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A recent review of recycled carbon fibre reinforced polymers: Recycling methods and their mechanical and electrical performance

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ABSTRACT

The increasing use of Carbon Fibre Reinforced Polymers (CFRPs) necessitates sustainable end-of-life solutions due to their environmental persistence and the high energy cost of virgin carbon fibre production. This work examines recent advancements in recycling technologies for CFRPs, including thermal, chemical, mechanical, and hybrid processes, and their impact on the mechanical and electrical properties of recycled carbon fibre composite. The review analyses how different recycling methods influence the overall composite performance. While mechanical properties like strength and stiffness are often prioritised, this review also addresses the less-studied area of dielectric properties, including electromagnetic interference shielding and electrical conductivity. The goal is to provide a comprehensive overview of the current state of recycled Carbon Fibre Reinforced Polymers (rCFRPs) technology, highlighting both opportunities and challenges for reuse and remanufacturing. The review concludes by identifying critical research gaps and future directions to fully realize the potential of rCFRPs as a sustainable alternative to virgin CFRPs in a wider range of structural and functional applications.

Keywords: *Carbon fibre reinforced polymer, Recycled carbon fibre, Recycling technology, Mechanical properties, Electrical properties*

1. INTRODUCTION

Engineering offers a unique combination of properties that exceed those of traditional materials. Traditionally, metals such as cast iron and aluminium alloys dominated engineering applications, but their limitations in terms of weight, efficiency, and performance constrained the development of advanced materials like Carbon Fibre Reinforced Polymers (CFRPs) [1]. CFRPs consist of high-strength Carbon Fibres (CF) embedded within a polymer matrix, such as thermosets, thermoplastics, or elastomers [2], resulting in a material with an exceptional strength-to-weight ratio [3], stiffness, and durability [1][4]. These properties have made CFRPs indispensable in industries ranging from aerospace and automotive to marine engineering, civil construction, wind energy, sports equipment, and robotics [5].

Apart from the mechanical properties, CFRP materials have advantages for low density, good dimensional stability and resistance to corrosion. CFRPs also exhibit electrical properties, which significantly enhance their versatility [6]. For example, the electrical conductivity of the materials enables the use in lightning strike protection for aircrafts. The composite could dissipate electrical currents effectively [7]. CFRPs can also be utilised for electromagnetic interference shielding, a critical requirement in aerospace sectors. Apart from that, the electrical properties allow CFRP parts to have a capability of generating heat when an electric current is applied. This makes them ideal for anti-icing systems in wind turbine blades [8].

The application of CFRPs is essential in aerospace sectors, where lightweight and high-strength materials are crucial for structural components. By the 1990s, the price of CFRPs had reduced significantly allowing the material to be applied in other sectors, such as sports equipment [9]. The use of CFRPs worldwide doubled between the year 1998 and 2006 while industry projections indicated a compound annual growth rate of 12.5% by 2018 [10]. The market has continued to evolve since then. Recent data estimates that the market size was approximately $5.9 billion in 2022 and is projected to reach $16.8 billion by 2032. This represents a compound annual growth rate of approximately 11% from 2022 to 2032 [11]. Gardiner [12] and Sivanur et al. [13] suggested that the demand for CFRPs in emerging applications, such as hydrogen storage tanks and electric vehicle components, will further drive the growth.

However, the increasing utilization of CFRPs has raised significant environmental concerns, particularly at the end of the CFRP lifecycle. A concerning parallel trend exists

between rising CF demand and the generation of CFRP waste, highlighting the urgent need for effective waste management strategies [14-15]. Gopalraj & Kärki [16] stated that 62,000 tonnes of unused end-of-life and CFRP production waste will accumulate every year, with aircraft and wind energy being major contributors. By 2050, the aviation industry alone is projected to generate approximately 500,000 tonnes of accumulated CFRP waste [17]. The environmental impact of these materials is further exacerbated by their exceptional durability and resistance to natural degradation. Conventional waste management routes, such as landfilling and incineration have been shown to be unsustainable. Incineration of CFRPs releases a high amount of carbon dioxide, leading to greenhouse gas emissions and other types of air pollution. The landfilling route poses risks of toxic substances leaching into the environment and consume land resources.

The CF waste usually retains much of its mechanical properties, making the disposal wasteful [18]. In 2020, total CFRP waste was estimated to be around 62,000 tonnes [16]. It is also estimated that the waste contains around 60 wt% of CF, which means approximately 37,200 tonnes of CFs could be potentially recovered [19]. The situation presents an economic opportunity, given that the demand of CF is escalating and production of virgin CF requires high resource intensity. The advancement of composite recycling technologies is key to recover this valuable resource. Recent technologies, such as microwave-assisted pyrolysis and chemical solvolysis, have demonstrated promising results in recovering CF with limited degradation in mechanical properties [20]. The technological advancements not only shows the viability of CFRPs recycling but also highlight the potential to reduce CFRPs production and end-of-life waste thereby supporting the circular economy agenda.

Recycled CF recovered through recycling processes from CFRP materials has potential for reuse, particularly in applications demanding high performance and cost-effectiveness [21]. The latest recycling technologies have demonstrated that recycled CF can retain a significant portion of its original mechanical properties, with some studies reporting up to 90% retention [18]. This excellent performance highlights the suitability of recycled CF for structural or semi-structural applications across industries such as automotive and aerospace. Several studies explored the properties of recycled CF for reuse purposes [22-25]. For instance, recycled CF has been integrated into automotive components, achieving material cost reductions and reduced environmental impact without compromising performance [26]. In addition, recycled CF has also been utilized in non-structural applications, such as panels and reinforcements in construction sector. In order to improve the interfacial bonding between recycled CF and new polymer matrices, surface treatment techniques such as chemical treatments or plasma processing are typically employed. The methods enable the utilization of enhanced recycled CF in advanced composites. The use of recycled CF in emerging applications, including hydrogen storage tanks and electric vehicle battery enclosures could contribute to sustainable manufacturing practices by addressing the growing demand for lightweight and durable materials. Several companies are already involved in the recovery and reuse of CF [27-28].

Recent review studies on CFRPs recycling [29-31] have primarily focused on the recycling methods, the properties of recycled CF, and the potential applications of recycled CFRPs. However, these studies have not analysed electrical properties of recycled CFRPs thoroughly, despite the importance in applications such as electromagnetic interference shielding, lightning strike protection, and anti-icing systems. One reason is that electrical properties of recycled CFRPs are often limited by the shorter length of fibres, compared to their virgin counterparts [18]. This affects electrical performance of recycled CFRPs. While mechanical properties such as tensile and flexural strengths remain a primary focus, the electrical conductivity and dielectric properties are equally important for recycled CFRPs to be used in advanced composite materials. This literature gap highlights the need for a comprehensive analysis that integrates both mechanical and electrical properties. With such analysis, potential of recycled CFRPs can be fully understood.

By considering studies published between 2010 and 2025, this review critically evaluates composite recycling technologies, including thermal, chemical, mechanical, and hybrid processes. The goal is to bridge existing gaps in the literature by addressing both mechanical and electrical performance as well as assessing the implications of using recycled CFRPS across diverse sectors.

2. CFRP RECYCLING METHODS

The unique physicochemical properties of CFRPs significantly influence the recycling process. These composite materials, typically fabricated via thermo-compression moulding, incorporate CF within a resin matrix. While this structure imparts excellent mechanical properties, it also results in significant anisotropy and low interlaminar strength. The epoxy resin, for example, recommended for its resistance to heat, corrosion, and aging, as well as its strong adhesion, forms an irreversible cross-linking structure during curing. This renders the resin insoluble and non-fusible, greatly complicating the recycling process [32]. Consequently, developing effective recycling methods for CFRPs remains a critical challenge in materials science and environmental sustainability [33]. Currently, CFRP can be recycled using four types of technologies. There are two main categories of CF waste. The first category includes virgin CF scraps generated during production from dry fibres and unused expired materials. The second category involves the recovery of fibres CFRPs waste. Figure 1 illustrates the recycling methods for composite waste [29].

2.1. Mechanical Recycling

Mechanical recycling involves breaking down composite materials into smaller fragments, known as recyclates, through shredding, crushing, and milling [29]. The process begins with size reduction using slow-speed cutting or shredding mills, which produce fragments approximately

50-100 mm in size. These fragments are then further processed through grinding or milling to achieve finer particle sizes ranging from 50 μm to 10 mm [29][34]. The resulting recyclates are classified into coarse recyclates, rich in fibres, and fine recyclates, with a higher resin content [3][29]. This classification is achieved using cyclones, sieves, or air classifiers to separate materials based on particle size and density. One of the key advantages of mechanical recycling is its energy efficiency compared to other recycling methods like thermal or chemical recycling. The energy demand for mechanical recycling ranges from 0.1 to 5.3 MJ/kg, significantly lower than chemical recycling (21 - 93 MJ/kg) or pyrolysis (3 - 30 MJ/kg) [35]. However, the process has limitations, including the degradation of mechanical properties in recycled fibres due to the loss of structural integrity during shredding and grinding. As a result, the recycled CF is often used in low-value applications such as fillers or reinforcements in non-structural products rather than high-performance composites. Despite its challenges, mechanical recycling contributes significantly to sustainability by reducing landfill waste and enabling the reuse of recyclates in new products. For instance, fine powders obtained from mechanical recycling can be used as polymeric fillers in cementitious materials or injection moulding applications. Mechanical recycling can also serve as a pre-treatment step for other recycling methods, such as chemical or thermal recycling, when the original composite waste does not meet process requirements [35].

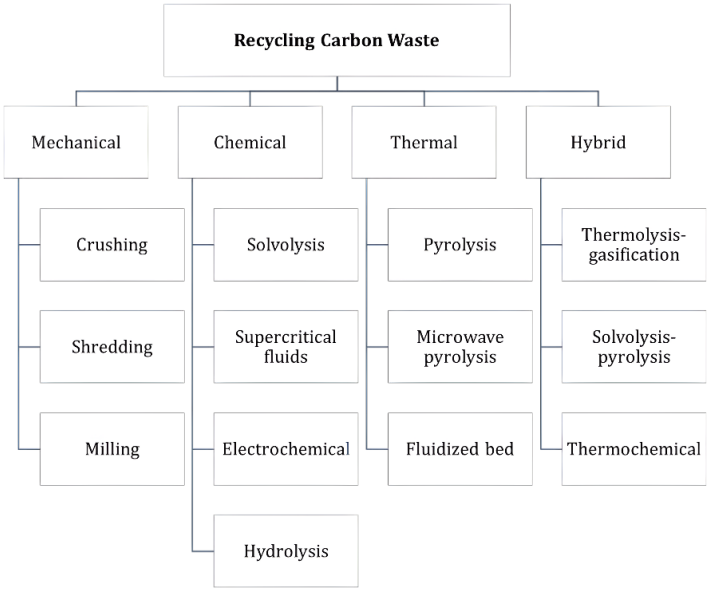

Figure 1. Recycling of CFRP Techniques

2.2. Chemical Recycling

Chemical recycling of CFRPs involves breaking down the polymer matrix into monomers or oligomers to separate fibres from the resin through a chemical reaction [34]. This approach preserves the mechanical properties of recovered CF while consuming significantly less energy than thermal methods like pyrolysis (~38 MJ/kg compared to ~198 - 595 MJ/kg for virgin CF production) [36]. The process typically begins with mechanical grinding of CFRPs waste to increase surface area, followed by dissolving the polymer matrix using acids, bases, or solvents. The primary mechanisms for chemical recycling include solvolysis and supercritical solvolysis. Studies have shown that chemical recycling can yield recycled CF with high retention of mechanical properties compared to virgin fibres. For instance, Li et al. [37] reported achieving a decomposition ratio of over 90% for the epoxy matrix while retaining more than 95% of the original strength of the CFs using a mild oxidative system. Huan et al. [18] demonstrated high retention ratios of 97.1% for tensile strength and 99.5% for modulus using a phosphoric acid-based reclamation process. However, factors like the type of solvent, temperature, and reaction time can significantly influence the properties of the recovered fibres. Some methods may lead to fibre damage or surface degradation, reducing their mechanical performance [38].

2.2.1. Solvolysis

Solvolysis is a primary method for chemical recycling, which operates under controlled conditions of temperature, pressure, and catalysts to depolymerize the resin matrix. Depending on the solvent system, solvolysis can occur at low temperatures (below 200 °C) under atmospheric pressure or in supercritical conditions at higher temperatures and pressures [3]. Common solvents include alcohols (e.g., methanol, ethanol), acetone, and water. Subcritical water and alcohol have demonstrated effectiveness in degrading epoxy resins while preserving fibre integrity. Using water as a reactive medium, hydrolysis offers an environmentally friendly alternative but requires elevated temperatures and pressures for effective resin breakdown [20]. The efficiency of solvolysis mostly depends on the choice of chemicals and operating parameters. For instance, nitric acid (HNO_3) achieves high resin degradation rates at moderate temperatures (~80 °C). Alkaline catalysts like potassium hydroxide (KOH) are particularly effective in subcritical methanol systems, achieving high degradation rates at temperature around

210 °C, which is relatively low compared to thermal process. Zinc chloride ($ZnCl_2$) has also been used successfully as a liquid catalyst, yielding clean fibres with minimal surface defects. Additives such as surfactants and ultrasonic assistance further enhance solvolysis, with ultrasonic-assisted solvolysis using diluted HNO_3 and hydrogen peroxide (H_2O_2) achieving up to 95% matrix decomposition at temperatures below 60 °C [39]. Despite these advances, the use of hazardous chemicals, including strong acids or bases, can generate toxic by-products if not properly managed. This highlighting the need of greener alternatives like subcritical water or alcohols.

2.2.2. Sub or Supercritical Solvolysis

Supercritical fluid technology represents a encouraging development in chemical recycling. Supercritical solvents such as ethanol or propanol combine liquid-like solvating abilities with gas-like diffusivity, qualify efficient penetration into composite matrices [36]. These properties make the solvents highly effective in resin matrix degradation, with recovery of fibres achieving up to 98% of the mechanical properties of virgin CF. However, these processes require specialised equipment capable of withstanding high pressures and temperatures, which increases operational costs and presents scalability challenges [20]. Additionally, the reliance supercritical systems often rely on expensive solvents and energy-intensive conditions, thus further hindering economic feasibility.

2.3. Thermal Recycling

Thermal recycling of CFRPs utilizes high-temperature processes to separate CF from the polymer matrix, producing recycled CF and various by-products, such as gases and oils [34]. This process can be achieved through methods such as pyrolysis, fluidized bed pyrolysis, or microwave pyrolysis. These methods rely on the principle of matrix decomposition under controlled thermal conditions, leaving the valuable fibres intact. The success of thermal recycling processes depends on optimised control of operational parameters, including temperature, reaction time, and oxygen concentration [20][40]. These factors directly influence the quality of the recycled fibres and the environmental impact of the process. However, a key disadvantage of thermal recycling is that the high temperatures can cause surface damage to the fibres, potentially leading to poor interfacial bonding with a new resin matrix or even fibre breakage, ultimately reducing the mechanical and electrical properties of the resulting composite [41].

2.3.1. Pyrolysis

Pyrolysis is a widely researched method that operates in an oxygen-free environment at temperatures ranging from 400 to 1000 °C [42]. During this process, the polymer matrix decomposes into gaseous, liquid, and solid by-products. Pyrolysis is notable for its energy efficiency, consuming only 5 - 10% of the energy required for virgin CF production. Under optimised conditions, it can retain up to 90 - 95% of the mechanical properties of the fibres [40]. However, the quality of the recycled fibres depends significantly on the process parameters. Inadequate temperatures result in incomplete decomposition of the matrix, leaving a residual carbonaceous layer on the fibre surface, which compromises bonding with new matrices. Conversely, excessively high temperatures reduce the fibre diameter and degrade the tensile strength. Both scenarios lead to a decline in mechanical performance [42]. While an auxiliary oxidation step can remove residual char, it introduces environmental challenges due to the release of toxic gases. Recent advancements, such as the incorporation of microwave heating in pyrolysis systems, have shown potential to improve thermal efficiency, minimize char formation, and reduce energy consumption [40]. However, the scalability of microwave pyrolysis remains limited, restricting its widespread adoption in industrial applications.

2.3.2. Fluidized Bed

The Fluidized Bed Pyrolysis (FBP) process offers an alternative approach to recycle CFRPs waste. In this process, mechanically reduced waste fragments are introduced into a heated bed of silica sand fluidized by hot air at temperatures between 400 and 650 °C. This method rapidly decomposes the polymer matrix, leaving behind recycled fibres [39]. FBP is advantageous due to its scalability and ability to process composites containing additives like paints, fillers, or metal inserts, which are challenging to separate through other recycling methods [40]. However, the mechanical properties of the recovered fibres are often significantly degraded, with tensile strength retention ranging from 10% to 75% due to the combined effects of mechanical damage caused by fluidized sand and thermal exposure. Additionally, maintaining a continuous flow of hot air is energy-intensive, and the process generates harmful emissions, including organic solvents and acid gases from halogenated additives, necessitating advanced emission control systems. Nonetheless, FBP remains a promising method for recycling CFRPs waste, particularly for composites with diverse material compositions.

2.3.3. Microwave Pyrolysis

Microwave pyrolysis is a technique for recycling CFRPs that utilises microwave energy to decompose the polymer matrix, leaving behind reusable fibres. The mechanism involves the interaction of microwaves with the dielectric properties of the material, generating heat internally within the composite. This leads to rapid and selective heating of the polymer matrix, which reduced reaction time by 56.67% and increased the recovery ratio by 15% compared to conventional pyrolysis methods. The rapid heating and shorter processing times also translate to lower energy consumption [44]. Furthermore, the selective heating of the matrix in microwave pyrolysis minimises the potential for fibre damage, resulting in recycled fibres with better preserved mechanical properties [45]. Seiler et al. [46] discussed microwave pyrolysis as a promising technology for separating the fibre-matrix composite, addressing the challenges in establishing a circular economy for CFRPs. Unlike conventional pyrolysis, which usually leave residual

char on the fibre surface, microwave pyrolysis often produces cleaner fibres, simplifying the post treatment [45]. However, like any process, microwave pyrolysis also has challenges. Optimising parameters such as microwave frequency and power is crucial for efficient and uniform heating. Despite these challenges, the potential of microwave pyrolysis as a sustainable and efficient method for CFRP recycling is evident in the growing body of research [47-48]. Studies have demonstrated its ability to achieve faster reaction times and higher heating rates compared to conventional pyrolysis [44-45]. For example, Hao et al. highlighted the potential of microwave heating to yield clean CF from thermoset composite waste due to its rapid and selective heating.

3. MECHANICAL PROPERTIES OF RECYCLED CFRP

Recycling of CFRP composites has gained significant attention due to increasing environmental concerns and the need for sustainable material utilization. Various recycling methods, including thermal, chemical, mechanical, and hybrid processes, have been explored to recover CFs while maintaining the mechanical properties of the remanufactured product. This section discusses the mechanical properties of composites made from recycled CF. The tensile properties of rCFRPs in terms of recycling techniques and retained strength are presented in Table 1.

Table 1. Retained Tensile Properties Compared to Control Product

Recycling Techniques	Process Conditions	Retained Tensile Properties Compared to Control Product (%)	References
Thermal (Pyrolysis)	Heating temperature of 500 °C and further oxidation of 500 °C	93.4	Nahil & Williams [49]
Thermal (Pyrolysis)	Heating temperature of 350 °C – 500 °C for 60 mins	82	Onwudili et al. [51]
Thermal (Catalytic Pyrolysis)	Samples were soaked in molten $ZnCl_2$, which was heated to 360 °C for 20-160 mins	95	Wu et al. [50]
Chemical (Electrochemical)	3% - 20% NaCl solution with 4 mA - 25 mA levels of applied current	80	Sun et al. [55]
Chemical (hydrolysis-oxidation synergistic catalytic strategy)	Ester bonds in UPRs were cleaved by hydrolysis using 80% hydrazine hydrate and NaOH, followed by carbon-carbon bond cleavage via the Fenton reaction	91.6	Wang et al. [53]
Hybrid (thermolysis-gasification)	Thermolysis at 500 °C – 700 °C, then followed by gasification process at 500 °C for 30–180 mins	~72	López et al. [43]
Chemical	CFRP was pretreated with 1M citric acid solution at 120 °C for 6 hours, followed by the introduction of *m*CPBA and DCM, initiating the decomposition reaction at 40 °C for 6 hours	93.6	Jeong et al. [52]
Hybrid (solvolysis-pyrolysis)	Solvolysis process using 0.1M acetic solution at 100 °C, followed by pyrolysis at 425 °C and oxidation under air at 550 °C	90.5	Wei & Hadigheh [57]
Chemical	CFRP decomposed by supercritical solvent (methanol, 1-propanol, 2-propanol, 1-butanol, 2-butanol, *tert*-butanol, acetone, or methyl ethyl ketone) at 320 °C for 6 – 120 mins.	100	Okajima et al. [58]
Chemical-electrochemical	CFRP as the anode and stainless steel as the cathode, separated by 25 mm within a DMSO and ammonium acetate electrolyte solution	93.55	Pei et al. [56]
Chemical	CFRP was immersed in 8M nitric acid aqueous solution (16 mL per 1 g of CFRP) at 80°C for 2-120 hours	128	Sakai et al. [54]
Hybrid (Mechanical-Thermal)	Simulation of injection moulding on Moldflow with injection pressure 50 MPa to 150 MPa	427 (Nylon 6) 781 (Polypropylene)	Tarkar et al. [60]
Mechanical	Hammer milling 25.4mm screen and shredding with 19 mm wide teeth	130	Li & Englund [59]
Mechanical	Regranulation by RSP 15 open-type rotor grinder	80	Colucci et al. [57]

3.1. Tensile Properties

Recycling methods have demonstrated varying degrees of success in retaining the tensile properties of CFs. Among thermal recycling, [49-51] investigated pyrolysis-based techniques. Nahil and Williams [49] achieved 93% tensile strength retention at 500 °C, whereas Wu et al. [50] demonstrated that catalytic pyrolysis using molten $ZnCl_2$ at 360 °C effectively preserved the graphitic structure of the fibres, achieving 95% tensile strength retention. Onwudili et al. [51] observed strength retention of 82% when applying pyrolysis at 350–500 °C in a nitrogen atmosphere. López et al. [43] combined thermolysis and gasification at 500 °C, recovering fibres with 70% tensile strength retention but maintaining high elasticity. These studies indicate that lower pyrolysis temperatures with catalytic agents enhance fibre quality.

Tensile properties of chemical recycling approaches have also been investigated. Jeong et al. [52] utilized meta-chloroperoxybenzoic acid (mCPBA), achieving 93.6% tensile strength retention, while Wang et al. [53] demonstrated a hydrolysis-oxidation strategy below 100 °C, with only an 8.4% strength reduction. While Sakai et al. [54] used nitric acid at 80 °C, unexpectedly enhancing tensile strength by 1.4 times. The SEM results from these studies consistently demonstrate that more complete resin removal leads to higher tensile strength retention, highlighting the critical role of a clean fibre surface for optimal performance in recycled composites. Electrochemical methods by Sun et al. [55] and Pei et al. [56] also preserved high fibre strength, with Pei et al. achieving 93.55% tensile strength retention through a combined chemical swelling in dimethyl sulfoxide (DMSO) and electrochemical oxidation process. These findings suggest that chemical and electrochemical methods are effective for fibre recovery with minimal thermal degradation. This is crucial because minimising thermal degradation helps to retain the fibre's surface properties and inherent strength, ensuring that the recycled CF can effectively reinforce new composites [18]. Tensile properties by hybrid and alternative techniques further expand CFRPs recycling strategies. Wei and Hadigheh [57] developed a hybrid solvolysis-pyrolysis process that maintained up to 90.53% of the original fibre strength. Supercritical fluid processing by Okajima et al. [58] effectively decomposed epoxy resin at 320 °C while preserving fibre structure. Mechanical recycling, demonstrated by Colucci et al. [59], resulted in a 20% reduction in tensile properties but retained structural integrity for applications such as automotive parts.

The tensile properties of rCFRPs, in relation to recycling techniques and retained strength, are illustrated in Figure 2. Specifically, Figure 2 highlights that the majority of studies on tensile property retention in rCFRPs report values between 80 and 100% of the original material's strength. Notably, the studies by Sakai et al. and Li & Englund demonstrate exceptional performance, even exceeding 100% retention. Retention more than 100% means the rCFRP sample has better properties compared to the virgin or control sample. This improvement may be attributed to factors such as a reduction in voids and reinforcement of fibre strength due to the formation of new polar functional groups via nitric acid treatment [54], or enhancements in the recycling process itself [61]. It is also important to consider that mechanical recycling methods are less common due to the significant size reduction of the fibres and the challenges associated with their reuse.

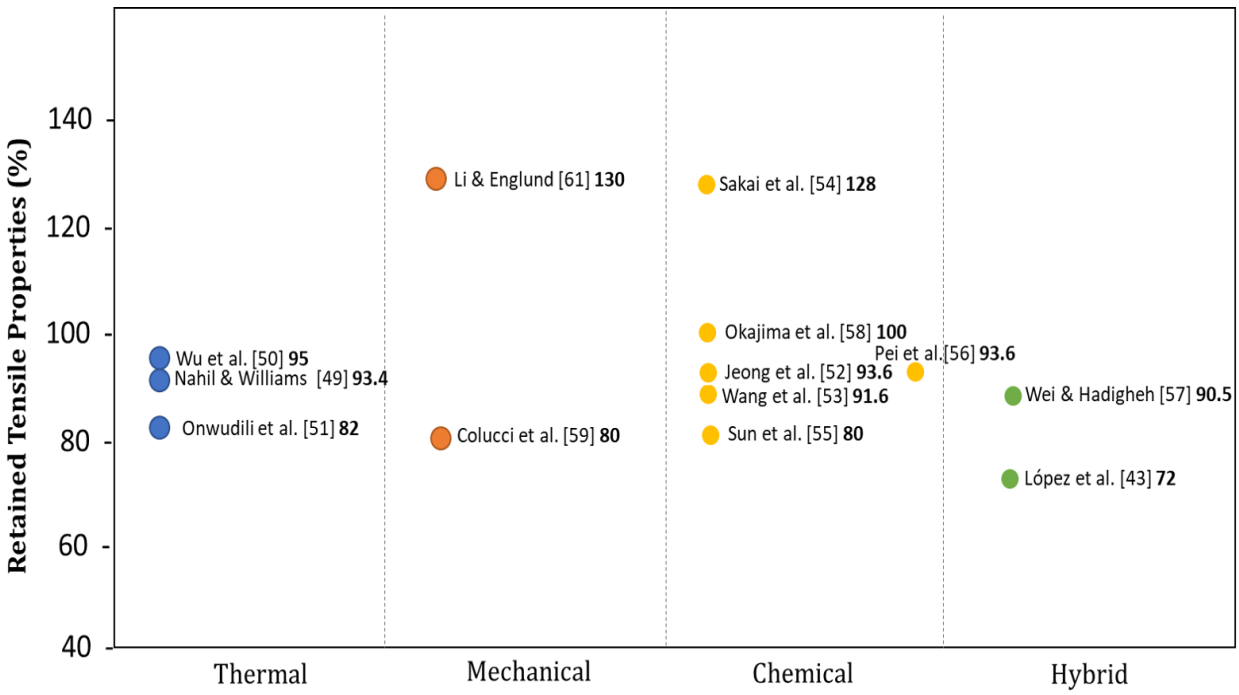

Figure 2. Tensile Properties According to Different Recycling Methods

3.2. Interlaminar Shear Strength

While research on the Interlaminar Shear Strength (IFSS) properties of recycled CFRP fibres remains limited, existing studies indicate promising outcomes. Jeong et al. [52] reported that fibres recovered through chemical oxidation exhibited superior bonding performance, particularly with epoxy resin and polyamide 6. Pei et al. [56] observed a 118.76% increase in IFSS for fibres recovered using electrochemical oxidation, suggesting enhanced fibre-matrix adhesion. This is because electrochemical oxidation increases the surface roughness and the number of surface functional groups on the recycled CF, which promotes mechanical interlocking and chemical bonding between the fiber and epoxy resin, leading to improved interfacial shear strength.

Sakai et al. [54] noted a 2.2 times increase in IFSS for fibres recycled via a nitric acid-based process, demonstrating the potential of chemical treatments to improve fibre compatibility in composite applications. Ballout et al. [62] introduced an environmentally friendly recycling method using formic acid at room temperature and atmospheric pressure, achieving up to 93% retention in shear strength. Compared to high-temperature processes, this approach effectively preserved fibre integrity while maintaining shear strength properties, offering a sustainable alternative for large-scale CFRPs recycling. The IFSS properties of the research where chemical was used as the recycling method of CFRPs are listed in Table 2, while Figure 3 shows the retained value of IFSS in graphical form.

Table 2. IFSS of rCFRP Products after Chemical Recycling

Recycling Technique	Process Conditions	Retained ISS Compared to Control Product (%)	References
Chemical	CFRP was immersed in 8M nitric acid aqueous solution (16 mL per 1 g of CFRP) at 80 °C for 2-120 hours	153.3	Sakai et al. [54]
Chemical	CFRP was pretreated with 1M citric acid solution at 120 °C for 6 hours, followed by the introduction of *m*CPBA and DCM, initiating the decomposition reaction at 40 °C for 6 hours	126	Jeong et al. [52]
Chemical (Solvolysis)	Composite panel immersed in a formic acid bath for 48 h	88.4	Ballout et al. [62]
Chemical (electrochemical)	CFRP as anode and stainless steel as the cathode, separated within a DMSO and ammonium acetate electrolyte solution	118.76	Pei et al. [56]

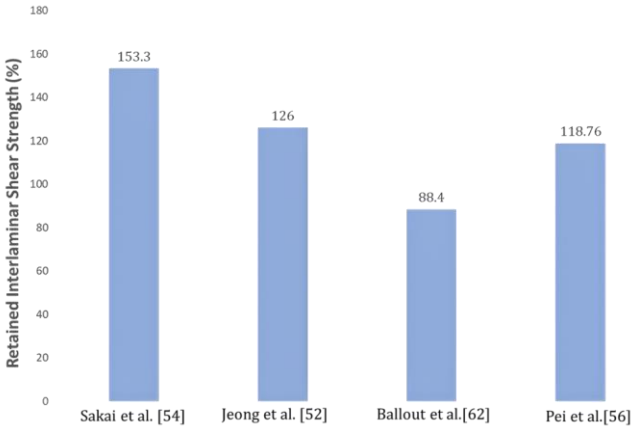

Figure 3. The Comparison of the IFSS Property of Chemical Recycling

3.3. Flexural Properties

The impact of recycling methods on flexural properties has also been extensively studied in several papers [50][63-68]. Work by Palmer et al. [63] investigated the use of recycled CF in SMC composites through a hammer milling process. The results showed that the SMC sample with 4.6% recycled CF by volume exhibited a 3% reduction in flexural modulus and a 9% decrease in flexural strength while maintaining properties comparable to the reference material. Thomas et al. [64] used recycled CF obtained from composite laminate cutting to enhance the flexural properties. The results showed that the sample with 20% recycled CF had significantly improved the flexural strength by 30%. Durante et al. [65] studied the down-milling process to analyse how cutting parameters affect fibre size. Recovered fibres were classified as fine (smaller than 0.3 mm) or coarse (larger than 0.3 mm) and were used in epoxy composites. Flexural tests showed that compared to pure resin, composites with coarse fibres improved flexural strength, showing a 45% increase.

According to Tian et al. [66], the 3D printing process was reversed to enable the recycling and remanufacturing of Carbon Fibre Reinforced Thermoplastic Polymers (CFRTPs). By retracing the original printing path, the process achieves 100% continuous CF recovery without compromising mechanical properties. Tests showed that remanufactured CFRTPCs had 25% higher bending strength. Jiang et al. [67] highlighted the flexural properties of microwave-assisted pyrolysis recycled CF composite. However, a comparison with virgin CF showed that the recycled CF composites exhibited 14% lower flexural strength and 25% lower modulus. It can be attributed to the high temperatures required for microwave pyrolysis, which can cause surface damage to the CF during the decomposition of the polymer matrix. This damage can lead

to poor interfacial bonding with a new resin or even fibre breakage, ultimately reducing the flexural properties. Furthermore, authors observed that even at 600°C, some residue and cavities form on the fibre surface, indicating this degradation. Table 3 lists the retained flexural strength values of rCFRP products.

Table 3. Main Results of Flexural Properties as Compared to Virgin and Control Samples

Recycling Technique	Process Conditions	Retained Flexural Properties Compared to Control Product (%)	References
Mechanical	Hammer mill with 8mm screen	81	Palmer et al. [63]
Mechanical	Cutting process of laminate composites	130	Thomas et al. [64]
Mechanical	Three flute end mills with a 20mm diameter	145	Durante et al. [65]
Reverse 3D printing	Hot air gun to remelt the matrix material	125	Tian et al. [66]
Microwave pyrolysis	CFRP scrap is heated to 400-600°C for 30 minutes	86	Jiang et al. [67]

4. ELECTRICAL PROPERTIES OF RECYCLED CFRP

The electrical properties of CFRPs are primarily governed by the conductive nature of CFs, which exhibit high electrical conductivity due to the CF graphitic structure. In virgin CF composites, the alignment and continuity of fibres create effective conductive networks, enabling applications such as Electromagnetic Interference (EMI) shielding, Electrostatic Discharge (ESD) protection, and sensing. However, the recycling process, whether through pyrolysis, solvolysis, or mechanical methods, can significantly alter the electrical properties of CFs. For instance, the high temperatures and chemical treatments involved in recycling may introduce defects, reduce fibre length, and degrade the graphitic structure, leading to diminished electrical conductivity and altered dielectric behavior.

Several studies have compared the electrical properties of recycled CF and virgin CF, revealing that recycling processes and post-treatment methods can significantly influence performance. Wong et al. [69] demonstrated that CFs recovered using a fluidized bed process maintained resistivity comparable to virgin CF. This finding suggests that the intrinsic electrical properties of the CF are not inherently compromised during recycling. super This highlights the potential to not only preserve but also improve the electrical properties of recycled CF through post-recycling treatments. Furthermore, research by Pang et al. [70] showed that treating fluidized bed recycled fibres with sulfuric and nitric acids (a doping process) could enhance both the electrical conductivity and Seebeck coefficient. The Seebeck coefficient, which measures a material efficiency in converting temperature differences into electrical voltage, was specifically shown to increase by up to 1.74 times in the N-direction.

Kim et al. [71], using a green recycling method with supercritical water, produced recycled CF reinforced composites with a cyclic butylene terephthalate matrix. These composites exhibited an electrical conductivity of 11.23×10^{-6} S/cm. While this value is considerably lower than that reported by Akonda et al. [72] for polypropylene composites, it is important to note that conductivity is influenced by both the fibre and matrix materials, as well as processing techniques. The lower conductivity observed by Kim et al. likely stems from the choice of matrix material and other processing differences [71]. Akonda et al. compared polypropylene composites reinforced with recycled CF and waste CF, finding that waste CF composites exhibited higher conductivity (10.75×10^{3} Sm^{-1}) than those made with recycled CF [72]. This difference was attributed to the longer fibre lengths present in the waste CF, which facilitated better electrical pathways. Both composite types were deemed potentially suitable for use as cost-effective heating elements in lightweight applications.

The studies above primarily focus on conductivity and resistivity. However, other electrical properties, such as EMI shielding effectiveness, are also relevant for many applications. For instance, Huan et al. [18] have shown that recycled CF composites can exhibit promising EMI shielding performance, particularly with optimized fibre alignment. While some studies have explored recycled CF's use in cement [73-75], there is a lack of direct comparison between recycled CF and virgin CF regarding electrical performance in polymers. This limited research hinders a full assessment of recycled CF's potential as a substitute for virgin CF in various applications. More studies are needed to evaluate key electrical properties such as dielectric behaviour, charge storage capabilities, and conductivity variations under different processing conditions. Addressing these gaps will provide a clearer understanding of the feasibility of recycled CF as a sustainable alternative to virgin CF in electrically functional materials.

5. CONCLUSION

This study comprehensively assesses the current state of composite recycling initiatives, focusing on the latest recycling methods and the resulting mechanical and electrical properties. The assessment covers several main recycling techniques namely thermal, chemical, mechanical and hybrid by analyzing the effect of the processes on recovered fibre performance and its suitability for reuse in new applications. Mechanical performance of rCFRPs such as tensile and flexural properties have been extensively

studied in literature, demonstrating the potential of retaining the properties and successful reuse with new polymer matrices. However, consideration of electrical properties remains scarce. This presents a knowledge gap that limits scientifically informed decision-making in evaluating suitability of rCFRPs in electrical and electronic applications. Previous studies have indicated potential for rCFRPs to be incorporated in functional applications, particularly in areas such as electromagnetic interference shielding and thermoelectric. Nonetheless, more investigations are required to fully understand and optimize the electrical properties of the rCFRPs.

Future work should emphasize optimising fibre recovery methods to improve electrical conductivity, investigate new composite formulations to enhance the dielectric performance and develop standardized methodology to ensure accurate and reliable assessment of the properties. Beyond technical advancement, future research must also address the industrial scalability and economic feasibility of recycling technologies. Large scale implementation depends not only on structural integrity and functional performance but also on processing costs and other resource consumption. Energy consumption, resin type and processing parameters directly influence both cost and environmental outcomes. Integrating life cycle assessments into recycling strategies can highlight reductions in carbon footprint, landfill burden and raw material demand.

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REFERENCES

[1] D. S. Vijayan, A. Sivasuriyan, D. Parthiban, A. Stefańska, Ł. Wodzyński, and E. Koda, "Carbon Fibre-Reinforced Polymer (CFRP) Composites in Civil Engineering Application - A Comprehensive Review," *Buildings*, vol. 13, no. 6, pp. 1509, 2023. https://doi.org/10.3390/buildings13061509

[2] B. A. Alshammari, M. Alsuhybani, A. M. Almushaikeh, B. M. Alotaibi, A. M. Alenad, N. B. Alqahtani, and A. G. Alharbi, "Comprehensive Review of the Properties and Modifications of Carbon Fibre-Reinforced Thermoplastic Composites," *Polymers,* vol. 13, no. 15, pp. 2474, 2021. https://doi.org/10.3390/polym13152474

[3] J. A. Butenegro, M. Bahrami, J. Abenojar, and M. Á. Martínez, "Recent Progress in Carbon Fiber Reinforced Polymers Recycling: A Review of Recycling Methods and Reuse of Carbon Fibers," *Materials*, vol. 14, no. 21, pp. 6401, 2021. https://doi.org/10.3390/ma14216401

[4] S. Termine, V. Naxaki, D. Semitekolos, A. F. Trompeta, M. Rovere, A. Tagliaferro, and C. A. Charitidis, "Investigation of Carbon Fibres Reclamation by Pyrolysis Process for Their Reuse Potential," *Polymers*, vol. 15, no. 3, pp. 768, 2023. https://doi.org/10.3390/polym15030768

[5] S. Yao, F. Jin, K. Y. Rhee, D. Hui, and S. Park, "Recent advances in carbon-fibre-reinforced thermoplastic composites: A review," *Composites Part B: Engineering*, no. 142, pp. 241 – 250, 2017. https://doi.org/10.1016/j.compositesb.2017.12.007

[6] D. Özkan, M. S. Gök, and A. C. Karaoğlanli, "Carbon Fibre Reinforced Polymer (CFRP) Composite Materials, Their Characteristic Properties, Industrial Application Areas and Their Machinability," *Engineering Design Applications III: Structures, Materials and Processes,* pp. 235, 2020. https://doi.org/10.1007/978-3-030-39062-4_20

[7] B. Wang, Y. Duan, Z. Xin, X. Yao, D. Abliz, and G. Ziegmann, "Fabrication of an enriched graphene surface protection of carbon fibre/epoxy composites for lightning strike via a percolating-assisted resin film infusion method," *Composites Science and Technology*, vol. 158, pp. 51-60, 2018. https://doi.org/10.1016/j.compscitech.2018.01.047

[8] J. Zhang, V. S. Chevali, H. Wang, and C. H. Wang, "Current status of carbon fibre and carbon fibre composites recycling," *Composites Part B: Engineering,* vol. 193, pp. 108053, 2020. https://doi.org/10.1016/j.compositesb.2020.108053

[9] Y. Liu, B. Zwingmann, and M. P. Schlaich, "Carbon Fibre Reinforced Polymer for Cable Structures - A Review," *Polymer*s, vol. 7, no. 10, pp. 2078 – 2099, 2015. https://doi.org/10.3390/polym7101501

[10] F. Meng, J. McKechnie, and S. J. Pickering, "An Assessment of Financial Viability of Recycled Carbon Fibre in Automotive Applications," *Composites Part A: Applied Science and Manufacturing*, vol. 109, pp. 207-220, 2018. https://doi.org/10.1016/j.compositesa.2018.03.011

[11] KD Market Insights, "Carbon Fiber Market Size, Share & Trends Analysis Report," 2024. https://www.kdmarketinsights.com/reports/carbon-fibre-composites-market/1104

[12] G. Gardiner, "Hydrogen is poised to fuel composites growth," 2021. https://www.compositesworld.com/articles/the-potential-for-hydrogen-to-fuel-composites-growth-part-1

[13] K. Sivanur, K. V. Umananda, and D. S. Pai, "Advanced Materials Used in Automotive Industry - A Review," In *AIP conference proceedings*, vol. 2317, no. 1. AIP Publishing, 2021. https://doi.org/10.1063/5.0036149

[14] A. K. Błędzki, H. Seidlitz, K. Gorący, M. Urbaniak, and J. Rösch, "Recycling of Carbon Fibre Reinforced Composite Polymers – Review - Part 1: Volume of Production, Recycling Technologies, Legislative

Aspects," *Polymers,* vol. 13, no. 2, pp. 300, 2021. https://doi.org/10.3390/polym13020300

[15] M. F. Khurshid, M. Hengstermann, M. M. B. Hasan, A. Abdkader, C. Cherif, "Recent Developments in The Processing of Waste Carbon Fibre for Thermoplastic Composites - A Review," *Journal of Composite Materials* vol. 54, no. 14, pp. 1925 – 1944, 2020. https://doi.org/10.1177/0021998319886043

[16] S. K. Gopalraj, and T. Kärki, "A Review on The Recycling of Waste Carbon Fibre/Glass Fibre-Reinforced Composites: Fibre Recovery, Properties and Life-Cycle Analysis," *SN Applied Sciences*, vol. 2, no. 3, pp. 433, 2020. https://doi.org/10.1007/s42452-020-2195-4

[17] D. N. Markatos, C. V. Katsiropoulos, K. I. Tserpes, and S. G. Pantelakis, "A holistic End-of-Life (EoL) Index for the Quantitative Impact Assessment of CFRP Waste Recycling Techniques," *Manufacturing Review*, vol. 8, pp. 18, 2021. https://doi.org/10.1051/mfreview/2021016

[18] X. Huan, T. Wu, J. Yan, X. Jia, L. Zu, G. Sui, and X. Yang, "Phosphoric Acid Derived Efficient Reclaimation of Carbon Fibre for Re-Manufacturing High Performance Epoxy Composites Reinforced by Highly-Aligned Mat with Optimized Layup," *Composites Part B Engineering,* vol. 211, pp. 108656, 2021. https://doi.org/10.1016/j.compositesb.2021.108656

[19] P. Y. Chen, R. Feng, Y. Xu, and J. Zhu, "Recycling and Reutilization of Waste Carbon Fibre Reinforced Plastics: Current Status and Prospects," *Polymers,* vol. 15, no. 17, pp. 3508, 2023. https://doi.org/10.3390/polym15173508

[20] H. Sukanto, W. W. Raharjo, D. Ariawan, and J. Triyono, "Carbon Fibers Recovery from CFRP Recycling Process and Their Usage: A Review," *IOP Conference Series: Materials Science and Engineering*, vol. 1034, no. 1, pp. 012087, IOP Publishing, 2021. https://iopscience.iop.org/article/10.1088/1757-899X/1034/1/012087/pdf

[21] S. Pimenta, and S. T. Pinho, "Recycling Carbon Fibre Reinforced Polymers for Structural Applications: Technology Review and Market Outlook," *Waste Management*, vol. 31, no. 2, pp. 378-392, 2011. https://doi.org/10.1016/j.wasman.2010.09.019

[22] Z. Liu, T. A. Turner, K. H. Wong, and S. J. Pickering, "Development of High Performance Recycled Carbon Fibre Composites with an Advanced Hydrodynamic Fibre Alignment Process," *Journal of Cleaner Production,* vol. 278, pp. 123785, 2021. https://doi.org/10.1016/j.jclepro.2020.123785

[23] K. Giannadakis, M. Szpieg, and J. Varna, "Mechanical Performance of a Recycled Carbon Fibre/PP Composite. *Experimental mechanics*, vol. 51, pp. 767-777, 2011. https://doi.org/10.1007/s11340-010-9369-8

[24] S. Palola, P. Laurikainen, S. García-Arrieta, E. G. Astorkia, and E. Sarlin, "Towards Sustainable Composite Manufacturing with Recycled Carbon Fiber Reinforced Thermoplastic Composites," *Polymers*, vol. 14, no. 6, pp. 1098, 2022. https://doi.org/10.3390/polym14061098

[25] W. Song, A. Magid, D. Li, and K. Y. Lee, "Application of Recycled Carbon-Fibre-Reinforced Polymers as Reinforcement for Epoxy Foams," *Journal of Environmental Management*, vol. 269, pp. 110766, 2020. https://doi.org/10.1016/j.jenvman.2020.110766

[26] P. R. Barnett, and H. Ghossein, "A Review of Recent Developments in Composites Made of Recycled Carbon Fiber Textiles," *Textiles,* vol.1, no.3, pp. 433, 2021. https://doi.org/10.3390/textiles1030023

[27] Carbon Fiber Recycling: Closing the Loop, 2023. https://carbonconversions.com/

[28] Carbon Fiber Remanufacturing, 2020. https://carbonfiberremanufacturing.com/

[29] A. Isa, N. Nosbi, M. Che Ismail, H. Md Akil, W. F. F. Wan Ali, and M. F. Omar, "A Review on Recycling of Carbon Fibres: Methods to Reinforce and Expected Fibre Composite Degradations," *Materials*, vol. 15, no. 14, pp. 4991, 2022. https://doi.org/10.3390/ma15144991

[30] M. Y. Khalid, Z. U. Arif, W. Ahmed, and H. Arshad, "Recent Trends in Recycling and Reusing Techniques of Different Plastic Polymers and Their Composite Materials," *Sustainable Materials and Technologies*, vol. 31, pp. e00382, 2022. https://doi.org/10.1016/j.susmat.2021.e00382

[31] D. De Fazio, L. Boccarusso, A. Formisano, A. Viscusi, and M. Durante, "A Review on the Recycling Technologies of Fibre-Reinforced Plastic (FRP) Materials Used in Industrial Fields," *Journal of Marine Science and Engineering*, vol. 11, no. 4, pp. 851, 2023. https://doi.org/10.3390/jmse11040851

[32] D. Borjan, Ž. Knez, and M. K. Marevci, "Recycling of Carbon Fiber-Reinforced Composites - Difficulties and Future Perspectives," *Materials*, vol. 14, no. 15, pp. 4191, 2021. https://doi.org/10.3390/ma14154191

[33] M. Yuan, Z. Li, and Z. Teng, "Progress and Prospects of Recycling Technology for Carbon Fiber Reinforced Polymer," *Frontiers in Materials*, vol. 11, pp. 1484544, 2024. https://doi.org/10.3389/fmats.2024.1484544

[34] A. E. Krauklis, C. W. Karl, A. I. Gagani, and J. K Jørgensen, "Composite Material Recycling Technology–State-of–the-Art and Sustainable Development for the 2020s," *Journal of Composites Science*, vol. 5, no. 1, pp. 28, 2021. https://doi.org/10.3390/jcs5010028

[35] V. Titone, L. Botta, and F. P. La Mantia, "Mechanical Recycling of New and Challenging Polymer Systems: A Brief Overview. *Macromolecular Materials and Engineering*, vol. 310, no. 1, pp. 2400275, 2025. https://doi.org/10.1002/mame.202400275

[36] J. Qureshi, "A Review of Recycling Methods for Fibre Reinforced Polymer Composites," *Sustainability*, vol. 14, no. 24, pp. 16855, 2022. https://doi.org/10.3390/su142416855

[37] J. Li, P. L. Xu, Y. K. Zhu, J. P. Ding, L. X. Xue, and Y. Z. Wang, "A Promising Strategy for Chemical Recycling

of Carbon Fiber/Thermoset Composites: Self-Accelerating Decomposition in A Mild Oxidative System," *Green Chemistry*, vol. 14, no. 12, pp. 3260-3263, 2012. https://doi.org/10.1039/c2gc36294e

[38] H. Cheng, H. Wang, J. Zhou, L. Guo, Q. Wang, and M. Tang, "Performance Analysis of Recycled Carbon Fiber Under Recycling Process Parameters Optimized Using Response Surface Methodology," *Journal of Composite Materials*, vol. 57, no. 18, pp. 2857- 2872, 2023. https://doi.org/10.1177/00219983231179092

[39] L. Giorgini, T. Benelli, G. Brancolini, and L. Mazzocchetti, "Recycling of Carbon Fiber Reinforced Composite Waste to Close Their Life Cycle in a Cradle-To-Cradle Approach, Current opinion in green and sustainable chemistry, vol. 26, pp. 100368, 2020. https://doi.org/10.1016/j.cogsc.2020.100368

[40] J. Wu, X. Gao, Y. Wu, Y. Wang, T. T. Nguyen, and M. Guo, "Recycling Carbon Fiber from Carbon Fiber-Reinforced Polymer and its Reuse in Photocatalysis: A Review," *Polymers*, vol. 15, no. 1, pp. 170, 2022. https://doi.org/10.3390/polym15010170

[41] M. Návrat, J. Závada, and V. Glogarová, "The Influence of Pyrolitic Degradation on Mechanical Properties of Carbon Fibres within Recycling Composite Materials," *GeoScience Engineering*, vol. 63, no. 4, pp. 8, 2017. 10.1515/gse-2017-0017

[42] F. Ferrari, G. A. Carallo, A. Greco, "Innovative Closed-Loop Recyclable Bio-Based Composites from Epoxidized Waste Flour and Recycled Carbon Fibers," *Polymers*, vol. 14, no. 18, pp. 3878, 2022. https://doi.org/10.3390/polym14183878

[43] F. A. López, O. Rodríguez, F. J. Alguacil, I. García-Díaz, T. A. Centeno, J. L. García-Fierro, and C. González, "Recovery of Carbon Fibres by the Thermolysis And Gasification of Waste Prepreg," *Journal of analytical and applied pyrolysis*, vol. 104, pp. 675-683, 2013. https://doi.org/10.1016/j.jaap.2013.04.01

[44] J. Deng, L. Xu, L. Zhang, J. Peng, S. Guo, J. Liu, and S. Koppala, "Recycling of Carbon Fibers from CFRP Waste by Microwave Thermolysis," *Processes,* vol. 7, no. 4, pp. 207, 2019. https://doi.org/10.3390/pr7040207

[45] S. Hao, L. He, J. Liu, Y. Liu, C. Rudd, and X. Liu, "Recovery of carbon fibre from waste prepreg via microwave pyrolysis," *Polymers*, vol. 13, no. 8, 1231, 2021. https://doi.org/10.3390/polym13081231

[46] E. Seiler, H. Urban, and U. Teipel, "Microwave Pyrolysis of Carbon-Fiber-Reinforced Plastics as Recycling Option," *Chemie Ingenieur Technik*, vol. 92, no. 4, pp. 469 - 475, 2020. https://doi.org/10.1002/cite.201900133

[47] Y. Ren, L. Xu, X. Shang, Z. Shen, R. Fu, W. Li, and L. Guo, "Evaluation of Mechanical Properties and Pyrolysis Products of Carbon Fibers Recycled by Microwave Pyrolysis," *ACS Omega,* vol. 7, no. 16, pp. 13529 - 13537, 2022. https://doi.org/10.1021/acsomega.1c06652

[48] N. M. Yatim, E. A. Shariff, Z. Shamsudin, A. Shaaban, and Z. Mustafa, "Thermal Decomposition Analysis of High End Application Waste Cured Carbon Fibre Reinforced Polymer for Secondary Industrial Application, *Journal Of Mechanics Of Continua And Mathematical Sciences,* no. 9, pp. 11-21, 2020. https://doi.org/10.26782/jmcms.spl.9/2020.05.00002

[49] M. A. Nahil, and P. T. Williams, "Recycling of Carbon Fibre Reinforced Polymeric Waste for the Production of Activated Carbon Fibres," *Journal of Analytical and applied pyrolysis*, vol. 91, no. 1, pp. 67-75, 2011. https://doi.org/10.1016/j.jaap.2011.01.005

[50] T. Wu, W. Zhang, X. Jin, X. Liang, G. Sui, and X. Yang, "Efficient Reclamation of Carbon Fibers from Epoxy Composite Waste Through Catalytic Pyrolysis in Molten Zncl 2," *RSC advances*, vol. 9, no. 1, pp. 377-388, 2019. 10.1039/C8RA08958B

[51] J. A. Onwudili, N. Insura, P. T. Williams, "Autoclave Pyrolysis of Carbon Reinforced Composite Plastic Waste for Carbon Fibre and Chemicals Recovery," *Journal of the Energy Institute*, vol. 86, no. 4, pp. 227–232, 2013. https://doi.org/10.1179/1743967113Z.00000000066

[52] J. Jeong, D. Oh, Y. Ju, and M. Goh, "Energy-Efficient Chemical Recycling of CFRP and Analysis of the Interfacial Shear Strength on Recovered Carbon Fibre," *Waste Management*, vol. 187, pp. 134-144, 2024. https://doi.org/10.1016/j.wasman.2024.07.017

[53] B. Wang, X. Wang, N. Xu, Y. Shen, F. Lu, Y. Liu, Y. Huang, and Z. Hu, "Recycling of Carbon Fibres from Unsaturated Polyester Composites via a Hydrolysis-Oxidation Synergistic Catalytic Strategy," *Composites Science and Technology*, vol. 203, pp. 108589, 2021. https://doi.org/10.1016/j.compscitech.2020.108589

[54] A. Sakai, W. Kurniawan, and M. Kubouchi, "Recycled Carbon Fibres with Improved Physical Properties Recovered from CFRP by Nitric Acid," *Applied Sciences*, vol. 13, no. 6, pp. 3957, 2023. https://doi.org/10.3390/app13063957

[55] H. Sun, G. Guo, S. A. Memon, W. Xu, Q. Zhang, J. H. Zhu, and F. Xing, "Recycling of Carbon Fibres from Carbon Fibre Reinforced Polymer Using Electrochemical Method," *Composites Part A: Applied Science and Manufacturing*, vol. 78, pp. 10-17, 2015. https://doi.org/10.1016/j.compositesa.2015.07.015

[56] C. Pei, P. Chen, S. C. Kong, J. Wu, J. H. Zhu, and F. Xing, "Recyclable Separation and Recovery of Carbon Fibres from CFRP Composites: Optimization and Mechanism," *Separation and Purification Technology*, vol. 278, pp. 119591, 2021. https://doi.org/10.1016/j.seppur.2021.119591

[57] Y. Wei, and S. A. Hadigheh, "Development of an Innovative Hybrid Thermo-Chemical Recycling Method for CFRP Waste Recovery," *Composites Part*

B: Engineering, vol. 260, pp. 110786, 2023. https://doi.org/10.1016/j.compositesb.2023.110786

[58] I. Okajima, K. Watanabe, S. Haramiishi, M. Nakamura, Y. Shimamura, and T. Sako, "Recycling of Carbon Fibre Reinforced Plastic Containing Amine-Cured Epoxy Resin Using Supercritical and Subcritical Fluids," *The Journal of Supercritical Fluids*, vol. 119, pp. 44-51, 2017. https://doi.org/10.1016/j.supflu.2016.08.015

[59] G. Colucci, O. Ostrovskaya, A. Frache, B. Martorana, and C. Badini, "The Effect of Mechanical Recycling on the Microstructure and Properties of PA66 Composites Reinforced with Carbon Fibers," *Journal of Applied Polymer Science*, vol. 132, no. 29, 2015. https://doi.org/10.1002/app.42275

[60] T. Tarkar, H. Padachh, and H. Shaikh, "Simulation Based Characterization of Recycled Carbon Fibre Reinforced Plastics in a Rod Specimen," *Materials Today: Proceedings*, vol. 44, pp. 909-916, 2021. https://doi.org/10.1016/j.matpr.2020.10.802

[61] H. Li, and K. Englund, "Recycling of Carbon Fiber-Reinforced Thermoplastic Composite Wastes from the Aerospace Industry," *Journal of composite materials*, vol. 51, no. 9, pp. 1265-1273, 2017. https://doi.org/10.1177/0021998316671796

[62] W. Ballout, N. Sallem-Idrissi, M. Sclavons, C. Doneux, C. Bailly, T. Pardoen, and P. Van Velthem, "High Performance Recycled CFRP Composites Based on Reused Carbon Fabrics Through Sustainable Mild Solvolysis Route," *Scientific Reports*, vol. 12, no. 1, pp. 5928, 2022. https://doi.org/10.1038/s41598-022-09932-0

[63] J. Palmer, O. R. Ghita, L. Savage, and K. E. Evans, "Successful Closed-Loop Recycling of Thermoset Composites," *Composites Part A: Applied Science and Manufacturing*, vol. 40, no. 4, pp. 490-498, 2009. https://doi.org/10.1016/j.compositesa.2009.02.002

[64] C. Thomas, P. H. R. Borges, T. H. Panzera, A. Cimentada, and I. Lombillo, "Epoxy Composites Containing CFRP Powder Wastes," *Composites Part B: Engineering*, vol. 59, 260-268, 2014. https://doi.org/10.1016/j.compositesb.2013.12.013

[65] M. Durante, L. Boccarusso, D. De Fazio, A. Formisano, and A. Langella, "Investigation on the Mechanical Recycling of Carbon Fiber-Reinforced Polymers by Peripheral Down-Milling," *Polymers*, vol. 15, no. 4, pp. 854, 2023. https://doi.org/10.3390/polym15040854

[66] X. Tian, T. Liu, Q. Wang, A. Dilmurat, D. Li, and G. Ziegmann, "Recycling and Remanufacturing of 3D Printed Continuous Carbon Fiber Reinforced PLA Composites," *Journal of Cleaner Production*, vol. 142, pp. 1609-1618, 2017. https://doi.org/10.1016/j.jclepro.2016.11.139

[67] L. Jiang, C. A. Ulven, D. Gutschmidt, M. Anderson, S. Balo, M. Lee, and J. Vigness, "Recycling Carbon Fiber Composites Using Microwave Irradiation: Reinforcement Study of the Recycled Fiber in New Composites," *Journal of Applied Polymer Science*, vol. 132, no. 41, 2015. https://doi.org/10.1002/app.42658

[68] D. Chen, "Development of Chemical Processes for the Recycling of Carbon Fiber/Epoxy Composites," *University of California, Los Angeles*, 2020.

[69] K. H. Wong, S. J. Pickering, and C. D. Rudd, "Recycled Carbon Fibre Reinforced Polymer Composite for Electromagnetic Interference Shielding," *Composites Part A: Applied Science and Manufacturing*, vol. 41, no. 6, pp. 693-702, 2010. https://doi.org/10.1016/j.compositesa.2010.01.012

[70] E. J. X. Pang, A. Chan, S. J. Pickering, "Thermoelectrical Properties of Intercalated Recycled Carbon Fibre Composite," *Composites Part A: Applied Science and Manufacturing*, vol. 42, no. 10, pp. 1406-1411, 2011. https://doi.org/10.1016/j.compositesa.2011.06.004

[71] Y. N. Kim, Y. O. Kim, S. Y. Kim, M. Park, B. Yang, J. Kim, and Y. C. Jung, "Application of Supercritical Water for Green Recycling of Epoxy-Based Carbon Fiber Reinforced Plastic," *Composites Science and Technology*, vol. 173, pp. 66 – 72, 2019. https://doi.org/10.1016/j.compscitech.2019.01.026

[72] M. H. Akonda, C. A. Lawrence, and H. M. EL-Dessouky, "Electrically Conductive Recycled Carbon Fibre-Reinforced Thermoplastic Composites," *Journal of Thermoplastic Composite Materials*, vol. 28, no.11, pp. 1550 - 1563, 2015. https://doi.org/10.1177/0892705713513294

[73] Y. Wang, L. Sun, A. Li, W. Li, and B. Guo, "Effect of Modified Recycled Carbon Fibers on the Conductivity of Cement-Based Materials," *Construction and Building Materials*, vol. 415, pp. 135033, 2024. https://doi.org/10.1016/j.conbuildmat.2024.135033

[74] M. Zambrzycki, J. Tomala, and A. Fraczek-Szczypta, "Electrical and Mechanical Properties of Granular-Fibrous Carbon-Carbon Composites with Recycled Carbon Fibres," *Ceramics International*, vol. 44, no. 16, pp. 19282-19289, 2018. https://doi.org/10.1016/j.ceramint.2018.07.154

[75] G. Faneca, I. Segura, J. M. Torrents, and A. Aguado, "Development of Conductive Cementitious Materials Using Recycled Carbon Fibres," *Cement and Concrete Composites*, vol. 92, pp. 135-144, 2018. https://doi.org/10.1016/j.cemconcomp.2018.06.009