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Structure–Property Relationships of Polylactic Acid Composites Reinforced with Chemically Recycled Carbon Fibers from CFRP Waste

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Abstract

The rapid growth in the use of carbon fiber-reinforced polymers (CFRPs) and fused-deposition-modeled (FDM) polylactic acid (PLA) has generated substantial non-biodegradable and thermoplastic waste streams, creating urgent needs for scalable recycling and valorization strategies. This study develops and evaluates an integrated route that chemically recovers carbon fibers (CFs) from CFRP waste and converts them into high-performance reinforcements for recycled PLA matrices. CFRP fragments were pre-swollen in acetic acid (120 °C, 1 h), then depolymerized by means of oxidation with 1 M $KMnO_4$ (100 °C, 2 h), washed, dried (100 °C, 24 h), and size-reduced by means of cryogenic milling. Recycled CFs (treated) and untreated CFRP fragments were blended with 3D-printing PLA waste at 10, 20 and 30 wt.% via melt mixing (175 °C, 5 min, 70 rpm) and molded into ASTM D638 dog-bone specimens. Materials were characterized via XRD, FTIR, Raman, SEM and mechanical testing. XRD and Raman confirmed retention of the graphitic backbone after treatment; FTIR and Raman revealed oxygen-containing surface functionalization consistent with oxidation, while SEM showed effective removal of epoxy and improved fiber surface cleanliness. Compared with neat PLA (tensile strength 45.4 MPa; modulus 2.6 GPa; elongation 6.3%), composites reinforced with chemically recycled CFs exhibited marked mechanical enhancement: at 30 wt.% treated CF, the tensile strength increased to 102.6 MPa (+126%), elastic modulus to 11.7 GPa (+350%), and toughness to 250.3 MPa, while ductility decreased to 2.9%. Equivalent composites with untreated CFRP exhibited smaller gains (30 wt.%: tensile 87.3 MPa; modulus 10.3 GPa), highlighting the benefit of epoxy removal and surface activation for fiber–matrix adhesion. The proposed chemical recycling pathway is operationally simple and cost-effective, produces reusable CFs with preserved graphitic structure and enhanced surface chemistry, and enables the fabrication of high-performance, waste-derived PLA composites suitable for structural and engineering applications. This work demonstrates a viable waste-to-value approach that advances circularity for both CFRP and 3D-printing polymer waste streams.

Keywords: chemical recycling; recycled carbon fiber; PLA waste; CFRP valorization; structure–property relationships

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1. Introduction

Carbon fiber-reinforced polymers (CFRPs) have become indispensable materials in high-performance engineering sectors such as aerospace, automotive, medical devices, and machine-tool systems due to their outstanding mechanical efficiency, dimensional stability, and resistance to harsh environments [1,2]. Their widespread adoption is driven primarily by the exceptional properties of carbon fibers (CFs), which exhibit tensile strengths an order of magnitude higher than steel while maintaining nearly one-quarter of its density, enabling the design of lightweight structures with superior specific strength and stiffness [3,4]. In addition to their mechanical advantages, CFRPs demonstrate favorable thermal expansion behavior, high heat resistance, chemical stability, and corrosion resistance, which collectively promote their substitution for conventional metallic materials in demanding structural applications [5–8].

The superior performance of CFRPs arises from the synergistic interaction between the reinforcing carbon fibers and the thermosetting epoxy matrix. The fibers serve as the principal load-bearing phase, while the epoxy resin ensures efficient stress transfer, fiber alignment stability, and resistance to buckling and crack propagation [5,7]. During curing, epoxy resins undergo irreversible cross-linking reactions that generate a rigid three-dimensional polymer network, resulting in enhanced chemical resistance and mechanical durability [6,9]. However, this cross-linked structure renders epoxy-based CFRPs insoluble and non-meltable after curing, fundamentally distinguishing them from thermoplastic composites and creating significant challenges for recycling and end-of-life management [10,11].

The rapid growth in CFRP usage has led to a parallel increase in manufacturing scrap and end-of-life composite waste. Global demand for carbon fibers reached approximately 35 kilotons in 2008, with an annual growth rate approaching 12% [12], and has since expanded to nearly 194 kilotons worldwide, with projections indicating continued growth of approximately 20 kilotons annually by 2025 [13]. This expansion has intensified environmental and economic pressures associated with CFRP waste disposal, reinforcing the urgent need for efficient recycling technologies that align with sustainability goals and circular economy frameworks [14,15].

Current CFRP recycling technologies are commonly classified into mechanical, thermal, and chemical approaches [10,16]. Mechanical recycling involves shredding, milling, or grinding CFRP waste into short fiber fragments, typically ranging from 10 to 50 mm in length [15]. The resulting recyclate is a heterogeneous mixture of resin powder and fibrous material [16,17]. While this approach avoids high temperatures and chemical solvents, the recovered fibers experience significant degradation in length, surface integrity, and mechanical performance, severely limiting their reuse in high-value structural applications [18].

Thermal recycling techniques, including pyrolysis and fluidized-bed processing, rely on elevated temperatures to decompose the polymer matrix and recover carbon fibers [19]. Pyrolysis typically operates at temperatures between 450 and 700 °C under controlled atmospheres, converting the polymeric matrix into gaseous and liquid products while releasing carbon fibers [20]. Although recycled fibers obtained through pyrolysis can retain approximately 70–80% of their original tensile strength, surface oxidation, charring, and the emission of hazardous gases remain major drawbacks [19]. Moreover, pyrolysis outcomes are highly sensitive to processing parameters such as heating rate, temperature, residence time, pressure, and waste composition [21,22], often resulting in structural disorder and inconsistent fiber quality [23,24]. Fluidized-bed recycling offers advantages such as energy recovery and tolerance to contaminated feedstocks; however, it commonly leads to shortened, fluffy fibers with reduced structural stability and mechanical integrity [25].

Chemical recycling, also referred to as solvolysis, has emerged as a promising alternative for recovering high-quality carbon fibers under comparatively mild conditions. This approach employs chemical solvents, catalytic systems, or supercritical fluids to depolymerize the epoxy matrix into oligomeric products, enabling the release of intact carbon fibers [15,26]. Chemically recycled CFs can retain up to 90% of the mechanical properties of virgin fibers, making them attractive for reuse in structural and semi-structural applications [27]. Nevertheless, many solvolysis-based techniques rely on expensive reagents, complex processing routes, and may generate environmentally hazardous byproducts, limiting their scalability and industrial implementation [27,28].

To contextualize the advantages and limitations of existing CFRP recycling routes and to highlight the need for integrated, scalable waste-to-value strategies, a comparative overview of current recycling approaches is summarized in Table 1.

Table 1. Overview of CFRP recycling technologies, recovered fiber quality, limitations, and implications for reuse in polymer composites.

Recycling Approach	Process Description	Typical Operating Conditions	Quality of Recovered Carbon Fibers	Key Limitations	Suitability for High-Performance PLA Composites	Representative References
Mechanical recycling	Shredding, milling, or grinding of CFRP into short fiber fragments mixed with resin powder	Ambient temperature; mechanical size reduction	Severely shortened fibers (10–50 mm); damaged surface; reduced strength and stiffness	Fiber breakage; poor surface integrity; limited reinforcement efficiency	Low—poor load transfer and weak interfacial bonding	[10,15–18]
Pyrolysis (thermal recycling)	Thermal decomposition of epoxy matrix under inert or controlled atmosphere	450–700 °C; inert gas	Fibers retain ~70–80% of tensile strength; surface oxidation common	High energy demand; surface damage; hazardous emissions; process sensitivity	Moderate—surface damage limits interfacial adhesion	[19–24]
Fluidized-bed processing	High-temperature oxidation of matrix in a fluidized environment	450–550 °C; oxidizing atmosphere	Shortened, fluffy fibers; reduced structural integrity	Fiber attrition; low mechanical performance	Low—unsuitable for structural composites	[25]
Chemical recycling (solvolysis)	Depolymerization of epoxy using solvents, catalysts, or supercritical fluids	Mild to moderate temperatures (80–250 °C)	Fibers retain up to ~90% of virgin properties; surface functionalization possible	Use of costly solvents; complex processing; scalability challenges	High—good mechanical performance and adhesion	[15,26–28]
This study (integrated chemical recycling + PLA valorization)	Acetic acid swelling + $KMnO_4$ oxidation followed by cryogenic milling and PLA reinforcement	100–120 °C; aqueous chemical system	Preserved graphitic backbone; clean surface; oxygen-containing functional groups	Minimal; low-cost reagents; scalable route	Excellent—superior strength, stiffness, and toughness	This study

In parallel with CFRP waste accumulation, the rapid expansion of additive manufacturing, particularly fused deposition modeling (FDM), has resulted in a substantial increase in thermoplastic waste streams, most notably polylactic acid (PLA). PLA is a bio-based aliphatic polyester synthesized from renewable resources via lactic acid fermentation followed by lactide polymerization [28]. Due to its biodegradability, ease of processing, and widespread availability, PLA is extensively used in 3D printing, packaging, and automation applications [29]. However, PLA exhibits relatively low thermal stability and limited mechanical performance compared to engineering-grade polymers, which restricts its reuse and recycling in demanding structural applications [28,30].

To overcome these limitations, PLA has been extensively modified through blending and reinforcement with metals, metal oxides, carbon nanotubes, and fibers, often achieving performance levels comparable to or exceeding those of petroleum-based polymers such as polyethylene and polypropylene [29,30]. Carbon fiber reinforcement has proven particularly effective in enhancing the mechanical properties of PLA, enabling its use in high-performance components and 3D-printed composite structures [13,30]. Additionally, natural fiber-reinforced PLA composites have been explored as fully biodegradable alternatives, offering favorable processing characteristics, reduced toxicity, and competitive mechanical performance [31–33]. Nevertheless, the incomplete environmental degradation of PLA and the growing volume of PLA-based waste underscore the importance of recycling strategies that enhance material performance while maintaining environmental compatibility [32,34].

Despite significant advances in CFRP recycling and PLA composite development independently, a critical research gap remains in the integrated valorization of chemically recycled CFRP-derived carbon fibers as reinforcements for recycled PLA matrices. In particular, systematic comparisons between untreated CFRP fragments and chemically recycled CFs focusing on fiber surface chemistry, structural integrity, and resulting composite mechanical performance are limited. Furthermore, few studies have explored low-cost, scalable chemical recycling routes capable of producing reusable CFs suitable for reinforcing waste-derived PLA, thereby simultaneously addressing two major polymer waste streams within a single materials framework [29,34].

This study addresses this gap by developing a chemically assisted recycling strategy for CFRP waste using acetic acid pretreatment followed by potassium permanganate oxidation to selectively remove the epoxy matrix while preserving the graphitic structure of the carbon fibers. The recovered fibers are subsequently cryogenically milled and incorporated into recycled PLA at varying loadings (10, 20, and 30 wt.%). The performance of these composites is directly compared with PLA composites containing untreated CFRP waste. Comprehensive characterization using SEM, XRD, FTIR, Raman spectroscopy, and mechanical testing is employed to elucidate the structure–property relationships governing composite performance. By integrating CFRP and PLA waste streams into high-performance composite materials, this work contributes a sustainable waste-to-value approach that advances circular economy strategies for fiber-reinforced polymer systems.

2. Results and Discussion

2.1. Structural Characterization of Chemically Recycled Carbon Fibers

2.1.1. X-Ray Diffraction (XRD) Analysis

The crystalline structure of carbon fibers following chemical recycling was examined using X-ray diffraction (XRD), and the resulting diffraction pattern is presented in Figure 1.

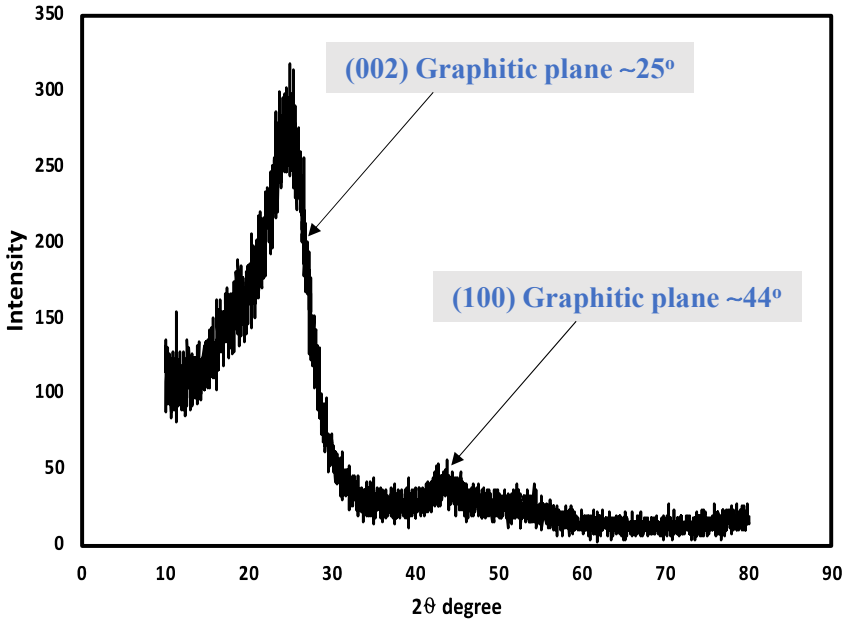


Figure 1. XRD pattern of chemically recycled carbon fibers showing characteristic graphitic reflections at ~25° (002) and ~44° (100), confirming preservation of the graphitic structure after chemical recycling.

Two characteristic diffraction peaks are observed at approximately $2\theta \approx 25^\circ$ and $2\theta \approx 44^\circ$, corresponding to the (002) and (100) planes of graphitic carbon, respectively [35]. The presence of these peaks confirms that the fundamental graphitic backbone of the carbon fibers is preserved after chemical treatment. Although XRD spectra of the untreated fibers were not included in the present study, the retained characteristic graphitic reflections after treatment indicate that the primary crystalline structure of the carbon fibers remained largely intact following chemical recycling. The conclusions presented here are therefore based on the preservation of the characteristic graphitic signatures commonly reported for carbon fibers in the literature rather than implying the complete absence of structural modification.

The broad nature of the (002) reflection indicates a turbostratic or partially ordered carbon structure, which is commonly reported for recycled carbon fibers due to the disruption of long-range order during composite fabrication and recycling processes. Importantly, no additional crystalline phases associated with epoxy resin or inorganic degradation products are detected, indicating effective removal of the polymeric matrix during the chemical recycling process.

Retention of the graphitic structure is a critical requirement for the reuse of recycled carbon fibers as reinforcing agents in polymer composites, as it directly governs stiffness, load transfer efficiency, and electrical conductivity. The XRD results therefore demonstrate that the applied acetic acid pretreatment and $KMnO_4$ oxidation successfully eliminate the epoxy resin without compromising the intrinsic structural integrity of the carbon fibers. However, minor surface-level structural changes and localized disorder may still occur during oxidative treatment. Future work involving direct comparative XRD analysis of untreated and chemically treated fibers may provide additional insight into subtle crystallographic changes induced during the recycling process.

2.1.2. Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy was employed to investigate the surface chemistry of the chemically recycled carbon fibers and to verify the removal of the epoxy resin. The FTIR spectrum recorded over the range 500–4000 cm^{-1} is presented in Figure 2.

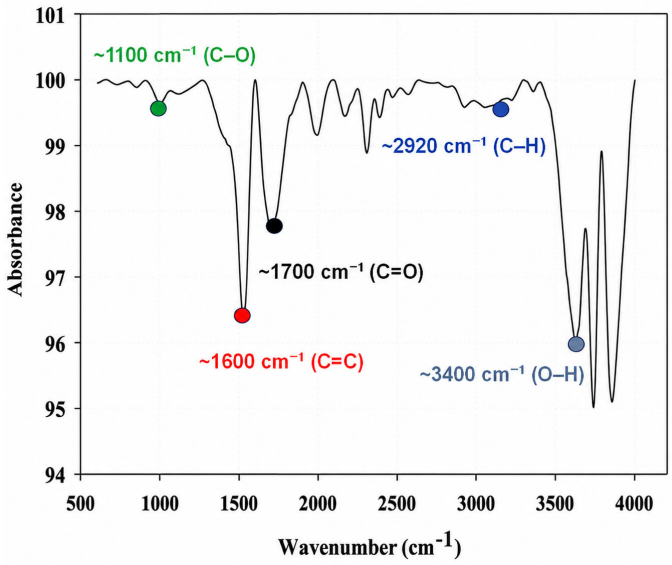


Figure 2. FTIR spectrum of chemically recycled carbon fibers highlighting O–H, C=C (graphitic), and C–O functional groups and confirming effective removal of epoxy resin.

A broad absorption band centered around ~3400 cm^{-1} is observed and attributed to O–H stretching vibrations, indicating the presence of hydroxyl functional groups introduced during oxidative chemical treatment [36]. The formation of these oxygen-containing functional groups is associated with partial surface oxidation induced by potassium permanganate and is beneficial for enhancing fiber–matrix interfacial adhesion in polymer composites.

Distinct absorption features in the range of 1500–1600 cm^{-1} correspond to C=C stretching vibrations characteristic of aromatic and graphitic carbon structures. The persistence of this band confirms that the carbon backbone remains intact following chemical recycling, in agreement with the XRD results. Additionally, absorption bands appearing in the region of 1000–1300 cm^{-1} are assigned to C–O stretching vibrations, which may arise from alcohol or ester groups formed on the fiber surface during oxidation.

Notably, the absence of characteristic epoxy-related absorption bands such as those associated with ether (C–O–C) and aliphatic C–H stretching provides strong evidence for the successful removal of the epoxy resin matrix. Compared with untreated CFRP-derived fibers, the chemically recycled fibers exhibited reduced epoxy-associated functional groups together with increased oxygen-containing surface functionalities, indicating selective resin removal and controlled surface oxidation during chemical treatment.

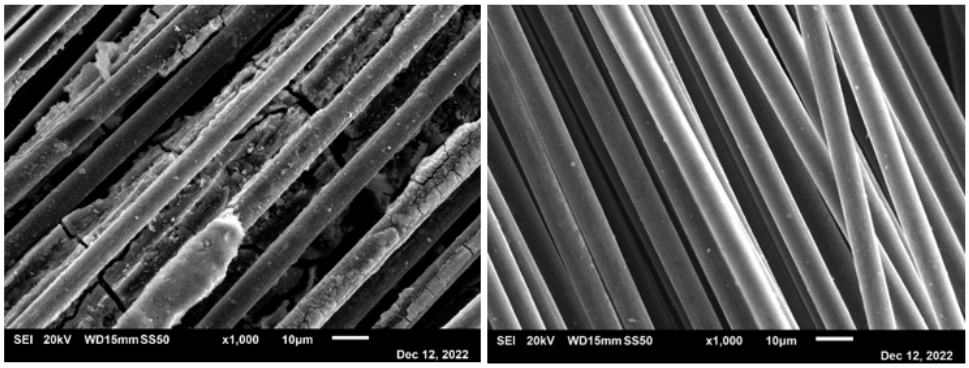
Overall, the FTIR results demonstrate that chemical recycling selectively modifies the fiber surface chemistry while preserving the graphitic structure, thereby improving surface reactivity without degrading the reinforcing capability of the fibers.

2.2. Surface Morphology of Recycled Carbon Fibers

The surface morphologies of untreated and chemically recycled carbon fibers were examined using scanning electron microscopy (SEM), and the representative micrographs are presented in Figure 3.

SEM analysis enables a direct visual comparison between untreated and chemically recycled fibers, thereby providing morphological evidence of the changes induced by chemical treatment. As shown in Figure 3a, the untreated CFRP-derived fibers exhibit a highly irregular and rough surface morphology, characterized by extensive coverage of epoxy resin residues. These residues appear as agglomerated, irregularly shaped deposits and white blocks adhering to the fiber surface, indicating incomplete matrix removal and

poor fiber surface exposure. The presence of such residual resin is detrimental to interfacial bonding, as it hinders direct contact between the carbon fiber surface and the polymer matrix, thereby limiting effective stress transfer in composite systems.



(**a**) (**b**)

Figure 3. (**a**) SEM image of untreated CFRP-derived carbon fibers showing extensive epoxy resin residues; (**b**) SEM image of chemically recycled carbon fibers exhibiting a clean and smooth surface morphology.

In contrast, the chemically recycled carbon fibers shown in Figure 3b displays a markedly smoother and cleaner surface morphology. The majority of the epoxy resin has been successfully removed, revealing well-defined fiber surfaces with longitudinal grooves characteristic of carbon fibers. Only a limited number of fine particulates are observed, which may be attributed to minor residues resulting from acetic acid pretreatment or oxidative depolymerization. Importantly, no severe surface etching, fiber fragmentation, or structural damage is observed, indicating that the chemical recycling conditions were sufficiently mild to preserve fiber integrity.

The pronounced difference between untreated and treated fibers confirms the effectiveness of the chemical recycling approach in selectively removing the epoxy matrix while maintaining the structural continuity of the carbon fibers. Such surface cleaning is particularly advantageous for composite fabrication, as exposed and slightly roughened fiber surfaces can promote mechanical interlocking and enhance interfacial adhesion with thermoplastic matrices such as PLA. These morphological observations provide direct microstructural evidence supporting the improved mechanical performance observed in chemically recycled CF/PLA composites.

2.3. Raman Spectroscopic Analysis of Chemically Recycled Carbon Fibers

Raman spectroscopy was employed to comprehensively evaluate the structural integrity, phase composition, and defect evolution of the chemically recycled carbon fibers. To clearly distinguish between inorganic vibrational features and graphitic carbon signatures, the Raman data were plotted in two separate spectral windows: 200–1050 cm^{-1} (Figure 4a) and 1000–1800 cm^{-1} (Figure 4b).

As shown in Figure 4a, the Raman spectrum in the low-wavenumber region is dominated by vibrational modes associated with inorganic and mineral phases. A broad feature observed between approximately 250 and 300 cm^{-1} is attributed to lattice vibrations of metal–oxygen bonds, commonly associated with calcium-, magnesium-, and iron-containing oxide phases [37]. Such features are characteristic of crystalline or semi-crystalline oxide frameworks and are consistent with residues originating from alkaline or mineral-rich environments encountered during chemical recycling.

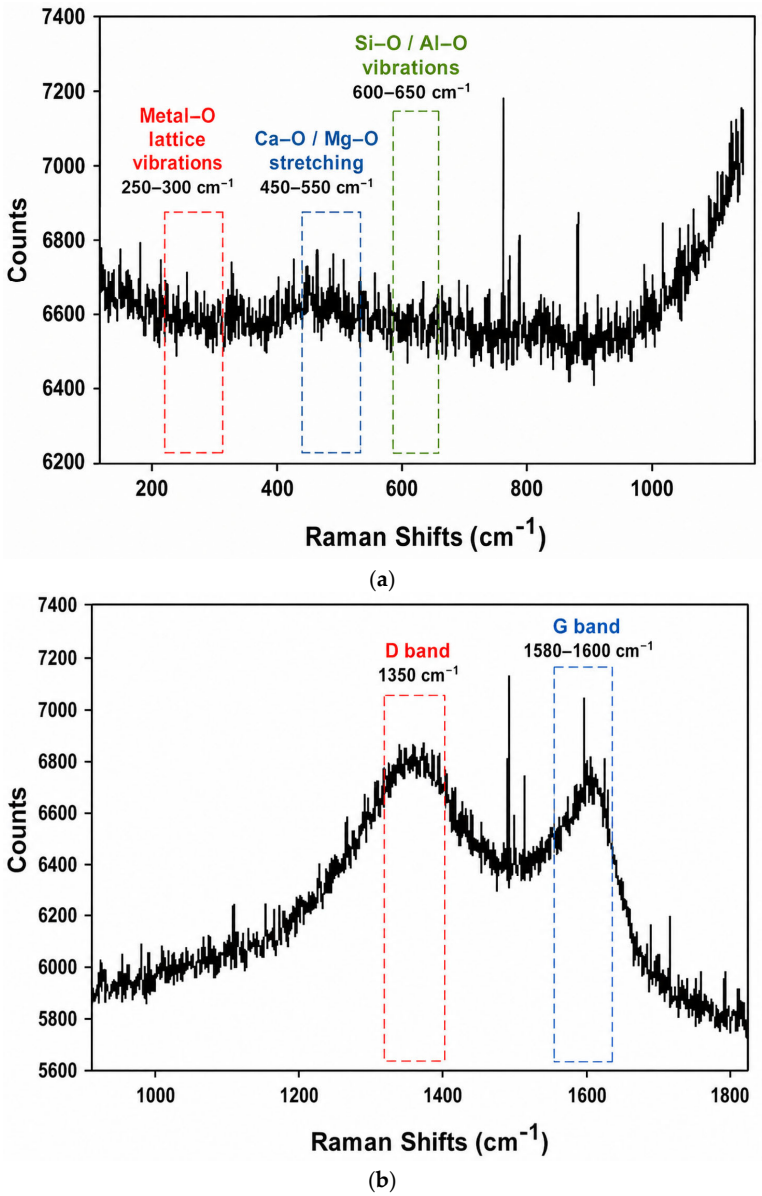


Figure 4. Raman spectra of chemically recycled carbon fibers: (**a**) Low-wavenumber region (200–1050 cm^{-1}) and (**b**) High-wavenumber region (1000–1800 cm^{-1}).

Distinct bands appearing in the 450–550 cm^{-1} range are assigned to metal–oxygen stretching vibrations, particularly Ca–O and Mg–O modes, which are typical of oxide- and slag-derived phases. Additional Raman features observed around 600–650 cm^{-1} correspond to Si–O and Al–O vibrational modes, indicating the presence of silicate or aluminosilicate structures. These bands suggest the formation or retention of a stable inorganic network on the fiber surface, in agreement with complementary XRD observations.

Localized sharp peaks in the 780–800 cm^{-1} region are attributed to defect-related vibrational modes or minor carbonaceous residues introduced during surface oxidation. Furthermore, a pronounced band in the 900–950 cm^{-1} region is characteristic of carbonate symmetric stretching vibrations (CO_3^{2-}) or highly crystalline oxide phases, confirming partial carbonation or oxide stabilization during the chemical treatment process.

The Raman spectrum in the higher wavenumber region (Figure 4b) reveals the characteristic features of graphitic carbon. Two prominent bands are observed: the D band centered at approximately 1350 cm^{-1} and the G band located around 1580–1600 cm^{-1} [38]. The G band is associated with the in-plane stretching vibrations of sp^2-bonded carbon atoms

within ordered graphitic domains, confirming that the fundamental graphitic backbone of the carbon fibers is preserved after chemical recycling.

Although Raman spectra of untreated fibers were not included for direct comparison, the retention of distinct D and G bands after treatment indicates that the primary graphitic structure remained preserved following chemical recycling. The observed spectral features therefore suggest preservation of the carbon fiber backbone together with controlled surface modification rather than severe structural degradation.

The presence of the D band reflects defect-induced breathing modes of sp^2 carbon rings, which become Raman-active in the presence of structural disorder, edge sites, or oxygen-containing functional groups. In the present case, the intensity of the D band is attributed primarily to surface-level defects and functional groups introduced during oxidative treatment, rather than bulk degradation of the fibers.

The increase in defect-related features is likely associated with localized oxidation and surface functionalization induced during $KMnO_4$ treatment, which may contribute positively to fiber–matrix interfacial adhesion in the PLA composites.

The introduction of oxygen-containing functional groups may also improve the chemical compatibility between the recycled carbon fibers and the PLA matrix. Since PLA contains polar ester groups, the oxidized carbon fiber surface can promote stronger interfacial interactions through improved wettability and possible hydrogen bonding interactions. This enhanced interfacial compatibility likely contributed to the improved stress transfer efficiency observed in the CF/PLA composites and may partially explain the substantial increases in tensile strength, elastic modulus, and toughness following chemical recycling treatment.

Importantly, the coexistence of well-defined D and G bands indicates controlled surface modification without disruption of the internal graphitic structure.

The combined Raman results demonstrate that chemical recycling induces a dual structural effect: preservation of the internal graphitic framework responsible for mechanical reinforcement, alongside the introduction of surface defects and inorganic functionalities that enhance interfacial activity. This interpretation is strongly supported by SEM observations, which confirm effective epoxy removal and exposure of clean, roughened fiber surfaces.

Such a balance between structural integrity and surface activation is highly advantageous for composite applications. The retained graphitic core ensures load transfer and stiffness, while surface defects and functional groups promote improved fiber–matrix adhesion. These features directly explain the enhanced mechanical performance observed in CF/PLA composites incorporating chemically recycled carbon fibers compared to those produced from untreated CFRP waste.

The observed preservation of graphitic carbon features after chemical treatment is consistent with previous studies on chemically recycled carbon fibers, which reported that controlled oxidative treatment can remove epoxy residues while maintaining the primary graphitic structure of the fibers [26,39]. Similar studies have also shown that oxidation-induced oxygen-containing surface functional groups can improve interfacial adhesion with thermoplastic matrices by increasing fiber surface polarity and wettability [27,40]. The present findings are therefore in good agreement with the broader literature on recycled carbon fiber surface activation and composite reinforcement.

Overall, the Raman spectroscopic analysis provides robust evidence that the adopted chemical recycling strategy successfully tailors the carbon fiber surface while maintaining the intrinsic reinforcing capability of the fibers, making them well suited for high-performance, sustainable polymer composite applications.

The principal spectroscopic features observed in XRD, FTIR, and Raman analyses are summarized in Table 2 along with their corresponding assignments.

Table 2. Summary of key XRD, FTIR, and Raman features of chemically recycled carbon fibers.

Technique	Peak/Band Position	Assignment	Interpretation
XRD	~25° (002)	Graphitic plane	Preserved graphitic structure
XRD	~44° (100)	In-plane carbon	Structural integrity
FTIR	~3400 cm^{-1}	O–H stretching	Surface oxidation
FTIR	1500–1600 cm^{-1}	C=C stretching	Graphitic backbone
FTIR	1000–1300 cm^{-1}	C–O stretching	Oxygen functional groups
Raman	~1350 cm^{-1} (D)	Defect-induced mode	Surface disorder
Raman	~1580 cm^{-1} (G)	sp^2 carbon vibration	Ordered graphitic domains

2.4. Mechanical Performance of CF/PLA and CFRP/PLA Composites

The mechanical performance of the PLA-based composites was systematically evaluated as a function of carbon fiber content (10, 20, and 30 wt.%) and fiber condition (chemically recycled CF versus untreated CFRP).

The mechanical performance of short fiber-reinforced composites is strongly influenced by fiber length, aspect ratio, dispersion quality, and interfacial adhesion. In the present study, cryogenic milling was used to facilitate fiber dispersion and reduce agglomeration within the PLA matrix. Although quantitative fiber length measurements were not performed, the observed improvements in tensile strength and elastic modulus suggest that the recycled fibers retained sufficient reinforcing capability after chemical treatment and milling.

In this work, tensile strength, elastic modulus, ductility, and toughness were determined using a universal testing machine, and the results are summarized in Table 3.

Table 3. Mechanical properties of the composites presented as mean ± standard deviation (n = 3).

Material	Tensile Strength (MPa)	Elastic Modoulus (GPa)	Ductility (%)	Toughness (MPa)
Pure PLA	45.4 ± 1.2	2.6 ± 0.5	6.3 ± 0.18	189 ± 2.0
90% PLA–10% CF	65.5 ± 1.3	6.7 ± 0.7	4.2 ± 0.30	219 ± 2.1
80% PLA–20% CF	86.8 ± 1.2	9.5 ± 0.7	3.6 ± 0.42	235 ± 1.8
70% PLA–30% CF	102.6 ± 1.1	11.7 ± 0.65	2.9 ± 0.33	250 ± 2.0
90% PLA–10% CFRP	48.1 ± 1.3	4.4 ± 0.7	4.3 ± 0.48	213 ± 1.7
80% PLA–20% CFRP	69.3 ± 1.5	7.3 ± 0.6	3.8 ± 0.27	230 ± 2.1
70% PLA–30% CFRP	87.3 ± 1.7	10.3 ± 0.55	3.5 ± 0.26	245 ± 2.2

The reported mechanical property values represent the average of three independent measurements, and the associated standard deviations are included to demonstrate experimental reproducibility and data reliability.

The mechanical improvements observed in the present study compare favorably with previously reported recycled carbon fiber-reinforced PLA systems. Omar et al. [41], for example, reported improvements in stiffness and tensile performance for recycled carbon fiber/PLA filaments fabricated via fused deposition modeling, although the reinforcement efficiency was strongly dependent on fiber surface condition and dispersion quality. Similarly, Tian et al. [29] demonstrated that recycled carbon fibers can significantly improve the mechanical properties of PLA composites when adequate fiber–matrix adhesion is achieved.

In the present work, the comparatively high tensile strength and elastic modulus obtained for the chemically recycled CF/PLA composites may be attributed to the combined effects of preserved graphitic structure and oxidation-induced surface functionalization.

2.4.1. Elastic Modulus

Elastic modulus is a critical parameter that reflects a material's resistance to elastic deformation under applied stress and is therefore a key indicator of stiffness in structural composites [42]. As Figure 5, the incorporation of both chemically recycled CFs and untreated CFRP significantly increased the elastic modulus of PLA compared to neat PLA (2.6 GPa).

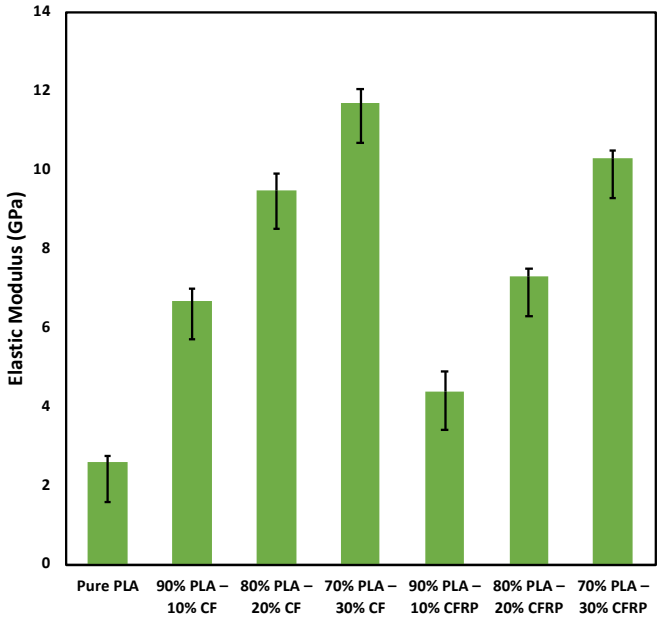


Figure 5. Elastic modulus of the composites.

This enhancement is attributed to the high intrinsic stiffness of carbon fibers and their ability to restrict polymer chain mobility within the PLA matrix.

At a fiber loading of 10 wt.%, the elastic modulus increased to 6.7 GPa for CF/PLA composites and 4.4 GPa for CFRP/PLA composites. The difference between treated and untreated systems becomes more pronounced with increasing fiber content. At 30 wt.% loading, the chemically recycled CF/PLA composite achieved the highest modulus of 11.7 GPa, compared to 10.3 GPa for the corresponding CFRP/PLA composite. This trend demonstrates that the removal of epoxy resin and exposure of clean carbon fiber surfaces significantly improve stress transfer efficiency between the fiber and the PLA matrix.

The superior modulus observed for CF/PLA composites is consistent with the SEM observations, which revealed improved fiber surface cleanliness and enhanced interfacial contact after chemical recycling. Additionally, FTIR and SEM suggested improved interfacial interactions and compatibility between the recycled carbon fibers and the PLA matrix [41]. These combined effects result in more effective load sharing between the matrix and the reinforcement, leading to higher stiffness.

2.4.2. Tensile Strength

The tensile strength results, presented in Figure 6, further highlight the advantages of chemically recycled carbon fibers over untreated CFRP waste.

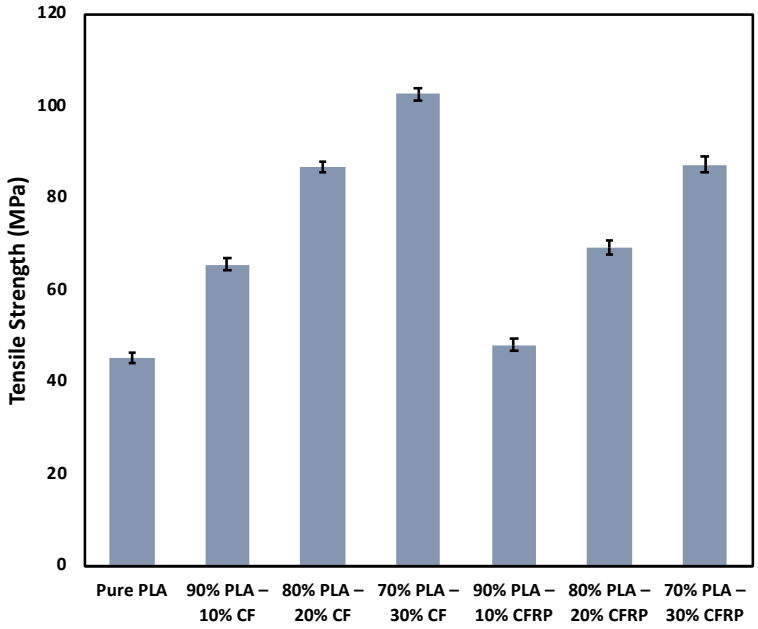


Figure 6. Ultimate tensile strength of the composites.

Neat PLA exhibited a tensile strength of 45.4 MPa, reflecting its limited load-bearing capability. Upon reinforcement with chemically recycled CFs, tensile strength increased substantially to 65.5 MPa, 86.8 MPa, and 102.6 MPa for 10, 20, and 30 wt.% loadings, respectively.

In contrast, CFRP/PLA composites showed more modest improvements, reaching tensile strengths of 48.1 MPa, 69.3 MPa, and 87.3 MPa at the same fiber contents. At 30 wt.% loading, the CF/PLA composite exhibited approximately 55% higher tensile strength than the corresponding CFRP/PLA composite. This pronounced difference underscores the detrimental effect of residual epoxy resin in untreated CFRP, which acts as a weak interfacial layer and inhibits effective stress transfer from the PLA matrix to the carbon fibers [43].

The improved tensile performance of CF/PLA composites can be attributed to several synergistic factors: (i) preservation of the graphitic structure of the recycled fibers, as confirmed via XRD and Raman analyses; (ii) enhanced surface chemistry resulting from oxidative treatment, which promotes fiber–matrix adhesion; and (iii) improved fiber dispersion achieved through cryogenic grinding. Together, these factors enable efficient load transfer and delay the onset of fiber pull-out or interfacial debonding during tensile loading.

2.4.3. Ductility

Ductility, expressed as elongation at break, provides insight into the deformation capability of composite materials prior to fracture. As expected, neat PLA exhibited the highest ductility (6.3%), reflecting its relatively flexible polymeric nature. The incorporation of both CFs and CFRP led to a progressive reduction in ductility with increasing fiber content, as shown in Figure 7.

At 30 wt.% loading, the ductility of CF/PLA composites decreased to 2.9%, compared to 3.5% for CFRP/PLA composites. The lower ductility observed in CF/PLA systems indicates increased stiffness and reduced plastic deformation, which is characteristic of well-reinforced composites with strong fiber–matrix interactions. The slightly higher ductility retained by CFRP/PLA composites suggests weaker interfacial bonding, allowing limited matrix deformation and fiber slippage before fracture [39].

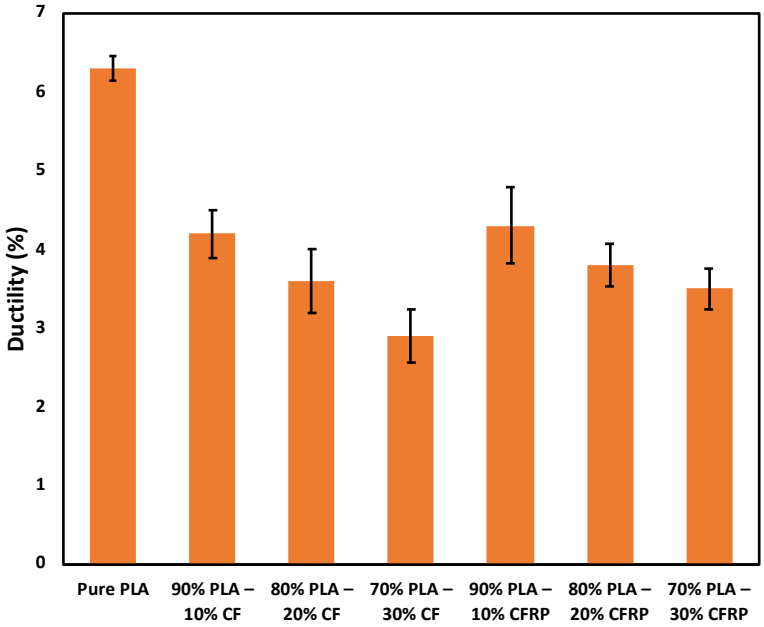


Figure 7. Ductility of the composite materials.

Although reduced ductility is often considered a drawback, in this context, it reflects improved reinforcement efficiency and enhanced load-bearing capability. The observed ductility reduction is therefore consistent with the increases in elastic modulus and tensile strength and supports the conclusion that chemically recycled CFs provide superior reinforcement compared to untreated CFRP waste.

2.4.4. Toughness

Toughness represents the energy absorption capacity of a material prior to failure and is particularly important for applications subjected to impact or cyclic loading. As shown in Figure 8, toughness increased steadily with increasing fiber content for both CF/PLA and CFRP/PLA composites.

At 10 wt.% loading, the toughness values were 218.9 MPa for CF/PLA and 213 MPa for CFRP/PLA composites, both of which exceeded the toughness of neat PLA (189 MPa). This trend persisted across higher fiber contents, with the maximum toughness of 250.3 MPa achieved by the 30 wt.% CF/PLA composite, representing a substantial improvement relative to pure PLA. Although the difference in toughness between treated and untreated systems at the same fiber content is relatively small (approximately 2%), the consistently higher toughness of CF/PLA composites indicates more effective energy dissipation mechanisms.

The enhanced toughness is attributed to improved crack deflection, fiber bridging, and controlled fiber pull-out mechanisms facilitated by strong fiber–matrix adhesion [40]. Compared with neat PLA, the reinforced composites exhibited improved resistance to crack propagation and greater energy absorption prior to failure, indicating that the incorporation of recycled carbon fibers effectively enhanced the damage tolerance of the PLA matrix. In CF/PLA composites, surface-functionalized fibers promote stable crack propagation and increased energy absorption, whereas residual epoxy in CFRP/PLA composites limits these mechanisms.

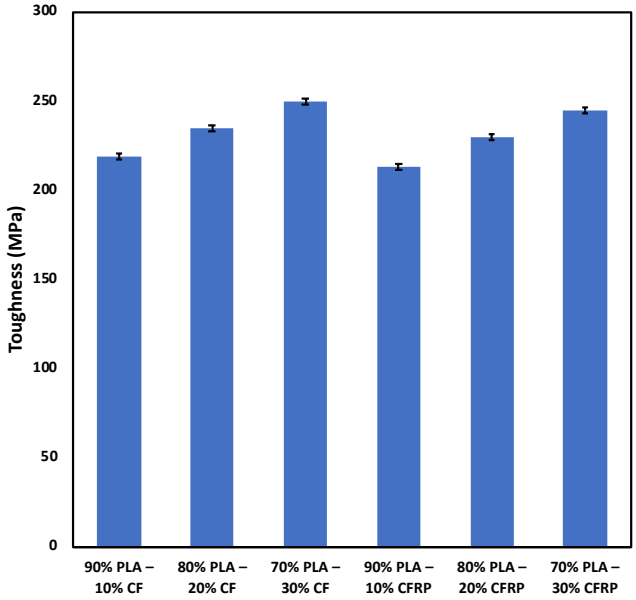


Figure 8. Toughness of the composites.

The mechanical results collectively demonstrate that chemically recycled carbon fibers provide a more effective reinforcement for recycled PLA than untreated CFRP waste. The combination of preserved graphitic structure, enhanced surface chemistry, and improved fiber–matrix interaction leads to superior stiffness, strength, and toughness, albeit at the expense of reduced ductility. The optimal performance observed at 30 wt.% CF loading reflects a balance between reinforcement efficiency and matrix continuity.

These findings are fully consistent with the microstructural and spectroscopic analyses presented earlier and confirm that chemical recycling not only recovers carbon fibers but also enhances their suitability for high-performance, waste-derived thermoplastic composites.

It should be noted that the present study did not include direct interfacial characterization techniques such as single fiber pull-out testing, interfacial shear strength (IFSS) measurements, or fracture surface pull-out length analysis. Therefore, the proposed improvement in fiber–matrix interfacial bonding is inferred indirectly from the combined spectroscopic observations, surface morphology analysis, and enhanced mechanical performance rather than quantitatively measured. Future work will incorporate direct interfacial testing and fracture surface analysis to further validate the relationship between oxidation-induced surface functionalization and composite reinforcement behavior.

In addition, SEM analysis in the present work focused primarily on evaluating the surface morphology of untreated and chemically recycled carbon fibers before composite fabrication. Fracture surface SEM analysis of the tested composites was not conducted; however, such analysis would provide important additional insight into fiber dispersion, fiber pullout behavior, crack propagation mechanisms, and fiber–matrix interfacial bonding. Future studies will therefore incorporate fracture surface characterization to further clarify the reinforcement mechanisms governing composite mechanical performance.

2.5. Implications for Sustainable Composite Design

Beyond the observed mechanical improvements, this study demonstrates a practical strategy for the simultaneous valorization of two major waste streams: CFRP waste and post-consumer PLA waste. The successful incorporation of chemically recycled carbon fibers into recycled PLA highlights the potential of integrated recycling approaches for the development of sustainable high-performance composite materials.

The chemical recycling route employed in this work not only enabled effective epoxy removal but also introduced oxygen-containing surface functionalities that enhanced interfacial compatibility between the recycled carbon fibers and the PLA matrix. This improved fiber–matrix interaction contributed to enhanced stress transfer efficiency and overall composite performance. In addition, the oxidative $KMnO_4$ treatment likely introduced oxygen-containing functional groups onto the carbon fiber surface, effectively generating a surface activation or sizing-like effect. Such oxidation-induced surface functionalization is expected to improve the interfacial compatibility and stress transfer efficiency between the recycled carbon fibers and the PLA matrix. Consequently, the improved mechanical performance is likely governed by a combination of preserved graphitic structure, enhanced surface chemistry, improved fiber dispersion, and oxidation-induced interfacial strengthening effects.

Importantly, the proposed process utilizes relatively mild operating conditions and conventional melt-processing techniques, including melt mixing and injection molding, which supports its potential scalability and industrial applicability. Compared with more energy-intensive or solvent-intensive CFRP recycling approaches, the present method provides a comparatively simple and cost-effective pathway for recovering functional reinforcement materials from composite waste. The developed CF/PLA composites exhibited enhanced stiffness, strength, and toughness, demonstrating their suitability for potential structural and semi-structural engineering applications where lightweight and sustainable materials are desired. Although ductility decreased with increasing fiber loading, the improved mechanical performance and energy absorption capability suggest promising applicability in recycled thermoplastic composite systems.

From an economic perspective, the proposed recycling route also offers potential advantages compared with conventional CFRP recycling technologies. Thermal recycling methods such as pyrolysis typically require temperatures exceeding 450–700 °C, inert gas atmospheres, and high energy consumption, while supercritical solvolysis methods often involve expensive solvents, elevated pressures, and specialized reactor systems. In contrast, the present approach employs comparatively mild operating conditions (100–120 °C), readily available reagents (acetic acid and $KMnO_4$), and conventional laboratory-scale processing equipment. These features may reduce operational costs, energy demand, and process complexity while improving scalability and practical implementation potential. Although a full techno-economic analysis was beyond the scope of the present study, the simplified process design and low-cost chemical system suggest promising feasibility for sustainable large-scale CFRP recycling applications.

Compared with many previously reported CFRP recycling approaches that rely on high-temperature pyrolysis or supercritical processing, the present method combines relatively mild operating conditions with effective surface activation of the recovered fibers. This combination is particularly important for recycled thermoplastic composites, where interfacial adhesion strongly governs mechanical performance. The results therefore support growing research efforts focused on integrating CFRP recycling with sustainable thermoplastic composite manufacturing.

Overall, this work contributes to ongoing efforts in circular materials engineering by demonstrating how chemically recycled carbon fibers can be transformed into value-added reinforcements for recycled thermoplastics. The findings provide useful insights for future optimization of recycling strategies, surface modification approaches, and sustainable composite design.

3. Materials and Methods

3.1. Overview of the Experimental Procedure

This study investigates the incorporation of chemically recycled carbon fibers (CFs) derived from CFRP waste into recycled polylactic acid (PLA) matrices to produce high-performance composite materials [44–47]. The overall experimental workflow is schematically illustrated in Figure 9, which outlines the six principal stages involved in the development of CF/PLA composites, including CFRP waste collection, chemical recycling, cryogenic grinding, composite formulation, melt processing, and injection molding.



Figure 9. Steps in creating the CF/PLA composite material.

For comparison, untreated CFRP waste was also directly incorporated into PLA using a parallel processing route. The mechanical, structural, and surface characteristics of the resulting composites were subsequently evaluated and compared.

3.2. Materials

Post-consumer PLA waste was sourced from fused deposition modeling (FDM) 3D-printing residues (Abu Dhabi, UAE). CFRP waste was supplied by STRATA Manufacturing (Abu Dhabi, UAE) and conformed to specification 977-2-35/40-12KHTS-268, with a resin content of 35–40 wt.%, curing grade 180, and a real fiber weight of 268 g m^{-2}. Analytical-grade acetic acid (CH_3COOH) and potassium permanganate ($KMnO_4$), used for chemical recycling of the CFRP waste, were purchased from Scientific Progress Medical and Scientific Equipment Company (Abu Dhabi, UAE) and used without further purification. The main materials used in this study, their specifications, and their roles in the experimental workflow are summarized in Table 4.

Table 4. Materials, specifications, and roles in CF/PLA composite fabrication.

Material	Source	Key Specifications	Role in Study
Recycled PLA	Post-consumer FDM waste	Thermoplastic; biodegradable; low stiffness	Polymer matrix
CFRP waste	STRATA Manufacturing (UAE)	35–40 wt.% epoxy; 268 g m^{-2} fiber areal weight; grade 180	Carbon fiber source

Table 4. *Cont.*

Material	Source	Key Specifications	Role in Study
Acetic acid (CH_3COOH)	Analytical grade	Mild organic solvent	Epoxy swelling pretreatment
Potassium permanganate ($KMnO_4$)	Analytical grade	Strong oxidizing agent	Epoxy depolymerization
Liquid nitrogen	Cryogenic grade	<123 K	Fiber embrittlement for grinding

3.3. Chemical Recycling of CFRP Waste

The chemical recycling of CFRP waste was conducted through a two-step process involving acetic acid pretreatment followed by oxidative depolymerization. Initially, CFRP waste sheets were manually cut into uniform fragments with an approximate surface area of 1.0 mm^2 to ensure homogeneous chemical exposure. These fragments were immersed in 100 mL of acetic acid and heated at 120 °C for 1 h using an oil bath to promote resin swelling and facilitate subsequent depolymerization. Following treatment, the samples were thoroughly rinsed with distilled water to remove residual acid and surface impurities, then oven-dried at 100 °C until complete moisture removal was achieved [48].

Subsequently, oxidative depolymerization was performed by introducing approximately 0.5 g of the pretreated CFRP fragments into 50 mL of 1 M $KMnO_4$ solution. The reaction mixture was maintained at 100 °C under continuous stirring for 2 h to selectively degrade the epoxy resin matrix. After completion, the recovered carbon fibers were extensively washed with distilled water to remove residual oxidants and organic byproducts. The fibers were then dried in an oven at 100 °C for 24 h prior to further processing [49]. The key parameters employed during chemical recycling are summarized in Table 5 for clarity and reproducibility.

Table 5. Operating conditions used for chemical recycling of CFRP waste.

Step	Reagent/Medium	Temperature (°C)	Time	Purpose
Swelling pretreatment	Acetic acid	120	1 h	Resin swelling and diffusion
Washing	Distilled water	Room temp.	—	Acid removal
Oxidative depolymerization	1 M $KMnO_4$	100	2 h	Epoxy matrix degradation
Final washing	Distilled water	Room temp.	—	Oxidant removal
Drying	Oven	100	24 h	Moisture removal

Real images of the chemically recycled carbon fiber samples are shown in Figure 10.

Chemical recycling was performed prior to mechanical size reduction to preserve the structural integrity of the recovered carbon fibers. Direct comminution of untreated CFRP waste may increase the exposed surface area for chemical reaction; however, it can also promote excessive fiber breakage because the carbon fibers remain strongly embedded within the cross-linked epoxy matrix. Therefore, acetic acid swelling followed by $KMnO_4$ oxidation was first used to weaken and remove the epoxy phase, facilitating fiber recovery while minimizing mechanical damage. Subsequent cryogenic grinding was then applied to the recovered fibers to achieve suitable particle size and dispersion within the PLA matrix. This sequence also improved washing, filtration, and handling by avoiding the generation of fine CFRP powder before chemical treatment. Although pre-comminution may enhance

chemical accessibility, future work may compare both processing sequences to further optimize epoxy removal efficiency, fiber length retention, and composite performance.



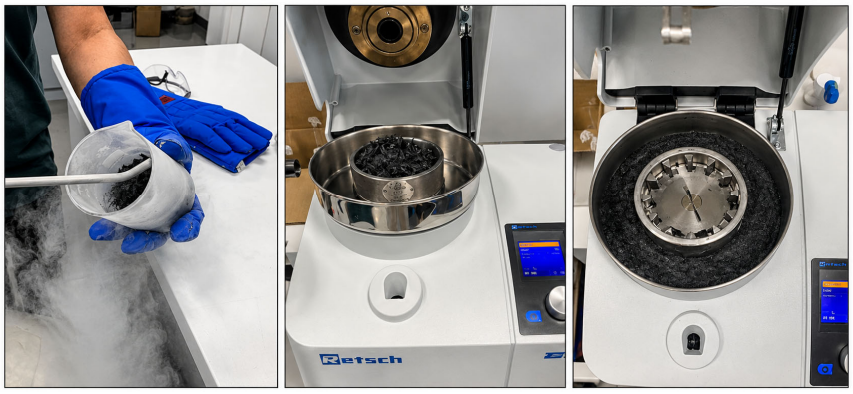
(**a**) (**b**)

Figure 10. Real images of chemically recycled carbon fiber samples using (**a**) acetic acid and (**b**) Potassium permanganate.

3.4. Cryogenic Grinding of Chemically Recycled Carbon Fibers

Due to the high strength and fracture resistance of carbon fibers at ambient conditions, cryogenic grinding was employed to reduce fiber size without compromising structural integrity [50,51]. In this process, chemically recycled CFs were immersed in liquid nitrogen for 5 min to induce embrittlement at temperatures below 123 K [52,53]. The frozen fibers were subsequently milled using a cryogenic grinder operating at 6000 rpm, yielding finely ground carbon fiber particulates suitable for homogeneous dispersion within the PLA matrix. Real images of the recycled carbon fiber samples immersed in liquid nitrogen and ground by the cryogenic grinder are shown in Figure 11.

Although cryogenic milling was employed to improve fiber size reduction and dispersion within the PLA matrix, a quantitative analysis of fiber length distribution before and after milling was not performed in the present study. Fiber length and aspect ratio are known to strongly influence stress transfer efficiency and mechanical reinforcement in short fiber composites. Future work will therefore include detailed fiber length distribution analysis to further correlate milling-induced morphology changes with composite mechanical performance.



(**a**) (**b**) (**c**)

Figure 11. Real images of (**a**) immersing carbon fiber in liquid nitrogen, (**b**) carbon fiber sample before grinding and (**c**) after grinding using a cryogenic grinder.

3.5. Preparation of CF/PLA Composites Using Recycled Carbon Fibers

Composite fabrication was carried out using a melt-mixing and injection-molding system consisting of a Model M-100 mixing apparatus with an ECB-001 controller, coupled with a Model S-100 injection-molding unit (Mix-Molder, Galomb, Inc., Allentown, PA, USA).

Recycled PLA waste was blended with chemically recycled CFs at fiber loadings of 10, 20, and 30 wt.%. The mixtures were processed in the mixing chamber at 175 °C for 5 min at a rotational speed of 70 rpm to ensure uniform fiber dispersion. The molten composite material was then directly injected into standardized dog-bone molds conforming to ASTM D638 geometry for subsequent mechanical testing.

3.6. Preparation of CFRP/PLA Composites Using Untreated CFRP Waste

For comparative analysis, untreated CFRP waste containing residual epoxy resin was processed separately. The CFRP fragments were size-reduced using a planetary ball mill (PM 100, Retsch GmbH, Haan, Germany). Milling was conducted at 450 rpm for 10 min, utilizing the combined action of impact and friction forces generated by the velocity difference between the grinding jar and milling balls [50,51].

The milled untreated CFRP particles were subsequently blended with recycled PLA at fiber contents of 10, 20, and 30 wt.% using the same melt-mixing and injection-molding conditions described in Section 2.5 (175 °C, 70 rpm), ensuring consistent processing parameters across all composite systems.

The formulations of all composite systems investigated in this study are summarized in Table 6.

Table 6. Composition of CF/PLA and CFRP/PLA composite systems.

Composite Code	PLA (wt.%)	Reinforcement Type	Fiber Content (wt.%)	Processing Route
PLA	100	—	0	Melt mixing
PLA–10CF	90	Recycled CF	10	Melt mixing + injection molding
PLA–20CF	80	Recycled CF	20	
PLA–30CF	70	Recycled CF	30	
PLA–10CFRP	90	Untreated CFRP	10	
PLA–20CFRP	80	Untreated CFRP	20	
PLA–30CFRP	70	Untreated CFRP	30	

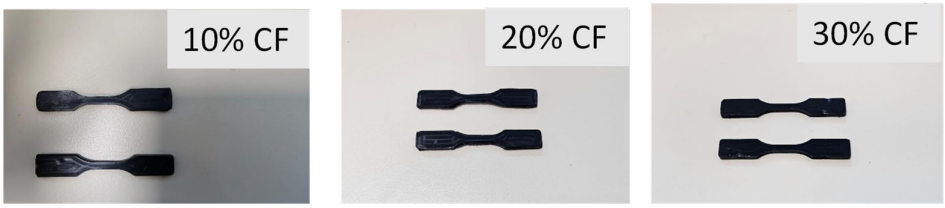
3.7. Statistical Analysis

Mechanical testing was conducted using at least three specimens for each composite formulation to ensure reproducibility and reliability of the measured properties. The reported tensile strength, elastic modulus, ductility, and toughness values represent the average values obtained from the tested specimens. Standard deviations were calculated and included where applicable.

For structural and surface characterization analyses, multiple measurements and sampling regions were examined to ensure representative results. SEM observations were obtained from several surface locations for each sample, while FTIR, Raman, and XRD measurements were repeated to confirm spectral consistency and reproducibility.

3.8. Mechanical Characterization

Mechanical properties of the developed composites were evaluated using a universal testing machine (UTM) (Model: WDW-100, manufacturers Jinan precision testing equipment, Jinan, China) in accordance with ASTM D638 standards [54], as shown in Figure 12.



(**a**) (**b**) (**c**)

Figure 12. Representative ASTM D638 dog-bone specimens fabricated from recycled PLA reinforced with chemically recycled carbon fibers at different fiber loadings, (**a**) 10%, (**b**) 20%, and (**c**) 30%, demonstrating successful composite processing and specimen uniformity.

Tensile tests were conducted using dog-bone-shaped specimens prepared according to the standard dimensions specified in ASTM D638.

The tensile testing was performed at a crosshead speed of 2 mm/min. Strain measurements were obtained from the crosshead displacement recorded by the universal testing machine during testing, and the obtained data were used to determine the Young's modulus, tensile strength, elongation at break, ductility, and toughness of the prepared composites.

For each formulation, at least three specimens were tested to ensure reproducibility and statistical reliability. The reported values represent the average of the measured results, and the corresponding standard deviations were calculated using standard statistical analysis methods.

3.9. Structural and Surface Characterization

3.9.1. X-Ray Diffraction (XRD)

X-ray diffraction (XRD) analysis was conducted to investigate the crystalline structure and phase composition of the carbon fibers and composites before and after chemical recycling. Measurements were performed using an X-ray diffractometer, PANalytical X'Pert PRO diffractometer (Malvern Panalytical, EA Almelo, The Netherlands), equipped with Cu Kα radiation (λ = 1.54 Å). The diffraction patterns were collected at a tube current of 30 mA and an operating voltage of 40 kV. The scanning range was conducted over a 2θ range of 5–70° with a scan speed of 2° min^{-1} to identify structural changes associated with resin removal and fiber treatment. The obtained diffraction peaks were analyzed and compared with standard reference patterns to identify the graphitic structures and other associated phases. Multiple measurements were conducted for representative samples to ensure reproducibility.

3.9.2. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) was employed to identify the functional groups present on the surface of chemically recycled carbon fibers. FTIR measurements were performed using an IRTracer-100 FTIR spectrophotometer (Shimadzu, Kyoto, Japan). The spectra were recorded within the wavelength range of 500–4000 cm^{-1} using a spectral resolution of 4 cm^{-1} and 34 scans for each sample. The analysis was conducted to confirm the removal of epoxy resin and evaluate the formation of oxygen-containing functional groups resulting from the chemical treatment process. Repeated measurements were carried out for selected samples to ensure consistency and reproducibility of the obtained spectra.

3.9.3. Scanning Electron Microscopy (SEM)

The surface morphology and microstructural characteristics of treated and untreated carbon fibers were examined using a high-resolution scanning electron microscope (SEM), (JSM-6610LV, JEOL Ltd., Tokyo, Japan). SEM observations were performed at multiple surface locations for each sample to ensure a representative evaluation of the fiber morphology and surface condition. Prior to imaging, the samples were coated with an approximately 300 Å gold layer to improve electrical conductivity and image quality. SEM observations were conducted at different regions of each sample to ensure representative surface characterization. In addition, energy-dispersive X-ray spectroscopy (EDS) analysis was performed to determine the elemental composition of the investigated samples. SEM analysis enabled direct observation of resin residues on untreated fibers and confirmed the effectiveness of the chemical recycling process in removing the polymeric matrix from the carbon fiber surface.

3.9.4. Raman Spectroscopy

Raman spectroscopy was used to evaluate the structural integrity and graphitic characteristics of the recycled carbon fibers. Measurements were conducted using a confocal Raman/PL microscope system (NOST Co., Ltd., Seongnam-si, Republic of Korea) equipped with a 532 nm excitation laser and a 75% neutral density filter. Raman spectra were collected over an appropriate Raman shift range to evaluate the structural order and defect density of the carbon fibers. The D-band (~1350 cm^{-1}) and G-band (~1580–1600 cm^{-1}) were analyzed to assess the preservation of the graphitic carbon structure after chemical recycling treatment. Multiple measurements were conducted at different sample locations to ensure reproducibility and consistency of the recorded spectra.

4. Conclusions

This study demonstrated a sustainable approach for recycling CFRP waste and reusing the recovered carbon fibers as reinforcements in recycled PLA composites. Chemical recycling using acetic acid pretreatment followed by $KMnO_4$ oxidation effectively removed the epoxy matrix while preserving the primary graphitic structure of the carbon fibers.

XRD and Raman analyses confirmed retention of the graphitic backbone after treatment, while FTIR and SEM analyses revealed effective epoxy removal together with oxidation-induced surface functionalization of the recycled fibers. The introduction of oxygen-containing functional groups likely improved the interfacial compatibility between the recycled carbon fibers and the PLA matrix, contributing to enhanced stress transfer and composite performance.

Mechanical testing showed that increasing carbon fiber loading significantly improved the tensile strength, elastic modulus, and toughness of the PLA composites, although ductility decreased with increasing reinforcement content. Among all formulations, the 30 wt.% CF/PLA composite exhibited the best mechanical performance, achieving a tensile strength of 102.6 MPa and an elastic modulus of 11.7 GPa, substantially outperforming composites reinforced with untreated CFRP waste.

Overall, the results demonstrate that chemically recycled carbon fibers can serve as effective high-performance reinforcements for recycled thermoplastics. The proposed recycling and composite fabrication route provides a practical waste-to-value strategy that supports sustainable materials engineering and circular economy applications for polymer composite waste streams.

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Abbreviations

The following abbreviations are used in this manuscript:

PLA	Polylactic Acid
CF	Carbon Fiber
CFRP	Carbon Fiber-Reinforced Polymer
CF/PLA	Carbon Fiber-Reinforced PLA Composite
CFRP/PLA	CFRP Waste-Reinforced PLA Composite
FDM	Fused Deposition Modeling
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction
FTIR	Fourier Transform Infrared Spectroscopy
$KMnO_4$	Potassium Permanganate
CH_3COOH	Acetic Acid
wt.%	Weight Percent

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