycles, indicating promise for supercapacitors and energy storage. Complementary reviews, such as Huang et al. (Huang et al., 2019), further position rCF as a sustainable conductive filler in biodegradable and recyclable polymer matrices, bridging high performance with environmental responsibility. Wider acceptance will depend on standardized qualification, fatigue data, and multifunctional benchmarking across industrial sectors.

6. Conclusions, future trends and outlook

The future development of carbon fiber-reinforced polymer

composites (CFRP) recycling is expected to evolve along integrated and synergistic pathways that improve process efficiency, material quality, and circularity across the entire value chain. As an emerging field, every new study contributes to expanding the collective understanding of how fiber reclamation quality, remanufacturing architectures, and composite performance are interlinked. This review highlights that the greatest gains will arise from technologies that tightly control reclamation parameters and translate reclaimed fiber quality into highly aligned, high-volume-fraction intermediates. Hybrid recycling methods show strong potential to maximize the fiber retention while restoring surface chemistry. When coupled with advanced alignment solutions such as TuFF and HiPerDiF, as well as hybrid yarn technologies, these approaches enable rCFRPs to achieve near-virgin mechanical performance. By considering qualitative mechanical data across processes, this review establishes a reference benchmark that future studies can use to position new findings relative to earlier work, strengthening comparability and accelerating progress toward high-performance circular composite systems.

Standardization and quality control must become a central research and policy focus to ensure these developments translate into industrial practice. The absence of harmonized testing, classification, and certification protocols for recycled carbon fibers (rCFs) currently constrains scalability and cross-sector interoperability. Standardized quality benchmarks—including fiber morphology, tensile retention, surface chemistry, and sizing compatibility—would enable consistent product qualification and supply-chain traceability.

Parallel progress in design-for-recycling is essential to embed circularity at the product level. Industry-wide guidelines for recycling-ready CFRP design, addressing fiber–matrix combinations, disassembly strategies, and compatible surface treatments, would help reduce waste generation and facilitate closed-loop processing. Digitalization, including multiscale modeling, machine learning, and digital twin frameworks, will further accelerate this transition by predicting process outcomes and optimizing recycling efficiency before manufacturing.

Economically, widespread adoption of rCF will depend on achieving cost parity with glass fiber and lowering process energy consumption. Life-cycle analyses suggest that achieving recycled fiber production costs of \$10–15/kg—compared to \$20–35/kg for virgin CF—could enable mass-market penetration in automotive, wind, and construction sectors. Reaching these thresholds requires automation, modular recycling plants, and integration of reclamation directly into composite manufacturing ecosystems.

Despite remarkable progress, persistent challenges remain:

- Lack of Standardization: A lack of harmonized protocols for quality assessment, testing, and classification of rCFs limits industrial scalability and cross-sector application.
- Material heterogeneity limits performance predictability and quality assurance.
- Interface engineering between rCFs and matrices remains insufficiently understood.
- Economic scalability is constrained by batch variability and process complexity.
- Process Integration: Further efforts are required to integrate rCF processing into existing composite manufacturing lines, with minimal disruption and maximum circularity.

Targeted research into surface functionalization, hybrid process integration, and industrial automation, combined with policy incentives and cross-sector collaboration, will be decisive in overcoming these barriers.

By embedding standardized quality protocols, advancing hybrid recycling technologies, developing recycling-conscious design guidelines, and defining economic thresholds for market entry, the composites industry can transform CFRP recycling from a niche research activity into a mainstream enabler of sustainable manufacturing—delivering both environmental and economic gains across multiple sectors.

CRediT authorship contribution statement

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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