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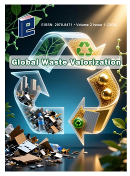

Review Article

A Comprehensive Review on the Recycling of Carbon Fibre – Reinforced Polymer Composite: Recovery Techniques, Material Performance, and Sustainability

Alhayat Getu Temesgen[1,2], Holger Cebulla[1]

[1]Chenmitz University of Technology, Chemnitz, Germany

[2]Wollo University, Kombolcha Institute of Technology, Kombolcha, Ethiopia

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ABSTRACT

Carbon fiber–reinforced polymer (CFRP) composites are increasingly used in the aerospace, automotive, wind energy, and construction sectors due to their superior mechanical properties, lightweight nature, and corrosion resistance. However, the rapid growth in CFRP applications has resulted in significant volumes of manufacturing scrap and end-of-life composite waste, posing environmental and economic challenges . Conventional disposal methods such as landfilling and incineration are unsustainable and increasingly restricted by environmental regulations. Consequently, recycling of CFRP waste has become a critical research and industrial focus. This review presents a comprehensive overview of current recycling technologies for carbon fiber–reinforced polymer composites, emphasizing fiber recovery techniques, properties of recycled carbon fibers, and sustainability considerations through life cycle analysis (LCA). Mechanical, thermal, and chemical recycling routes are discussed in detail, along with their advantages, limitations, and technological maturity. The influence of recycling processes on fiber morphology, surface chemistry, and mechanical performance is analyzed. Furthermore, environmental impacts, energy consumption, and economic feasibility of different recycling pathways are compared. Key challenges, industrial barriers, and future research directions toward circular and sustainable CFRP utilization are also highlighted.

*CORRESPONDING AUTHOR

Alhayat Getu Temesgen; Wollo University, Kombolcha Institute of Technology, Kombolcha, Ethiopia; Email: alhayat@kiot.edu.et

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1. Introduction and Background on CFRP Waste Generation

1.1. Carbon Fibre–Reinforced Polymer (CFRP) Applications and Market Growth

Carbon fiber-reinforced polymer (CFRP) composites have emerged as the preferred materials in a variety of high-performance engineering sectors due to their exceptional properties, which include a high strength-to-weight ratio, superior stiffness, excellent fatigue resistance, and outstanding corrosion resistance [1,2]. The aerospace industry continues to be the largest consumer of CFRP materials, with modern commercial aircraft like the Boeing 787 Dreamliner and Airbus A350 XWB using up to 50% composite materials by weight in their structural components [3]. CFRP technology is increasingly being used in the automobile industry to meet tight fuel efficiency rules and minimize vehicle emissions, with prominent applications including high-performance vehicles and electric vehicle battery enclosures [4,5]. Another notable application domain is wind energy, where CFRP materials are widely employed in turbine blade fabrication to produce longer blade lengths and increased energy capture efficiency [6]. The global CFRP market has expanded dramatically during the last two decades, with annual production volumes exceeding 100,000 tons and expected to reach 200,000 tons by 2030 [7,8]. This rapid expansion, although showcasing CFRP materials' scientific prowess, has raised serious environmental issues about waste management and end-of-life disposal.

1.2. CFRP Waste Generation and Environmental Challenges

CFRP waste comes from a variety of sources during the material's lifecycle, including manufacturing scrap, which accounts for 30-40% of production volume, off-spec components, production trim waste, and end-of-life products [9,10]. Manufacturing trash alone creates roughly 30,000 tones per year, while the accumulated stock of end-of-life CFRP products, particularly from early aircraft applications and first-generation wind turbines, is approaching the disposal stage [11]. The inherent features of the most common-based CFRPs, which account for about 80% of current composite applications [12], add to the environmental dilemma. Unlike thermoplastic polymers, thermoset resins undergo irreversible cross-linking during curing, making them non-reprocessable using traditional melting and remolding procedures [13]. As a result, traditional waste management methods such as landfilling and incineration have long been used, despite their severe environmental disadvantages. Landfilling CFRP trash raises several difficulties, including long-term environmental persistence due to the non-biodegradability of carbon fibers and polymer matrices, use of limited landfill area, and irreversible loss of important carbon fiber materials [14]. While incineration reduces trash volume, it does not recover valuable carbon fiber reinforcement and emits large amounts of carbon dioxide [15]. Virgin carbon fiber production has a significant environmental impact, with estimates ranging from 183 to 286 MJ/kg of energy usage and 20 to 31 kg CO_2 equivalent emissions per kilogram produced [16,17]. These values significantly exceed those associated with conventional structural materials such as aluminium and steel, emphasizing the critical importance of material recovery and recycling strategies.

1.3. Regulatory Framework and Industry Drivers

In response to these environmental issues, and motivated by circular economy concepts, legislative frameworks around the world have imposed stricter regulations governing composite waste disposal [18]. The Waste Framework Directive and End-of-Life Vehicles Directive of the European Union have defined hierarchical waste management priorities, with prevention, reuse, recycling, and recovery taking precedence over disposal [19]. Similarly, the United States Environmental Protection Agency has designated certain composite industrial wastes as hazardous compounds, requiring careful handling and disposal [20]. These legal requirements, together with corporate sustainability pledges and rising environmental consciousness, have fueled extensive research and development efforts into CFRP recycling solutions [21]. Virgin carbon fibers attract high prices, ranging from $15 to $35 per kilogram for industrial-grade materials to more than $150 per kilogram for aerospace-grade fibers [22]. Depending on quality and processing route, recycled carbon fibers can potentially be generated for 20-50% of the cost of new material, giving compelling economic incentives for material recovery [23].

2. Carbon Fibre–Reinforced Polymer (CFRP) Material Architecture and Composition

2.1. Constituent Materials and Structure

CFRPs are made up of high-strength carbon fibers embedded in a polymer matrix phase such as epoxy, polyester, or vinyl ester resins [24]. Carbon fibers, which form the principal reinforcing phase, are created by controlled thermal degradation and carbonization of organic precursor materials such as polyacrylonitrile (PAN), pitch, or regenerated cellulose [25]. To obtain the desired crystalline structure and characteristics, the manufacturing process includes precursor fiber spinning, stabilization through oxidation (200-300°C), carbonization at elevated temperatures (1000-1500°C), and optional graphitization (2000-3000°C) [26]. The resultant carbon fibers have remarkable mechanical properties, with tensile strengths ranging from 3 to 7 GPa, tensile moduli from 200 to 900 GPa, and elongation at break typically between 1 and 2% [27]. PAN-based carbon fibers, which account for over 90% of global output, have a turbostratic carbon structure with imperfectly aligned graphitic crystallites orientated preferentially along the fiber axis [28]. Fibre widths typically range from 5 to 10 micrometers, with continuous fiber lengths restricted primarily by production and handling limits.

2.2. Matrix Systems and Interfacial Characteristics

The polymer matrix phase performs a variety of key tasks in CFRP composites, including load transfer between fibers, fibre protection from environmental degradation, transverse and shear strength, and determination of overall composite processing properties [29]. Because of their superior mechanical qualities, dimensional stability, chemical resistance, and compatibility with a wide range of manufacturing processes, thermoset resins, particularly epoxy systems, dominate high-performance CFRP applications [30]. Epoxy resins are created by crosslinking interactions between epoxide groups and curing agents, resulting in a three-dimensional network structure that is infusible and insoluble after curing [31]. Alternative matrix systems include polyester and vinyl ester resins, which are extensively used in low-cost applications like wind turbine blades, as well as thermoplastic matrices like PEEK, PEI, and PPs for specific high-temperature applications [32]. The matrix system used has a considerable impact on composite performance, processing requirements, and recyclability properties. The fiber-matrix interface is an important location for determining load transfer efficiency and environmental durability of CFRP composites [33]. Effective interfacial bonding necessitates suitable fibre surface chemistry, which is achieved by controlled oxidation to introduce oxygen-containing functional groups and the use of sizing agents that promote wetting and chemical bonding with the matrix [34]. Preserving or restoring proper fiber surface chemistry during recycling operations is critical for optimal reuse in secondary composite applications.

3. Overview of Carbon Fiber–reinforced Polymer (CFRP) Recycling Technologies

3.1. Classification of Recycling Approaches

Contemporary CFRP recycling processes are traditionally classified into three types: mechanical recycling, thermal recycling, and chemical recycling, as illustrated in Table 1 [35,36]. This group indicates significant differences in processing processes, operational factors, capital requirements, environmental implications, and recovered material properties. Each technological category has several distinct process variants, and hybrid techniques that combine aspects from other categories have also been researched. Mechanical recycling methods rely mostly on size reduction and physical separation techniques to recover composite materials in particle or short-fibre form [37]. These techniques gradually reduce CFRP waste to manageable particle sizes using standard comminution equipment such as shredders, hammer mills, cutting mills, and pin mills. The capacity to process mixed or polluted waste streams without requiring considerable pre-treatment, minimum energy usage, ease of operation, and comparatively low capital investment are only a few of the intrinsic benefits of mechanical recycling [38]. In order to recover comparatively clean carbon fibers, thermal recycling systems use high temperatures to break down the polymer matrix by pyrolysis, combustion, or fluidized bed processing [39]. The most extensively studied thermal method, pyrolysis, is heating CFRP waste in an oxygen-depleted atmosphere at temperatures usually between 400 and 700°C, resulting in thermal breakdown of the matrix resin while maintaining the integrity of carbon fiber [40]. Chemical recycling, also known as solvolysis, includes procedures that selectively dissolve or depolymerize polymer matrices using solvents and chemical reagents at high temperatures and pressures [41,42]. Water (hydrolysis), alcohols (alcoholysis), supercritical fluids, organic solvents, and ionic liquids are among the solvent systems that have been studied; each has unique benefits and difficulties.

3.2. Technology Selection Criteria

Numerous criteria, such as material composition, contamination level, waste volume, geographic location, accessible infrastructure, target application for recovered materials, and economic considerations, influence the choice of an acceptable recycling route for a particular waste stream [43]. Several performance characteristics, such as recovered fiber quality, processing costs, energy consumption, environmental implications, scalability, and suitability for various waste streams, must be considered when comparing recycling technologies [44]. According to recent techno-economic analyses, the most commercially viable and industrially developed method for large-scale CFRP recycling is thermal recycling, especially pyrolysis, which balances acceptable fiber quality with affordable processing costs and technical viability [45]. Chemical recycling shows promise for specialized applications requiring premium recycled fibers, but cost reduction and process simplification are required for widespread industrial adoption [46]. Mechanical recycling is still appealing for mixed waste streams and applications that can tolerate lower fiber performance.

Table 1. Overview of Carbon Fibre-Reinforced Polymer (CFRP) Recycling Technologies.

Technology	Process Description	Operating Conditions	Advantages	Disadvantages	Fibre Recovery Rate	Environmental Impact
Mechanical Recycling	Physical grinding, milling, or shredding of CFRP waste into smaller particles	Ambient temperature, no chemical/thermal treatment	• Low energy consumption • Simple equipment • Low cost • Environmentally friendly	• Significant fibre damage • Short fibre length (0.1-10mm) • Reduced mechanical properties • Matrix contamination	95-100%	Low CO_2 emissions, minimal waste
Pyrolysis	Thermal decomposition of resin matrix in inert atmosphere (N_2, Ar)	450-700°C, oxygen-free environment	• High fibre recovery • Retained fibre length • Good mechanical properties (90-99% tensile strength) • Scalable process	• High energy consumption • Fibre surface contamination • Toxic gas emissions • Requires post-treatment	80-95%	Moderate emissions, requires gas treatment
Fluidized Bed Process	Thermal degradation using hot gas stream with sand particles	450-550°C, fluidized bed reactor	• Continuous process • Good fibre recovery • Relatively clean fibres • Industrial scale available	• Fibre breakage due to abrasion • Reduced fibre length • Energy intensive • Complex equipment	70-90%	Moderate energy use, controlled emissions

Technology	Process Description	Operating Conditions	Advantages	Disadvantages	Fibre Recovery Rate	Environmental Impact
Chemical Recycling (Solvolysis)	Dissolution of resin using solvents, acids, or bases at elevated temperatures	150-350°C, various chemicals (alcohols, acids, supercritical fluids)	• Excellent fibre quality • Preserved fibre properties (95-100%) • Clean fibre surface • Potential resin recovery	• Chemical disposal issues • High solvent costs • Long processing times • Safety concerns	85-98%	Chemical waste generation, requires treatment
Supercritical Fluid	Use of supercritical water or CO_2 to decompose resin matrix	300-400°C, 20-40 MPa pressure	• Excellent fibre quality • No toxic emissions • Clean process • Complete resin removal	• Very high pressure requirements • Expensive equipment • High operational costs • Limited scalability	90-98%	Low emissions, environmentally favorable
Electrochemical	Electrochemical oxidation of resin in electrolytic solution	Room to 80°C, electrochemical cell	• Low temperature • Minimal fibre damage • Good energy efficiency • Clean fibres	• Slow process • Limited industrial application • Electrolyte management • Small scale only	80-95%	Low energy, minimal emissions
Microwave Pyrolysis	Selective heating using microwave radiation to decompose matrix	400-600°C, microwave field	• Rapid heating • Energy efficient • Selective heating • Good fibre properties	• Scale-up challenges • Non-uniform heating • Equipment costs • Limited penetration depth	85-95%	Lower energy than conventional pyrolysis

4. Mechanical Recycling of CFRP Composites

4.1. Process Description and Equipment

A variety of size reduction and physical separation techniques are used in the mechanical recycling of CFRP composites in order to recover composite materials in particle, flake, or short-fiber form that can be used in secondary products [47]. In order to break and separate the composite structure and, ideally, free individual fibers or fiber bundles from the surrounding matrix material, the basic method entails gradually comminution of CFRP waste using mechanical forces. To prepare waste materials for size reduction, pre-processing procedures are usually the first step in the mechanical recycling process. To reduce big components to dimensions compatible with later grinding equipment, initial shearing or cutting may be necessary [48]. To prevent equipment damage and enhance recyclize quality, it is frequently required to remove metallic fixtures, fasteners, core materials, or other non-composite ingredients. Bulky composite waste is first reduced in size to coarse particles or strips, usually 10-50 mm in size, using shredding procedures using revolving blades or hammers [49]. Shredders are appropriate for the primary processing of various waste streams since they can handle big feed materials and have a high throughput capacity. Shredding, however, results in extremely erratic particle morphologies with wide size variations, requiring further refinement steps. To impact and grind composite materials, hammer mills use freely swinging hammers fixed on a high-speed rotor inside a grinding chamber. Material is retained within the chamber until particles are sufficiently small to pass through discharge screens, enabling control of maximum particle size [50]. In contrast to impact-based techniques, cutting mills precisely shear composite materials into granulates using fixed and revolving blade arrays configured in a scissor-cutting arrangement, resulting in more uniform particle sizes with less fiber damage [51]. Material is exposed to high-speed impact and attrition between spinning and fixed pins arranged in concentric circles in pin mills, a specialized comminution technology. Strong shearing and grinding pressures produced by this arrangement can reduce composite materials to extremely fine powders, usually less than 500 micrometers [52]. In order to embrittle the matrix phase and enable more effective fracturing, cryogenic grinding entails cooling composite materials to temperatures below the glass transition temperature of the matrix resin, usually using liquid nitrogen, before mechanical processing [53].

4.2. Particle Characteristics and Energy Consumption

Processing factors and equipment choice have a significant impact on the morphology and particle size distribution of mechanically recycled CFRP materials. Particle sizes typically vary from less than 100 micrometers for finely ground powders to several millimeters for coarsely shredded materials [54]. Mechanical recycles have extremely polydisperse fiber length distributions, with mean lengths usually ranging from 0.1 to 3 mm, depending on the degree of processing. For mechanically recycled fibers, aspect ratios (length-to-diameter ratio), a crucial factor in determining reinforcing efficiency, typically range from 10 to 100. This is significantly lower than the aspect ratios surpassing 1000 that are typical of continuous virgin fibers, as shown in Table 2.Depending on target product size, material properties, and equipment efficiency, mechanical recycling uses a wide range of energy. Specific energy requirements have been reported to range from 0.2 to 2.0 kWh/kg, with larger energy input often needed for finer grinding [55]. Even though these values are significantly less than those of thermal or chemical recycling methods, they nonetheless entail high operating expenses. Another significant economic factor is equipment wear, since carbon fibers' abrasive properties quickly deteriorate cutting edges and grinding surfaces, requiring regular repair and replacement.

Table 2. Mechanical Properties of Recycled CFRP Composites.

Property	Virgin Carbon Fibres	Mechanically Recycled Fibres	Pyrolysis Recycled Fibres	Chemical Recycling Fibres	Supercritical Fluid Recycled	Testing Standard
Tensile Strength	3500-7000 MPa	1000-2500 MPa (29-71% retention)	3200-6500 MPa (90-99% retention)	3400-6800 MPa (95-100% retention)	3450-6900 MPa (97-100% retention)	ISO 527, ASTM D3039
Tensile Modulus	230-900 GPa	180-500 GPa (65-78% retention)	220-880 GPa (88-98% retention)	225-890 GPa (93-99% retention)	228-895 GPa (95-100% retention)	ISO 527, ASTM D3039
Elongation at Break	1.5-2.4%	0.8-1.5%	1.4-2.3%	1.5-2.4%	1.5-2.4%	ISO 527
Fibre Length	Continuous (>50mm)	0.1-10 mm (short fibres)	10-100 mm (medium to long)	20-150 mm (long fibres)	30-200 mm (long fibres)	Microscopy analysis
Fibre Diameter	5-7 μm	5-7 μm (unchanged)	5-7 μm (slight increase)	5-7 μm (unchanged)	5-7 μm (unchanged)	SEM analysis
Surface Quality	Clean, sized	Contaminated with matrix residue	Minor char residue (1-3%)	Clean, minimal residue (<0.5%)	Very clean (<0.1% residue)	TGA, XPS analysis
Density	1.75-1.95 g/cm³	1.70-1.90 g/cm³	1.74-1.93 g/cm³	1.75-1.95 g/cm³	1.75-1.95 g/cm³	ASTM D792
Composite Flexural Strength	800-1500 MPa	250-600 MPa (31-75% retention)	650-1350 MPa (81-90% retention)	720-1425 MPa (90-95% retention)	760-1470 MPa (95-98% retention)	ASTM D790
Composite Flexural Modulus	70-150 GPa	40-90 GPa (57-75% retention)	60-135 GPa (86-90% retention)	65-142 GPa (93-95% retention)	67-147 GPa (96-98% retention)	ASTM D790
Impact Strength (Izod)	80-150 kJ/m²	25-60 kJ/m² (31-75% retention)	65-130 kJ/m² (81-87% retention)	70-140 kJ/m² (88-93% retention)	75-145 kJ/m² (94-97% retention)	ASTM D256
Interfacial Shear Strength	60-100 MPa	20-40 MPa (33-67% reduction)	45-85 MPa (75-85% retention)	50-92 MPa (83-92% retention)	55-97 MPa (92-97% retention)	Single fibre pull-out test
Void Content in Composite	<2%	3-8%	2-4%	1-3%	1-2%	Microscopy, density
Fibre Volume Fraction (achievable)	50-65%	15-35% (discontinuous)	35-55%	40-60%	45-62%	Burn-off test

4.3. Material Properties and Applications

Fiber length distribution, fiber orientation, fibre-matrix interfacial bonding in secondary composites, and the existence of residual matrix material all significantly influence the mechanical properties of recycled CFRP materials, as illustrated in Figure 1 [56]. Mechanical recycling invariably shortens fibers and causes structural degradation, both of which limit the effectiveness of reinforcement. Although there is significant variation based on processing severity, the tensile strength of mechanically recycled carbon fibers normally falls between 50 and 80% of virgin fiber strength [57]. Depending on the fiber content, dispersion quality, and matrix system, composite materials with mechanically recycled CFRP as discontinuous fiber reinforcement usually achieve tensile strengths of 50–200 MP a and tensile moduli of 10–30 GPa [58]. These characteristics make mechanically recycled materials ideal for non-structural or semi-structural uses. One of the principal applications for mechanically recycled CFRP materials is injection molding, where short fiber-reinforced pellets appropriate for traditional injection molding procedures are created by compounding ground composite with thermoplastic resins [59]. This method makes it possible to incorporate recycled carbon fibers into consumer goods, industrial parts, electrical housings, and automobile components. The mechanical properties are in the middle of those of continuous fiber composites and unreinforced thermoplastics, with typical fiber loadings ranging from 10 to 40 weight percent. Similar to this, compression molding applications create sheet molding compounds (SMC) or bulk molding compounds (BMC) by combining mechanically recycled CFRP with thermoplastic or thermoset matrices [60]. Another important use of industry is construction materials, especially in cementitious composites and concrete reinforcement. To improve flexural strength, impact resistance, and fracture resistance, ground CFRP recycle can be partially substituted for traditional steel or polymeric fiber reinforcement in concrete mixtures [61]. A similar use is asphalt modification, which involves adding mechanically recycled CFRP to bituminous mixtures for building roads. It has been demonstrated that adding recycled carbon fiber to asphalt pavements increases low-temperature crack resistance, decreases rutting, and improves fatigue resistance [62]. Mechanically recycled CFRP materials have inherent performance constraints, but their affordability and ease of processing make them useful for achieving circular economy goals.

Figure 1. Effect of Fiber properties on the mechanical Performance of Recycled CFRP.

5. Thermal Recycling Technologies

5.1. Pyrolysis Process and Parameters

Offering a compromise between recovered fiber quality, process complexity, and economic feasibility, pyrolysis is the most thoroughly studied and widely used thermal recycling technique for CFRP composites [63]. In order to thermally break down the polymer matrix into volatile organic compounds, condensable liquids, and solid, while maintaining the carbon fiber reinforcement, the pyrolysis process entails heating CFRP waste in an oxygen-depleted or inert atmosphere at high temperatures, usually 400–700°C [64]. Bond scission, depolymerization, and secondary reactions of main decomposition products are among the intricate free radical mechanisms that drive epoxy resin pyrolysis [65]. At temperatures between 300 and 350°C, the degradation begins with the cleavage of the weakest bonds, usually hydroxyl groups and ether linkages. At higher temperatures, the degradation progresses to more extensive backbone fragmentation. Carbon dioxide, water, aromatic hydrocarbons, phenolic compounds, and several low molecular weight volatiles are the main products of pyrolysis. The configurations of pyrolysis systems differ significantly based on the size of the processing, the properties of the feed material, and the intended process control. Batch pyrolysis systems provide operational simplicity and flexibility by loading discrete amounts of CFRP waste into a reactor, heating it to the desired temperature, keeping it there for a predetermined amount of time, then cooling and unloading it [66]. However, there is a lot of thermal cycling in batch processing, which limits energy efficiency and throughput. Through steady-state operation and the possibility of waste heat recovery, continuous pyrolysis systems allow for increased throughput and enhanced energy efficiency [67]. In pyrolysis processing, temperature selection represents a trade-off between conflicting goals. Lower temperatures, usually between 400 and 500°C, reduce energy consumption and fiber deterioration, but they also necessitate longer residence durations and may leave recovered fibers with significant char residue [68]. Higher temperatures (600–700°C) speed up matrix breakdown and lessen the creation of char, but they also use more energy and raise the danger of fiber oxidation if residual oxygen is present. To balance these factors, the majority of industrial pyrolysis facilities run between 500 and 600°C.

5.2. Fibre Quality and Post-Treatment

The processing conditions and subsequent post-treatments have a significant impact on the quality of pyrolyzed carbon fibers. 75–95% of the initial tensile strength is usually retained by as-recovered fibers, with greater retention at lower processing temperatures and shorter residence times [69]. Nevertheless, residual char, which is made up of partially graphitized carbon from incomplete resin breakdown, contaminates fiber surfaces. In secondary composites, this char layer, which is usually 10–100 nanometers thick, interferes with fiber-matrix bonding and needs to be eliminated by oxidative post-treatment. In oxidative char removal, recovered fibers are heated to 400–600°C for 10–60 minutes in air or oxygen-enriched environments. Because of its higher surface area and lesser graphitic order than the underlying carbon fiber, the char oxidizes preferentially, allowing for selective removal without significant fiber damage [70]. Optimizing oxidation conditions is crucial, though, since insufficient treatment results in residual contamination while excessive treatment oxidizes the fiber surface and reduces strength. To restore the functionality and size of the fiber surface, post-pyrolysis surface treatment may also be necessary. Nearly all of the surface oxygen groups and sizing agents that were initially present on virgin fibers are eliminated by pyroly sis, which may jeopardize interfacial bonding in recycled composites. Composite performance can be significantly enhanced by reapplying commercial sizing chemicals suitable for target matrix systems [71].

5.3. Fluidized Bed and Microwave Processing

An alternate thermal recycling method is called "fluidized bed processing," in which CFRP trash is added to a heated bed of granular material, usually sand or alumina particles, and kept fluidized by upward-flowing gas [72]. Intense turbulent mixing, superior heat transmission, and continuous processing of heterogeneous waste streams are all made possible by fluidization. The usual operating temperature range is between 450 and 550°C. When compared to traditional pyrolysis reactors, the fluidized bed environment has a number of unique benefits, such as even temperature distribution and the removal of hotspots that could lead to localized fiber degradation [73]. However, because of constant abrasion and interaction with bed particles, fluidized bed processing places mechanical pressures on fibers, resulting in a loss in fiber length. In contrast to the 10–50 mm that can be achieved in static pyrolysis procedures, recovered fibers usually have mean lengths of 3–10 mm [74]. A possible alternative to thermal recycling is micro wave-assisted pyrolysis,which uses electromagnetic radiation at frequencies of 2.45 GHz to quickly and volumetrically heat CFRP waste [75]. The basic idea allows for selective and effective matrix heating by taking advantage of the polymer matrix's differential absorption of microwave energy, which typically shows higher dielectric loss than arbon fibers. Compared to traditional methods, microwave pyrolysis offers significantly faster processing times; full matrix breakdown can be accomplished in minutes as opposed to tens of minutes or hours [76]. Instead of heating the massive thermal masses of reactor structures, direct energy coupling to the material can result in higher energy efficiency. Studies show that microwave pyrolysis uses 1.8–5.0 MJ/kg of energy, which is 30–60% less than traditional thermal processing [77].However, maintaining consistent microwave field distribution within processing chambers and the high capital cost of commercial microwave generators are two technical obstacles that prevent microwave-assisted processing from being widely used in industry.

5.4. Industrial Implementation and Economics

The significant thermal energy needed for heating and the possibility of recovering energy from pyrolysis volatiles are reflected in the energy balance of pyrolysis recycling. Depending on reactor efficiency, operating temperature, and degree of heat recovery, pyrolysis processing energy consumption usually ranges from 6 to 15 MJ/kg of processed waste [78]. A partial energy offset from the combustion of condensable liquids and pyrolysis gases may lower net energy consumption to 3–8 MJ/kg. According to an economic analysis of pyrolysis recycling, the cost of producing recovered fibers ranges from $7 to $15/kg, depending on the size of the plant, the cost of acquiring feedstock, the cost of energy, and the need for labor [79]. These amounts amount to between 20 and 50 percent of the cost of raw carbon fiber, making them potentially profitable for markets that tolerate shorter fibers with somewhat lower mechanical qualities.Depending on processing capacity and level of automation, commercial-scale pyrolysis facilities can require a capital investment of $5–20 million. For the purpose of recycling CFRP, a number of businesses have established commercial pyrolysis facilities. One of the biggest pyrolysis recyclers, ELG Carbon Fibre Ltd. operates facilities in the UK and processes manufacturing scrap and end-of-life compo sites from automotive and aerospace sources [80]. These commercial applications show that pyrolysis recycling at a significant scale is both technically and financially feasible.

6. Chemical Recycling and Solvolysis Methods

6.1. Hydrolysis and Supercritical Water Processing

Chemical recycling, also known as solvolysis, includes procedures that use chemical reagents and solvents at high temperatures and pressures to selectively dissolve or depolymerize polymer matrices, as shown in Figure 2. This allows for the recovery of intact carbon fibers with better qualities than thermally recycled materials. The basic method takes use of chemical processes that break backbone linkages and crosslinks in thermoset resins while mostly sparing carbon fibers [41]. The most straightforward conceptual strategy is hydrolysis, which uses water as the depolymerizing agent. Water gradually breaks down the crosslinked network in epoxy and polyester resins by reacting with ester linkages, amide bonds, and other hydrolyzable groups under subcritical circumstances (temperature below 374°C, pressure below 22.1 MPa) [42]. The use of acids, bases, or catalysts can speed up reaction rates under subcritical circumstances, which are typically slow and take hours to days to fully dissolve the matrix. Operating above the water's critical point (374°C, 22.1 MPa), supercritical water (scH_2O) solvolysis shows significantly increased reactivity because of altered physicochemical characteristics like low viscosity, high diffusivity, and a decreased dielectric constant. Water may dissolve a variety of chemical molecules and facilitate penetration into crosslinked polymer networks under supercritical circumstances because it behaves as both a polar and non-polar solvent [43]. At temperatures between 400 and 450°C and pressures between 25 and 30 MPa, supercritical water processing completely degrades epoxy resin in 10 to 60 minutes.

6.2. Alcoholysis and Organic Solvent Processes

Alcohols, usually methanol, ethanol, or propanol, are used as depolymerizing agents at subcritical or supercritical environments in alcoholysis processes, as shown in Figure 2. Through transesterification with ester linkages and nucleophilic assault on epoxide groups, alcohols react with epoxy resins, gradually depolymerizing the network [44]. In order to speed degradation, subcritical alcoholysis often calls for temperatures between 150 and 250°C, pressures between 2 and 5 MPa, and reaction periods between one and four hours. Acid or base catalysts are frequently used. Supercritical alcoholysis, which is carried out above the solvent's critical point (usually 240–290°C and 5–10 MPa for common alcohols), produces faster and more thorough degradation in 30–90 minutes without the need for catalysts. Compared to hydrolysis, alcoholysis has a number of benefits, such as the opportunity to recover valuable degradation products, lower operating temperatures and pressures for supercritical processing, and usually faster breakdown rates for epoxy resins [45] Acetone, dimethylformamide (DMF), N-methyl-2-pyrrolidone (NMP), and custom solvent blends are among the polar aprotic solvents used in organic solvent-based recycling processes to swell and dissolve polymer matrices at moderate temperatures, usually 150–250°C.In order to avoid the financial and safety issues related to high-pressure supercritical processing, these methods typically function at atmospheric or slightly higher pressure [46]. Depending on the solvent formulation, component thickness, and matrix composition, processing timeframes might vary from one to eight hours. Excellent fiber recovery with little mechanical damage and well -preserved surface characteristics is possible using organic solvent techniques. However, complete solvent recovery, which calls for distillation or other separation technologies, is crucial for both economic and environmental reasons. Even at low percentages, solvent losses raise serious operational expenses and environmental issues [47].

6.3. Emerging Solvent Systems

Ionic liquids (ILs) are a new class of solvents for CFRP recycling that have several significant advantages, including low vapor pressure (which eliminates solvent emissions), good thermal stability, customizable solvent characteristics, and great dissolving capability for various polymers, as shown in Figure 2. Research has shown that ionic liquids may effectively depolymerize epoxy, polyester, and other matrices at temperatures ranging from 150 to 250°C, with recovered fibres having tensile strengths greater than 95% of virgin values [48]. However, ionic liquid recycling confronts significant obstacles, including extremely expensive solvent prices ($50-500/kg), viscosity issues, and a lack of understanding of decomposition product chemistry. Supercritical carbon dioxide (scCO_2) has been examined as an environmentally benign solvent for CFRP recycling, offering advantages such as non-toxicity, low cost, and readily accessible critical conditions (31°C, 7.4 MPa). Supercritical CO_2 has low polarity and poor solvating power for thermoset resins, which requires co-solvents or chemical additions [49]. Despite technical difficulties, research on CO_2-based processing is nevertheless motivated by its environmental and safety benefits.

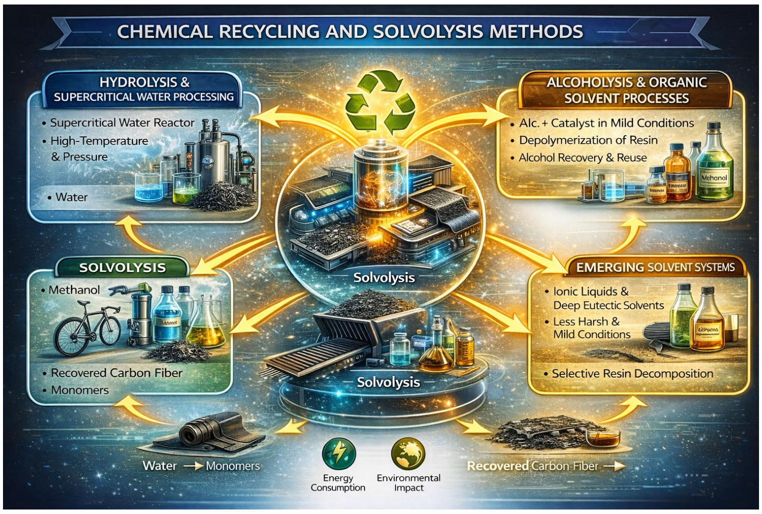

Figure 2. Common Chemical Recycling and Solvolysis Methods.

6.4. Fibre Quality and Economic Modeling of CFRP Recycling

The qualities of chemically recycled carbon fibers vary depending on the processing parameters and matrix composition, although they often outperform those of thermal recycling. Tensile strength retention of 90-100% relative to virgin fibers has been recorded for optimum solvolysis procedures, indicating low heat or chemical damage during processing [50]. The fiber length distribution is retained, allowing continuous fibers to be recovered from unidirectional laminates. Surface chemical changes are usually minimal, with oxygen concentration and functional group distributions similar to virgin fibers. However, chemical recycling faces tremendous economic and technical challenges to widespread industrial adoption. High-pressure processing equipment, solvent recovery systems, and auxiliary equipment have much higher capital costs than mechanical or pyrolytic techniques, with commercial-scale operations requiring an estimated facility investment of $15-40 million [51]. The anticipated cost of producing recovered fiber is $12–25/kg due to operating expenses. These economics are only partly feasible for recycled fibers of aerospace quality that fetch high prices. Chemical recycling involves significant process safety considerations, especially for supercritical fluid processes. To avoid catastrophic failures, high-pressure vessels must be rigorously designed, inspected, and maintained. Numerous solvents provide risks related to flammability, toxicity,or reactivity that call for suitable containment, ventilation, and emergency response systems [52]. Chemical recycling research is still ongoing despite technological and financial obstacles because of the promise for closed-loop material cycles and the superior quality of recovered fibers. Economic modeling of CFRP recycling facilities reveals that capital expenditures range from €2-10 million for small-to-medium scale pyrolysis plants to over €50 million for large industrial solvolysis operations, with annual operating costs significantly influenced by energy consumption, solvent recovery efficiency, and waste disposal requirements. Levelized cost estimates for recycled carbon fibers (rCF) vary substantially by technology, with pyrolysis-derived rCF typically costing €8-15 per kilogram compared to €15-25 per kilogram for high-quality solvolysis-recovered fibers, both remaining competitive only against virgin carbon fiber prices of €20-40 per kilogram depending on grade and specification. The economic feasibility of recycling operations depends critically on achieving sufficient throughput volumes, securing stable feedstock supplies from end-of-life products and manufacturing scrap, and developing premium markets for rCF that value the environmental benefits and accept the slightly reduced mechanical properties compared to virgin fibers.

6.5. Industrial Scale Recycling Processes

Industrial-scale CFRP recycling has been implemented through several commercial facilities utilizing pyrolysis and solvolysis technologies, with companies like ELG Carbon Fibre in the UK and CFK Valley Stade Recycling in Germany processing thousands of tons of composite waste annually from automotive and aerospace industries. Pyrolysis-based operations typically operate at temperatures between 450-700°C in controlled atmospheres to thermally decompose the resin matrix while preserving fiber integrity, with the recovered carbon fibers subsequently processed into non-woven mats, chopped fibers, or milled powders for reintegration into new composite applications. Solvolysis facilities employ chemical processes using solvents under elevated temperature and pressure conditions to dissolve polymer matrices, enabling higher fiber quality recovery compared to pyrolysis, though requiring sophisticated solvent recovery systems and hazardous waste management protocols to ensure environmental compliance. Despite these technological advances, industrial-scale recycling still faces economic challenges, including high operational costs, limited market demand for recycled fibers, and competition from low-cost virgin materials, resulting in recycling rates remaining below 10% of total CFRP waste generation globally.

7. Properties and Applications of Recycled Carbon Fibres

7.1. Characterization of Recycled Fibres

The economic value and environmental advantages of recycling operations are ultimately determined by the characteristics of recovered carbon fibers, which also play a crucial role in determining their appropriateness for subsequent uses, as illustrated in Figure 3 and Table 3. A thorough characterization includes morphological characteristics like length distribution and surface condition, mechanical characteristics like tensile strength and modulus, chemical characteristics with an emphasis on surface functionality, and physical characteristics like density and electrical conductivity [53]. Individual fiber strength can be directly measured via single-fiber tensile testing. Research comparingvirgin and recycled carbon fibers shows systematic differences: mechanically recycled fibers show the worst strength degradation, with typical decreases of 30–60% ascribed to internal flaws and surface damage [54]. Pyrolyzed fibers show a moderate strength retention of 75–90%, with surface effects caused by char and thermal oxidation being the degradation processes [55]. When processing conditions are optimized, chemically regenerated fibers retain 90–100% of their virgin strength [56]. Compared to strength, tensile modulus, as shown in Table 3, a measure of fiber stiffness, usually shows more resistance to degradation brought on by recycling. The main factors influencing the elastic modulus are the orientation and structure of carbon crystals, which are often insensitive to mild heat or chemical exposures [57].Even after significant strength losses, mechanically recycled fibers sometimes retain 80-95% of their virgin modulus. Pyrolyzed and chemically regenerated fibers usually retain 95-100% of their initial modulus values. Surface morphology and contamination have a substantial impact on the interfacial bonding of fibers and matrix in recycled composites. Surface treatments such as oxidative etching and sizing are meticulously tailored on virgin carbon fibers. Pyrolysis eliminates sizing and may destroy some surface functionality, while also depositing char residues that must be oxidatively removed [58]. Chemical recycling often maintains surface cleanliness more successfully than thermal processing, with fibers showing minimal contamination after proper washing techniques.

7.2. Secondary Applications and Market Development

One of the most important factors supporting sustainable CFRP recycling is the creation of profitable markets and uses for recycled carbon fibers. Low-value bulk commodities and comparatively high-performance engineered materials are just two examples of the wide range of current and developing uses [59]. A significant commercial use for recycled carbon fibers, especially those from thermal recycling, is the creation of a nonwoven mat. Recovered fibers are processed using carding, air-laying, or wet-laying methods to create random-orientation mats with areal weights that range from 25 to 400 g/m². These mats are used as conductive media in battery electrodes, reinforcement in compression-molded composites, and surface layers in sandwich constructions [60].For semi-structural parts like battery trays and underbody panels, the automotive industry has embraced recycled carbon fiber nonwoven mats. Another high-volume application is thermoplastic compounding, which uses extrusion or injection molding to incorporate mechanically or thermally recycled fibers into polymer matrices.10–40 weight percent recycled carbon fibers are used as reinforcement in polyamides (PA6, PA66), polypropylene (PP), and other technical thermoplastics [61]. Applications include consumer electronics, sporting products, industrial equipment, and automobile parts. Recycled carbon fiber thermoplastics greatly outperform virgin glass fiber reinforced materials, although their mechanical qualities are not as good as those of continuous fiber composites. It has been commercially proven that recycled carbon fibers may be used to produce bulk molding compound (BMC) and sheet molding compound (SMC). Chopped fibers are combined with fillers, additives, and unsaturated polyester or vinyl ester resins in these thermoset-based formulations [62]. Complex shapes for industrial components, electrical enclosures, and automobile body panels can be produced using compression molding. Applications for concrete reinforcement take advantage of carbon fibers' superior tensile strength and resistance to corrosion. Flexural strength, impact resistance, and durability are enhanced by mechanically or thermally recycled fibers at doses of 0.5–2.0 vol% [63]. Precast concrete components, tunnel linings, and bridge deck overlays are examples of applications. However, widespread usage is now restricted by the comparatively expensive cost of recycled carbon fibers in comparison to traditional concrete admixtures.

Figure 3. Application of Recycled Carbon Fibers and its composite.

7.3. Market Dynamics and Pricing

With current volumes estimated at 2,000–5,000 tonnes yearly compared to virgin fiber output surpassing 100,000 tonnes, the market for recycled carbon fibres is still relatively immature. However, it is anticipated that the market will rise by 15% to 25% a year due to increased recycling capacity, waste availability, and improved performance of recycled materials [64]. Demonstration of dependable supply, consistent quality, suitable certification and norms, and competitive economics are necessary to establish market acceptance. The supply chain, quantity, and quality of recycled carbon fibers all have a significant impact on price dynamics. For industrial grades, thermally recycled fibers usually fetch \$7–15/kg, which is roughly 30–50% of virgin equivalent pricing [65]. Higher-quality chemically recycled fibers could cost \$15–25/kg, which is still far less than the \$150/kg price of virgin aerospace-grade materials. Materials that are mechanically recycled are worth

$3–$8/kg. Applications that are prepared to pay premiums over virgin glass fibers ($2–5/kg) in order to offset increased processing costs are necessary for economic viability.

Table 3. Applications of Recycled CFRP Composites.

Application Sector	Specific Applications	Recycled Fibre Form Used	Required Properties	Current Industry Status	Key Manufacturers/ Projects	Challenges
Automotive	• Interior panels • Underbody shields • Battery housings (EV) • Engine covers • Acoustic insulation	Short fibres (mechanical) SMC/BMC compounds Non-woven mats	Moderate strength Lightweight Cost-effective Flame retardant	Commercially established	BMW, Audi, Ford, Toyota, ELG Carbon Fibre	Cost competitiveness with glass fibres, quality consistency
Aerospace	• Secondary structures • Interior cabin components • Cargo liners • Fairings • Non-critical parts	Long fibres (pyrolysis/chemical) Remanufactured prepreg	High strength retention (>85%) Certified quality Traceability	R&D/pilot stage	Boeing, Airbus, Gen 2 Carbon, ELG	Certification requirements, traceability, quality assurance
Wind Energy	• Blade reinforcement • Non-structural components • Nacelle covers • Access platforms	Medium/short fibres Chopped fibre compounds Compression molding	Good stiffness Fatigue resistance Cost reduction	Emerging/pilot projects	Vestas, Siemens Gamesa, CETEC, Procotex	Large volume handling, blade dismantling logistics
Sporting Goods	• Bicycle frames • Hockey sticks • Ski poles • Protective equipment • Racquets	Medium fibres Woven/non-woven fabrics Molding compounds	Good strength-to-weight Impact resistance Aesthetic quality	Commercially available	Various sporting goods manufacturers, Vite En Vrac, Karbon Kinetics	Consumer perception, premium market acceptance
Construction	• Reinforcement bars • Concrete reinforcement • Facade panels • Bridge strengthening • Seismic retrofit	Short/medium fibres Chopped strands Non-woven mats	Corrosion resistance High tensile strength Durability	Growing market	Infrastructure projects, Carbon Conversions	Building codes, long-term durability data
Electronics & Consumer Goods	• Laptop/phone cases • Drone frames • 3D printing filaments • Protective cases • Wearables	Short fibres Powder/pellet compounds Thermoplastic composites	Electromagnetic shielding Thermal management Surface finish	Commercially available	Various consumer electronics OEMs, Toray, Mitsubishi	Aesthetic requirements, thin-wall molding
Marine	• Non-structural components • Interior panels • Hull reinforcement • Deck fittings	Medium fibres SMC/BMC Hand layup compounds	Water resistance UV stability Corrosion resistance	Emerging applications	Boat manufacturers, marine composite suppliers	Marine certification, long-term water exposure data
Industrial Equipment	• Pressure vessels • Drive shafts • Rollers • Machine frames • Tooling	Long/medium fibres Filament winding Pultrusion	High stiffness Fatigue resistance Dimensional stability	Niche applications	Industrial manufacturers	Performance validation, quality certification
Rail Transport	• Interior panels • Seat components • Luggage racks • Floor panels	Short/medium fibres Non-woven mats Compression molding	Fire resistance Smoke/toxicity standards Durability	Growing adoption	Train manufacturers (Alstom, Bombardier), ELG	Fire safety regulations, smoke emission standards
Energy Storage	• Compressed gas tanks • Hydrogen storage • Battery enclosures • Structural batteries (EV)	Long fibres (chemical recycled) Filament winding High performance compounds	High strength Pressure resistance Crash safety	R&D/early adoption	EV manufacturers, hydrogen projects	Safety certification, pressure vessel standards
Additive Manufacturing	• 3D printing filaments • Rapid prototyping • Custom parts • Tooling inserts	Milled short fibres Powder compounds Thermoplastic pellets	Printability Layer adhesion Dimensional accuracy	Growing market	Markforged, 9T Labs, various filament suppliers	

7.4. Design For Recyclability

To enhance the practical relevance of design for recyclability in CFRP composites, several key strategies have been successfully implemented across industries, supported by concrete examples of closed-loop systems. Modular design approaches that facilitate disassembly, such as automakers' use of mechanical fasteners instead of adhesive bonding in their electric vehicle's CFRP passenger cell, enable easier separation of components for recycling at end-of-life. The substitution of traditional thermoset matrices with thermoplastic resins allows for remelting and reforming, as demonstrated by Airbus's thermoplastic CFRP components in the aircraft,which can be reshaped and reprocessed without losing structural integrity. Industrial closed-loop initiatives further illustrate practical implementation: Aircraft's recycling program recovers manufacturing scrap from their production and reprocesses it into chopped fiber reinforcement for automotive interior parts, while Vestas has developed a chemical recycling process that breaks down end-of-life wind turbine blades and reintroduces recovered fibers into new blade manufacturing. These examples demonstrate that incorporating recyclability considerations during the design phase, through material selection, joint design, and manufacturing process optimization, creates tangible pathways toward circular economy models in the CFRP industry.

8. Life-Cycle Assessment and Sustainability

8.1. Environmental Impact Analysis

Life-cycle assessment (LCA) offers methodical frameworks for comparing the environmental effects of recycling technologies to other scenarios, such as the creation of virgin materials, landfilling, and incineration, as illustrated in Figure 4. All life-cycle phases, such as material collection and transportation, recycling processing, upgrading and remanufacturing of recovered materials, and final disposal, are addressed in thorough life-cycle assessments [66]. When compared to the manufacture of virgin fiber, numerous life cycle assessments have repeatedly shown that recycling CFRP has significant environmental advantages. In comparison to the manufacturing of fresh carbon fiber, which requires 183–286 MJ/kg, pyrolysis recycling shows an energy consumption of 5–10 MJ/kg, including post-treatment, which represents a 95–97% reduction [67]. Pyrolyzed fibers emit 1.5-3.5 kilogram CO_2-eq/kg, while virgin manufacturing emits 20-31 kg CO_2-eq/kg. Chemical recycling has a higher environmental impact than thermal processing, with energy consumption of 8-15 MJ/kg and GHG emissions of 2.5-5.0 kg CO_2-eq/kg. The higher impacts reflect the energy requirements for high-pressure processing, solvent recovery, and wastewater treatment [68]. Mechanical recycling has the lowest energy consumption (0.2-2.0 MJ/kg) and the fewest GHG emissions, but the lower quality of recovered materials limits environmental advantages when considering complete system boundaries.

***Technical Challenges**:* Current recycling methods struggle to preserve the original mechanical properties of reclaimed carbon fibers, with recovered fibers often showing reduced tensile strength and length compared to virgin materials, making them unsuitable for high-performance applications. Separating carbon fibers from the polymer matrix without damaging the fiber structure remains technically difficult, as harsh chemical or thermal processes can degrade fiber integrity and surface properties.

Economic Challenges: The cost of recycling carbon fiber composites often exceed the price of virgin carbon fibers due to the energy-intensive nature of thermal processes and the expensive chemicals required for solvolysis methods, creating little economic incentive for widespread adoption. Additionally, the lack of established supply chains and collection infrastructure for end-of-life composite materials increases logistical costs and limits the scalability of recycling operations.

Environmental Challenges: Pyrolysis and high-temperature thermal recycling methods consume substantial energy and can produce harmful emissions if not properly controlled, potentially offsetting some environmental benefits of recycling. Chemical recycling processes using strong solvents raise concerns about hazardous waste generation, safe disposal of spent chemicals, and the overall environmental footprint when considering the entire lifecycle of the recycling process.

8.2. Comparative End-of-Life Scenarios

Comparisons of end-of-life scenarios show that recycling is clearly better for the environment than traditional disposal. Embedded resources are completely lost when CFRP waste is landfilled since there is no material or energy recovery [69]. Landfilling sacrifices the potential environmental advantages of material recovery, even though it uses very little energy (only for transportation). Energy recovery incineration produces 2-3kg CO_2-eq/kg emissions and destroys carbon fibers while capturing 20-30 MJ/kg thermal energy from matrix burning. Environmental evaluations are offered by consequential life cycle assessment (LCA) methods, which take into consideration market-mediated effects such as the replacement of alternative products and the substitution of virgin resources. These evaluations show that recycling's positive effects on the environment are heavily dependent on the materials and applications that are displaced [70]. The greatest environmental savings come from using recycled carbon fibers in place of virgin carbon fibers in comparable applications. The lower environmental impact of glass manufacture is reflected in the moderate benefits of substituting virgin glass fibers (13–30 MJ/kg). The choice of system boundaries has a big impact on life cycle assessment (LCA) results, especially when it comes to how trash is collected, transported, and sorted. Frameworks for uniform boundary definition, and allocation processes are offered by the International Organization for Standardization (ISO) 14040-14044 standards [71]. Comparative analysis demonstrates that even accounting for recycling process impacts, all recycling routes substantially outperform landfilling and incineration from lifecycle environmental perspectives.

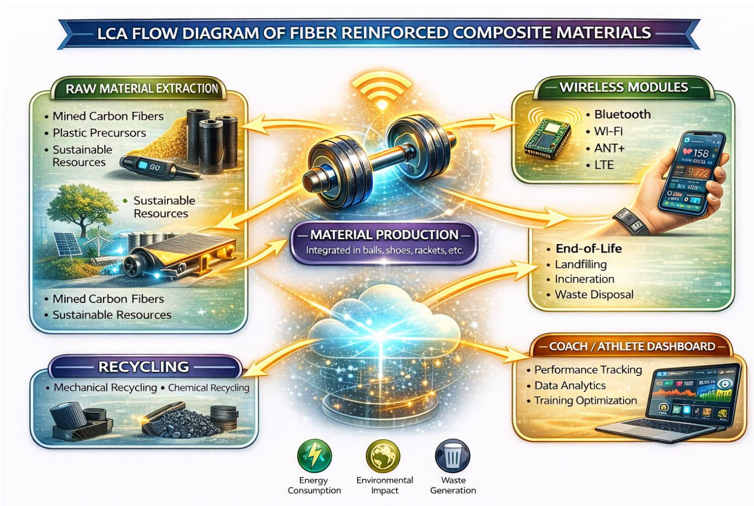

Figure 4. LCA Diagram for Fiber Reinforced Composite.

9. Future Perspectives and Circular Economy

9.1. Technology Development Priorities

Carbon fiber-reinforced polymer composites must integrate technological innovation, governmental frameworks, industry collaboration, and market development in order to move toward circular economy principles [72]. Even though the current recycling infrastructure shows technical viability, it is still unable to handle the anticipated volumes of CFRP trash that will emerge over the next few decades. Inventing less expensive chemical recycling techniques, enhancing fiber quality through thermal methods, automating sorting and pre-processing procedures, and inventing hybrid processes that combine the benefits of several strategies are among the top targets for technological improvement. There is potential for improving the quality of pyrolyzed fiber through research into catalytic pyrolysis, which uses zeolites or other catalysts to alter the decomposition chemistry and decrease char formation [73]. As potentially energy-efficient substitutes, microwave and plasma-assisted processing deserve more research. Deep eutectic solvents and bio-derived substitutes are examples of novel chemical recycling solvents that should be investigated as potentially more sustainable choices. Closed-loop composite recycling may be made possible by vitrimeric polymers, a new material class with dynamic covalent networks that allow reprocessing while preserving thermoset-like characteristics during service [74].

9.2. Design for Recyclability

A complementary approach is designed for recyclability, which takes recycling into account at the outset of composite design and manufacture. Choosing recyclable matrix systems like thermoplastics or recyclable thermosets, designing for disassembly to make component separation easier, and standardizing material systems to streamline recycling processing are some strategies [75]. Although greater material prices now restrict adoption, a number of thermoplastic matrix systems, including PEEK, PPS, and PEI, allow recyclability through remelting and reforming. For recycled carbon fibers to gain market trust, standards and certification systems are crucial. Market development is now hampered by the lack of industry-accepted standards for recycled fiber qualities, testing procedures, and quality grades [76]. Standards are being developed by organizations such as ASTM International, ISO, and industry consortia, but full frameworks that cover material specifications, test techniques, and certification processes are still lacking.

9.3. Supply Chain and Policy Support

Establishing effective networks between trash producers, recycling centers, and end users is necessary for supply chain development. Opportunities for regional recycling clusters are created by the geographic concentration of CFRP waste in wind farm locations and aerospace industrial regions [77]. However, low-density composite trash has high transportation costs, which may favor regional consolidation facilities or distributed processing. Landfill limitations and disposal levies, mandates for recycled content, extended producer responsibility programs, public procurement preferences for recycled materials, and funding for research and development are some of the policy measures that promote CFRP recycling. Economic incentives for recycling have been created by the implementation of landfill bans or increased disposal prices for composite trash in several European countries [78]. By allocating end-of-life management expenses to producers, extended producer responsibility frameworks encourage recyclable design. With an estimated 20,000–40,000 tons of annual blade waste by 2030, the wind energy industry faces immediate issues that will drive intense cooperation on recycling solutions [79]. Infrastructure development, policy advocacy, and research are all being coordinated by industry initiatives. Establishing best practices and recycling procedures is a similar endeavor in the aircraft industry.

9.4. Economic Modeling and Pathways

According to economic modeling of circular CFRP systems, a mix of market development, legislative support, and technology innovation is needed to achieve cost-competitive recycling. Large-scale processing facilities (>5,000 tonnes/year capacity), effective automation, favorable energy costs, and established markets that accept recycled materials are required in scenarios where recycled fiber costs of $5–10/kg are achieved [80]. The development of economically sustainable operations may be accelerated via public-private partnerships that support capital investment. Opportunities for information exchange and coordinated strategies are provided by international cooperation on CFRP recycling research and infrastructure development. Collaborative research on recycling technologies, applications, and market development is being carried out by academic and industrial consortia in Europe, North America, and Asia. International trade in recycled materials would be facilitated by harmonizing standards, laws, and best practices among governments.

9.5. European Union and Global Regulations on CFRP Recycling

Briefly, the European Union's Waste Framework Directive (2008/98/EC) and the amended End-of-Life Vehicles Directive (2000/53/EC) mandate that 95% of vehicle weight must be reused or recovered by 2025, directly pressuring automotive manufacturers to develop recycling solutions for CFRP components. The EU's Circular Economy Action Plan, launched in 2020 and reinforced in 2023, explicitly targets composite materials, including CFRP, for improved recyclability and promotes the development of sustainable product design standards across all member states. In the aviation sector, the International Civil Aviation Organization (ICAO) has established carbon offsetting requirements through CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), indirectly incentivizing airlines and manufacturers to pursue CFRP recycling as part of their carbon reduction strategies. The European Commission's proposal for an Ecodesign for Sustainable Products Regulation (ESPR), expected to replace the current Ecodesign Directive, will introduce mandatory recyclability requirements and digital product passports that track material composition, making CFRP recycling traceability and end-of-life management legally enforceable. Additionally, Extended Producer Responsibility (EPR) schemes are being implemented across multiple countries, including France's AGEC law (Anti-Waste for a Circular Economy) enacted in 2020, holding manufacturers accountable for the entire lifecycle of composite products, creating financial incentives for designing recyclable CFRP systems and establishing collection infrastructure.

10. Conclusions

This comprehensive review has examined the current state and prospects of carbon fiber–reinforced polymer composite recycling, encompassing technological approaches, material characterization, sustainability assessment, and pathways toward circular economy implementation. Several key conclusions emerge from this analysis: First, a variety of recycling technologies, including mechanical, thermal, and chemical approaches, have been developed and shown to be technically feasible; each has unique benefits and drawbacks. Although mechanical recycling offers economical bulk waste processing, it severely degrades fiber qualities, restricting recovered materials to lower-value uses. Thermal recycling, especially pyrolysis, has reached commercial scale and strikes a balance between industrial feasibility and acceptable fiber quality. Although chemical recycling yields higher-quality fiber, its use is limited to specialized applications due to financial and technological obstacles. Second, the qualities of recycled carbon fibers vary greatly depending on the processing route and conditions, with tensile strength retention ranging from 50-70% for mechanically recycled materials to 90-100% for optimal chemical recycling. These property variations imply appropriate applications, ranging from concrete reinforcement and thermoplastic compounding to nonwoven matting and structural components. While the market for recycled fibers is growing, it is hampered by limited availability, quality inconsistency, a lack of rigorous standards, and competition from low-cost raw glass fibers. Third, life-cycle assessments consistently show that CFRP recycling has significant environmental benefits over virgin manufacture and conventional disposal, with energy savings of 90-98% and proportionate greenhouse gas emission reductions. These benefits give compelling environmental justification for recycling infrastructure investment, especially as CFRP waste volumes grow considerably in the next few decades. Fourth, future research priorities should include lowering chemical recycling costs through process intensification and novel solvents, improving thermal recycling fibre quality through catalytic and hybrid approaches, developing design-for-recycling strategies and recyclable matrix systems, establishing comprehensive standards and certification frameworks, and fostering market development through demonstration projects. International engagement and knowledge exchange will hasten progress towards sustainable composite lifecycle management. The shift to circular CFRP consumption is neither technically nor economically prohibitive; however, it requires coordinated work from researchers, industry, governments, and end users. Environmental legislation, resource efficiency, business sustainability obligations, and rising trash volumes all contribute to the need and potential for viable recycling infrastructure. With continuing technological innovation, favorable legislative frameworks, and market development, recycled carbon fibers can become mainstream materials that contribute to sustainable manufacturing and resource conservation. The success of this effort will not only address waste management issues but will fundamentally redefine CFRP composites as truly sustainable materials for 21st-century engineering applications.

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