JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2023;26:2291–2309

Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Review Article

A review of 3D printing of the recycled carbon fiber reinforced polymer composites: Processing, potential, and perspectives

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ARTICLE INFO

Article history:
Received 10 April 2023
Accepted 19 July 2023
Available online 4 August 2023

Keywords:
Recycle carbon fiber
Additive manufacturing
Carbon fiber reinforced polymer composites
Waste

ABSTRACT

The rapid increase in the application of carbon fiber-reinforced polymer composites in the fabrication and development of modern industrial products is attributed to their lightweight nature, excellent mechanical properties, and corrosion resistance, among other factors. Additive manufacturing of recycled carbon fiber (rCF), which has garnered significant attention in recent years owing to the massive potential waste obtained from carbon fiber-reinforced polymer composites (CFRPC) and the manufacturing of rCF after the surface treatment produced the parts with excellent properties comparable to virgin carbon fiber (vCF). Additive manufacturing of rCF obtained after recycling has received much interest over the past few years because of the massive potential waste of the carbon fiber and the excellent properties after the surface treatment of the rCF. This research examines additive manufacturing of the rCF, surface treatment for enhancing the properties of the printed specimens, the potential waste of the carbon fiber obtained from the different sectors, and applications of reclaimed carbon fiber composites in manufacturing various products. Specifically, the mechanical characteristics of the printed specimens using rCF and the different percentages of the rCF reinforcement in the other polymer's matrix composites are discussed. This work demonstrates that an additive manufacturing-based recycling approach can recycle carbon fiber-reinforced polymer composites (rCFRPC) waste and create high-performance engineering parts with complicated geometries that are both cost-effective and environmentally acceptable. This review also defines the significant challenges and outlook for future developments in manufacturing of rCFRPC.

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https://doi.org/10.1016/j.jmrt.2023.07.171

List of acronyms

rCF	Recycled carbon fiber
vCF	Virgin carbon fiber
CFRP	Carbon fiber-reinforced polymer
FDM	Fused deposition modelling
AM	Additive manufacturing
CFRPC	Carbon fiber-reinforced polymer composites
CCF	Continuous carbon fiber
PLA	polylactic acid
DMA	Dynamic mechanical analysis
CFRTPC	carbon fiber reinforced thermoplastic composites
CF/EP	carbon fiber reinforced epoxy resin
SEM	Scanning electron microscope
PEEK	Polyether ether ketone
PAI	Polyamide-imide
PI	Polyimide
FFF	Fused filaments fabrication
rCFRP	Recycled carbon fiber reinforced polymer
PP	Polypropylene
rCFRPC	Recycled carbon fiber reinforced polymer composites
PPS	Polyphenylene sulfide
PED	Primary energy demand
pDop-rSCF	polydopamine surface-modified recycled short CF
EMI	electromagnetic interference
PP	polypropylene
CO_2	Carbon dioxide

1. Introduction

Additive manufacturing (AM) is the most emerging technology in advanced and fast manufacturing areas. The AM technology can be employed to fabricate the components with complicated designs owing to its benefits like cost savings and better production productivity [1–3]. The advantage of the AM technique is shown in Fig. 1 (a). There are different AM techniques like stereolithography, fused deposition modeling, laminated object manufacturing, and selective laser sintering, which are utilized for the manufacturing of the various materials available in different forms [1,4,5]. Yet, so far, the fused deposition modeling (FDM) method is particularly tempting due to its low cost, decreased waste of created resources, and convenience of use [6]. The FDM technique utilizes filaments of various materials that can melt into a semi-liquid phase at the nozzles. These filaments are then ejected layer by layer onto the build plate, where they combine to form the final objects. The performance of manufactured parts can be modified by adjusting printer parameters such as raster angle, layer height, printing orientation, raster width, and air gap [7]. Simultaneously, FDM provides some control over fiber orientation [8], allowing for expanded available variety in the design of the manufactured objects [9].

CFRPC are composed of fibers that bear the load, while a polymeric matrix provides stability and protection against environmental degradation [10,11]. CFRPC offers significant advantages over metals due to their lightweight nature, excellent stiffness and strength, and corrosion resistance [12]. Carbon fiber reinforced polymer (CFRP) are commonly utilized in the automobile, aviation, and wind energy sectors, where weight reduction is critical since such sophisticated materials have high specific toughness, significant specific rigidity, are lightweight, and excellent corrosion resistance [13–15]. However, the high cost of CFRP has primarily restricted their usage in the aircraft industry, posing a significant barrier to their broader application in other high-volume sectors such as automotive. The rising cost of manufacturing vCF also presents an opportunity to extract substantial value from CFRP waste products. The utilization of rCF has the potential to reduce environmental impacts compared to vCF manufacturing, and the lower price of rCF could facilitate the emergence of a new global market for lightweight materials. Additionally, manufacturing of vCF requires tremendous energy (183–286 MJ/kg) [16].

Recycling CFRP waste has garnered significant attention in recent years due to its potential to reduce life cycle costs and environmental impacts associated with CFRP products. The 3D printing of rCFRPC solves the problem of the increasing demand for carbon fiber in different applications. The carbon fiber extracted from CFRP scrap was recycled by separating the matrix components and blending them with fresh matrix materials to produce a new CFRP composite sample. Carbon fiber recovery from CFRP is difficult owing to the matrix's strong corrosive resistance and inertness. Several carbon fiber reclamation processes, such as mechanical, thermal, and chemical, have been created and effectively validated. Fig. 1 (c) illustrates the typical recycling technique for recovering carbon fiber. The energy inputs for the production of rCF are generally significantly lower compared to the manufacturing of vCF, although this can vary depending on the specific recycling method employed. The primary energy demand (PED) required for manufacturing recycled carbon fiber is less than the vCF, as illustrated in Fig. 1 (b). When considering both comparable stiffness and corresponding strength bases, the overall PED for the rCFRP component (51.1 MJ/part under related stiffness; 51.8 MJ/part with equivalent strength) is 50–51% of the vCFRP 1 part and 56–68% of the vCFRP 2 component. This is mainly owing to the significant PED associated with vCF production, which accounts for 53% of the total PED for the vCFRP1 component and 80% for the vCFRP2 component. Guo et al. [17] rCF was manufactured by subjecting carbon fiber-reinforced epoxy resin composites (CF/EP) to pyrolysis at 800 °C for 30 min. Microscope images revealed the presence of distinct residual pyrolytic carbon atoms on the substrate of the rCF.

Recycling plays a pivotal role in the circular economy, particularly when materials possess structural properties that facilitate efficient conversion. Generally, the circular economy uses renewable energy, eliminates harmful chemicals, and reduces waste through improved materials, devices, processes, and core business innovation [18]. Carbon conversions Ltd., ELG carbon Fiber Ltd., Karborek Ltd., Mitsubishi Ltd., and several other companies are major global carbon fiber recycling industry sectors. For example, ELG carbon Fiber Ltd. recycles carbon fibers that maintain at least 90% of their tensile strength, but at a cost 40% lower than vCF with a carbon fiber

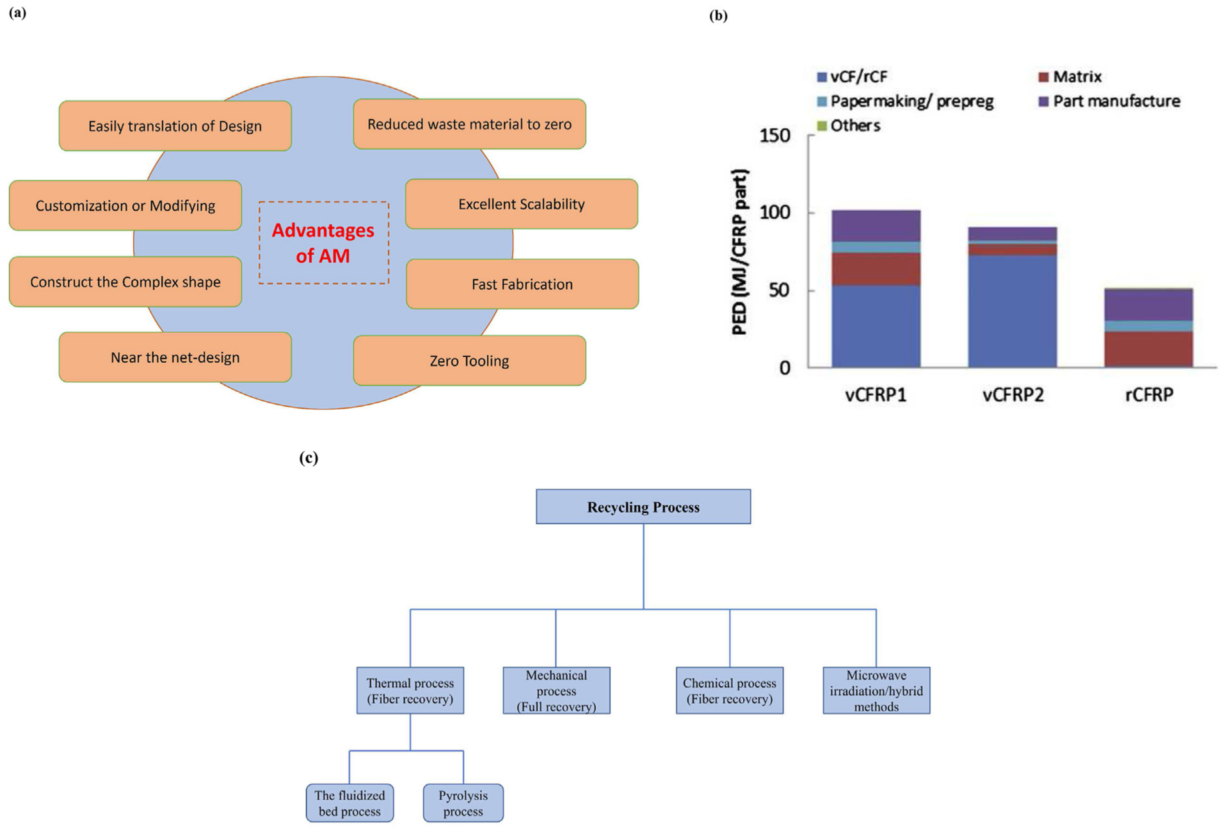

Fig. 1 – (a) Benefits of the AM technique. (b) PED for manufacturing the rCF, vCF 1, and vCF 2 [29] . (c) Recycling technique employed for recovering carbon fiber.

reuse price of only $15/kg when the ability achieves 100 tons/year [19]. Most recoverable items, primarily fibers, and resin breakdown products, are systematically analyzed and indicate that they can be regenerated. For instance, rCF (typically discontinuous since the materials must be divided into smaller pieces before processing) have been successfully included in a few experiments [20–23].

Recent review studies [24–26] provide a different recycling approach for the carbon fiber from CFRP obtained from various applications after its life cycle. These studies discuss the potential of carbon fiber obtained worldwide and distinct factors which affect the recycling process for recovering the carbon fiber from CFRP composites. However, despite these extensive analyses that focus on the essential volume of rCF, various recycling techniques, and significant factors affecting its output, there remains a lack of information regarding the additive manufacturing of rCF with other polymer matrices, its applications, and a comprehensive overview of rCF.This review paper aims to comprehensively provide an overview of the AM of the rCFRPC. It will evaluate the state-of-the-art technologies for recovering and manufacturing rCF, while also examining the current and future applications of rCF. In addition, we assess carbon fiber potential from the CFRPC obtained from the different sectors. We examine and evaluate how different percentages of rCF in composites material influence AM parts mechanical properties (particularly distortion and fracture). This systematic review also points out the manufacturing of rCF and the fracture of the manufactured parts due to different challenges and outlines the essential themes, which can assist new researchers in focusing on the problem-solving theme during their research.

The review paper is organized as follows; Section 2 will specify the manufacturing of the rCF-reinforced polymer composites. Whereas section 3 discusses the potential waste of carbon fiber. Section 4 observes the applications of rCFRPC. Section 5 summarizes the conclusion for using the rCF and future direction.

2. Additive manufacturing (AM) of the recycled carbon fiber (rCF)

AM, commonly known as three-dimensional (3D) printing, has revolutionized the production of complex designs with customizable features, opening doors for its application in various industries, including aerospace, automotive, retail, and healthcare. Fig. 6 (a) illustrates a typical fabrication process of a 3D part via the FDM technique. 3D printing has experienced rapid growth in recent years, and it is anticipated to revolutionize the manufacturing sector by facilitating the production of advanced high-performance materials [27]. Among the various AM techniques, fused filament fabrication (FFF) is one of the most utilized techniques for producing conceptual models [28]. Material extrusion by FFF, is a 3D

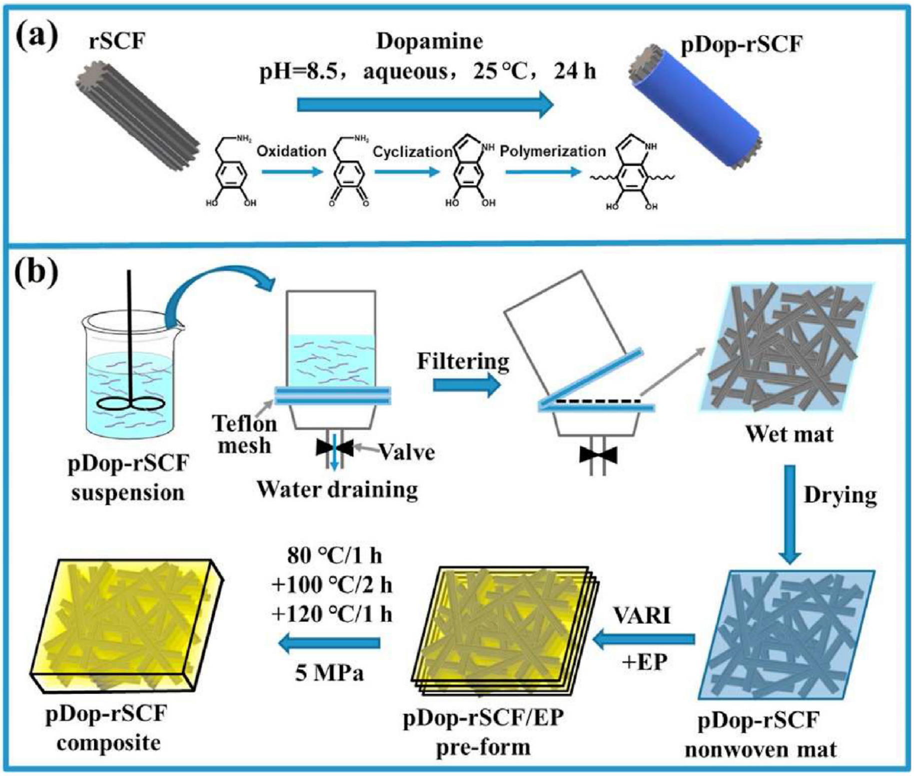

Fig. 2 – A diagram depicting the manufacturing process of (a) pDop-rSCF nonwoven mat and (b) pDop-rSCF/EP composites [42].

printing technique that stacks molten materials from the nozzle in a preset path layer by layer.

The main challenges in manufacturing rCFRPC were effectively controlling the dispersion of rCF and creating robust interfacial bonds within the matrix. vCF are coated with a polymeric-sized layer to improve interface adherence to the matrix resin compared to the rCF. As a result, for rCF recycling, additional treatment for the surface is required [30]. The surface treatment of the rCF can make a strong adhesion between the rCF and matrix materials. Poor interfacial bonding between the rCF and polymers matrix leads to the poor mechanical characteristics of the printed part using these composites. Various treatments of carbon fiber have been studied, such as electrochemical treatments [31,32], chemical oxidation [33,34], plasma treatment [35–37], and surface functional group grafting procedures [38,39], etc.

Carbon fiber surface treatments and resizing procedures for aerospace epoxy thermosetting matrices have been created throughout the years, providing high interfacial fiber-matrix bonding strength and desirable mechanical characteristics. Adhesion among the carbon fiber and polymer matrix is a significant factor that can transfer the stress from the matrix to the reinforcement. The surface treatment of rCF may increase bonds and, as a result, the mechanical characteristics of CFRP. Various researchers performed the surface treatment of the carbon fiber can improve the composites' performance having the carbon fiber [40,41]. The surface treatment of the carbon fiber can enhance the adhesion bonding among the matrix with the reinforcement, which can be absorbed by the high energy that increases the composites' mechanical properties. Huan et al. [42] modified the rCF by using the 1 g recycled short carbon fiber (rSCF) was soaked in 2000 ml H2O for 30 min before being treated with 800 W ultrasonication and 0.1 g dopamine. The complete treatment process is shown in Fig. 2. At the end of the process, the outcome of the surface treatment was centrifuged, cleaned multiple times with deionized water, and dried in a vacuum chamber for 24 h at 40 °C to obtain the polydopamine surface-modified recycled short carbon fiber (pDop-rSCF). The flexural strength and modulus of pDop-rSCF/EP treatment composites were increased by 35.4 and 14.2%, respectively, as contrasted with rSCF/EP composites. These observed results show that surface treatment and equal dispersion of the rCF provide excellent mechanical properties of the specimens as compared to the specimens manufactured using the untreated surface.

Lee et al. [43] performed the plasma surface treatment on the rCF to observe the performance and adhesion of the rCFRPC. Plasma surface treatment works by inserting dielectric insulation among metal electrodes while using high frequencies and voltage. The interfacial adhesion between the rCF and Polypropylene (PP) was improved by the plasma treatment on the rCF. The three-point bending results show that the flexural strength of the part manufactured using the CFRP increased by 17% compared to that of untreated rCF. The mechanical characteristics of the surface treated were comparable to the vCF due to the activated surface of the rCF.

To enhance the mechanical properties of remanufactured composites, proper fiber orientation is necessary. Various researchers align the carbon fiber to enhance the mechanical properties of the printed samples [44,45]. The fiber-matrix interfacial bonding heavily influences the mechanical characteristics of rCFRPC. The presence of strong interfacial adhesion between the rCF and the polymer matrix is crucial for ensuring effective load transmission from the matrix to the fiber. This, in turn, reduces stress concentrations and enhances the overall characteristics of fiber-reinforced composites [46]. Jiang et al. [47] investigated the contact angles and interfacial bonds of carbon fibers recycled through pyrolysis and discovered that T800 carbon fibers exhibited lower interface shear strength with thermosetting resins than fresh T800 fibers. Wu et al. [48] arranged the carbon nanofiber to fabricate specimens along the printing orientations using the carbon nanofiber/polycaprolactone composites. They observed that the part printing using the printing directions increased the electromagnetic interference efficiency with the electromagnetic interference (EMI) shielding efficacy of up to 58.7 db compared to part printing in the unplanned orientation.

Globally, the rapid demand of CFRPC in the wind turbine and aeronautical sectors consume a massive amount of the resources and energy employed for manufacturing of vCF. Now, one of the century's primary concerns is to plan a path to environmentally friendly development of carbon fiber to achieve an equilibrium between current social and economic requirements and a better environment for potential productions. For this purpose, using rCF in manufacturing various parts is employed in multiple applications. Also, rCF manufacturing is inexpensive, requires less energy, and is more environmentally beneficial than production of vCF [49]. These benefits of rCF offer them a viable option to existing synthetic fibers when considering both mechanical efficiency and the environmental effect.

The fabrication of the rCF polymer composites provides outstanding mechanical characteristics with complicated shapes of samples manufactured using FDM. The rCF was usually available in a short form with different length distribution because the trash of the carbon fiber polymer composites needed to be cut during the recycling process. The morphology of the milled rCF is shown in Fig. 3(c). The milled rCF mean length is about 95.4 μm [50]. The chemical composition of rCF is depicted in Fig. 3(a and b). The existence of silicone on the fiber interface was detected by energy-dispersive X-ray spectroscopy (EDS) (Fig. 3 (a)). Little amounts of silicone (around 0.18%) can be attributable to sodium silicate-based epoxy resin that remains bound to the surface of rCF. The specimens' x-ray diffraction (XRD) results confirmed the EDS findings. The XRD finding (Fig. 3 (b)) revealed the existence of silicon residues (Si (111)) from the remaining polymer matrix adhered to the fiber surface. XRD studies indicated two dominating peaks at around 25° and 43° (2), which correspond to (002) and (100) structures of carbon in rCF, accordingly.

The short carbon fiber powder obtained through the pyrolysis recovery method was used in the production of various engineering applications using FDM technology. The powder of rCF and the polymer matrix pellets are mixed using a twin extruder, ensuring the uniform dispersion of rCF within the polymer for the fabrication of filament. To initiate the process, the polymer pellets and rCF powder are loaded into the extruder's hopper, and the speed is controlled to produce composite pellets with the desired percentage of rCF. Once the parameters of the twin-screw extruder are set, the composite material pellets, reinforced with rCF, are extruded from the die in a uniform size. After obtaining the rCF-polymer composite pellets, the Noztek Xcalibur filament extrusion system produces filaments from the composite pellets. Various parameters of the filament extruder, including the temperature of three zones and motor speed, must be configured to achieve the desired filament diameter (1.75 mm or 2.85 mm). The fabricated filament produced using the filament extruder, is then utilized in the FDM printer to manufacture various specimens. The complete manufacturing of the rCF available in powder form, is illustrated in Fig. 6 (b).

Replacing vCF with rCF would result in a significant reduction in the cost of composite filaments. Various studies have utilized rCF in combination with other polymer matrices to achieve outstanding mechanical properties for diverse applications. The summary of the studies which used rCF with different polymers is illustrated in Table 1. Tian et al. [51] developed a novel method for recovering and remanufacturing composite materials using 100% rCF and polylactic acid (PLA) plastic. The recovery rates achieved were 100% for continuous carbon fiber (CCF) and 73% for PLA, with energy consumption of 67.7 MJ/kg and 66 MJ/kg, respectively. The remanufacturing process of the carbon fiber is illustrated in Fig. 4. In the reverse direction of the production process, a warm air gun was utilized to locally melt the matrix material on the 3D-printed carbon fiber reinforced thermoplastic composites (CFRTPC). After carbon fiber is obtained from remanufacturing, the rCF could be directly applied to 3D printing. The samples were manufactured using FDM, containing about 8.9% of the rCF and 91.1% of the PLA polymer. The tensile and flexural properties of the part manufactured using this technique observed the 263 MPa and 13.3 GPa. This technology has the advantage of attaining a 100% material recovery rate for CCF and 73% for PLA matrix, which is more favorable for the environment. rCF can be employed to create new composite materials, which reduces the demand for raw carbon fibers and trash.

In contrast to vCF, rCF is typically utilized in the form of chopped or short fibers resulting from shredding and cutting processes involved in the recovery process [52]. Omar et al. [53] manufactured the rCF with different percentages of the 10, 20, and 30% weight loading with the PLA polymer and investigated the strength, surface roughness, water absorptivity, and density test. Different percentages of carbon fiber have different impacts on printed specimen's mechanical properties with the length of the rCF. They observed the strength of the filaments which were manufactured using the different lengths 63 μm, 75 μm, and 150 μm of the rCF. The incorporation of rCF with a fiber length of 63 μm and a weight percentage of up to 10% into the PLA matrix improved the tensile characteristics of the filaments. When incorporating recycled rCF with fiber sizes larger than 63 μm, adding more than 10% rCF resulted in a reduction in both tensile strength and modulus. The inclusion of rCF was apparent to minimize the quantity of water absorbed by PLA-based goods. This

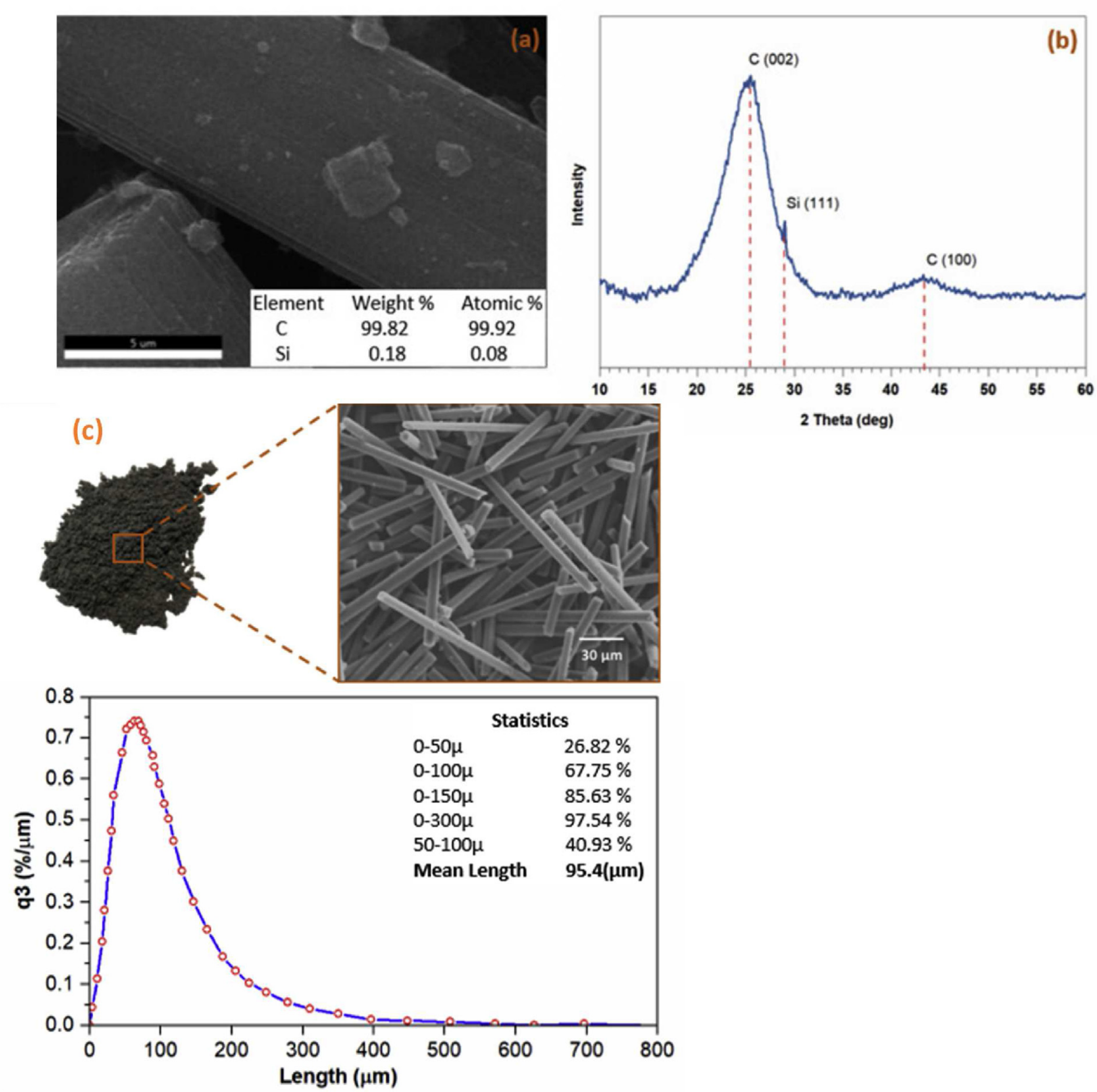

Fig. 3 – Scanning electron microscope (SEM) of the rCF along with mean length (a) Recycled carbon fiber surface morphology with the element composition, (b) X-ray diffraction pattern of recycled carbon fibers, (c) Recyled carbon fiber with length distribution [50].

indicates the possibility of using rCF filler in PLA matrices in a moisture environment. The filament with 63 μm fibers and 20% loading had the greatest density value of 1.87 g/cm^3, while the filament with 63 μm fibers and 10% filling had the lowest density of 1.30 g/cm^3, which was practically identical to the regulated filaments. The roughness of the surface was determined using arithmetical mean roughness in this investigation, and the result indicated that 30% weight loading provides the highest surface roughness. The SEM image of the specimens which were manufactured using the three different lengths of the rCF is illustrated in Fig. 5. Fig. 5(a) shows that rCF with the length of 63 μm was attached to the PLA matrix materials which make to strong bond, indicating that the low viscosity of PLA thermoplastic has a strong bonding with the rCF. At the same time, the fiber was pulled out and could not make a strong bond in the case of 75 μm and 150 μm (Fig. 5(b and c)).

Giani et al. [54] also observed the rCF with a 5% and 10% loading percentage in the PLA polymer matrix. Dynamic mechanical analysis (DMA) was employed to examine the mechanical characteristics of filaments. The sample was warmed at a rate of 3 °C min^{-1} from 25 °C to 100 °C; the parts were evaluated in tensile mode, with an extreme load of 8.0 N and a filament distortion of 40 m. The DMA spectrum reveals that composite filaments exhibit superior mechanical performance compared to regular PLA. The storage modulus shows improvement, increasing from 2500 MPa to approximately 5500 MPa for filaments reinforced with 5 wt % of rCF, and

Table 1 – Summary studies for the fabrication of rCFRPC.

Matrix Materials	Reinforcement information	Content of the reinforcement (%)	Testing Involve	Main outcomes	Source
PA6	rCF with a length of 3.00 ± 1.17 mm is used.	10, 20, 30, and 40 wt%.	Tensile strength and modulus were observed in 20–30 wt%: tensile strenmth was increasing by 175–243% (up to 187.12 MPa) and modulus was 329–562% (up to 12.04 GPa).	The 20% FDM rCFRP demonstrated outstanding mechanical characteristics, with low porosity and excellent fiber orientation.	[61]
PLA	Continuous rCF	8.9 vol %	The flexural strength and the flexural modulus observed were 263 MPa and 13.3 GPa.	Remanufactured carbon fiber achieved a 25% enhancement of flexural strength in a relationship with the pure 3D manufactured composites.	[51]
PLA	The fiber length of the rCF was 63 μm, 75 μm, and 150 μm utilized.	10 wt%, 20 wt%, and 30 wt%.	Tensile Modulus and strength were observed maximum at 10 wt % with the fiber length 63 μm.	The surface roughness was lowest, with 10% of the rCF, and maximum surface roughness was observed in the composites with 30% of rCF with a fiber length of 63 μm.	[53]
PP	Chopped rCF with length 6.3 mm and diameter 7 μm.	10 and 20 wt%.	Tensile properties of the samples were observed maximum having the hemp fiber 10% + rCF 20% + PP 68% MAPP 2%. The flexural strength of the sample was observed with rCF fiber 30% + PP 70%.	After treatment of the natural fiber with the maleic anhydride, the tensile strength of the composites increased by 35–40%, while the flexure characteristics of the composites increased by 30%.	[55]
PEEK	rCF powder	10 wt%.	The parts printed show the flexural strength and flexural modulus of 118.41 MPa and 3402.38 MPa.	The electric conductivity of the parts printed using the rCF/PEEK composites was 2.97 X 10^{-11} S/cm, with an improvement rate of about 96.69% compared to the pure PEEK.	[62]
PEEK	rCF powder	10 wt %	The tensile strength and tensile modulus of the parts manufactured were 91.89 MPa and 1486.73 MPa, respectively. The three-point bending test shows the flexural strength and flexural modulus were obtained at 118.41 MPa and 3402.38 MPa, Whereas the Impact Strength was 7.82 kJ/m^2	rCFRP wear rates were substantially lower than pure PEEK and somewhat more significant than vCF/PEEK. The electrical conductivity and thermal conductivity of the rCF/PEEK composites were improved by 96.69% and 21.65% compared to the pure PEEK polymer.	[60]

exceeding 7500 MPa for filaments containing 10 wt % of rCF. Shah et al. [55] fabricated the specimens using the rCF with the PP thermoplastic polymers having the content of the rCF of about 10 and 20%. This analysis revealed that reinforcing rCF with hemp fiber increased tensile strength by 10–15%. Flexure strength increased by 30–35% after reinforcement with hemp fiber of regenerated carbon fiber. The impact strength of hemp fiber reinforced rCF with the PP composite's materials increased by 35–40%.

Giani et al. [16] fabricated the specimens using PLA matrix materials with a rCF length of about 7 mm in the M400 3D printer at about 230 °C. The samples were manufactured with a percentage of 5 and 10% of the rCF at the two different printing angles 0°, 90°. When compared to 90° alignments, the composite containing 10 % wt. of the rCF 3D manufactured at 0° regarding the applied load orientation has about a doubling of both elastic modulus and peak stress. The fabricated specimens having the rCF content of about 10% at the angle 0° produced the maximum tensile strength of 81.2 ± 0.6 MPa. For the samples printed using the 10% rCF at the 90° deposition angle, the tensile test shows a strength of about 39.1 ± 3.2 MPa due to the fiber pull out from the specimens. The SEM image of the fracture specimen having 5% and 10% of rCF printed at 90° is illustrated in Fig. 7. These findings were especially noteworthy given the ease of producing a rCF-reinforced filament appropriate for FDM applications.

Various researchers used thermosetting polymer composites for recovering carbon fiber. Wang et al. [56] synthesized polyurethane thermosetting resin (PU-HMDO) by reacting acetal glycol with a hexamethylene diisocyanate

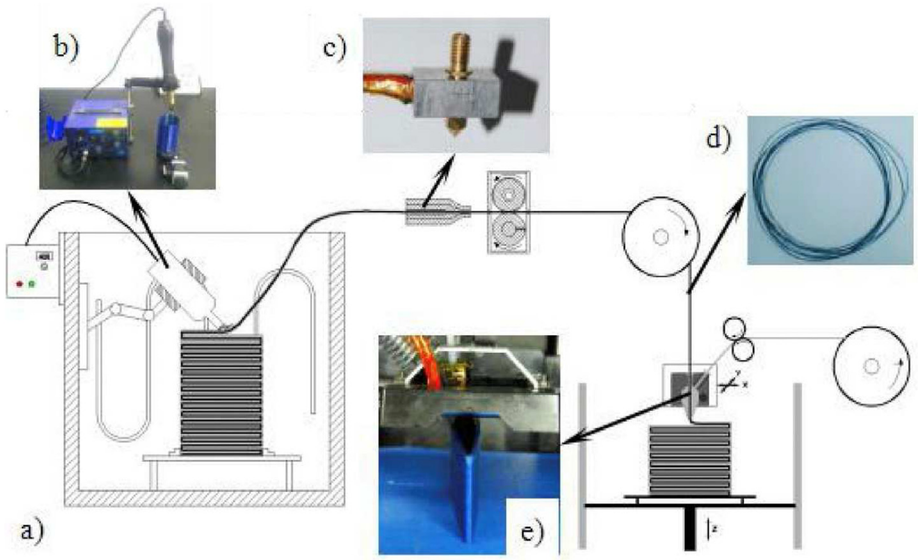

Fig. 4 – Recycling and remanufacturing process for 3D printed CFRTPC (a), including critical ingredients for each step: (b) a hot air gun technology, (c) a remoulding nozzle, (d) Recycled impregnated filament, and (e) the remanufacturing procedure [51].

trimer. The recyclable CFRP was created by utilizing the characteristic that the acetal group can be cleaved upon exposure to a mild acid mixture. Fig. 8 depicts the procedure of synthesis and reaction procedure. The visible framework, micromorphology, and mechanical characteristics of the carbon fibers retrieved by this approach were comparable to those of vCF. Knight et al. [57] used the supercritical water procedure for recycling to reclaim carbon fiber from high-

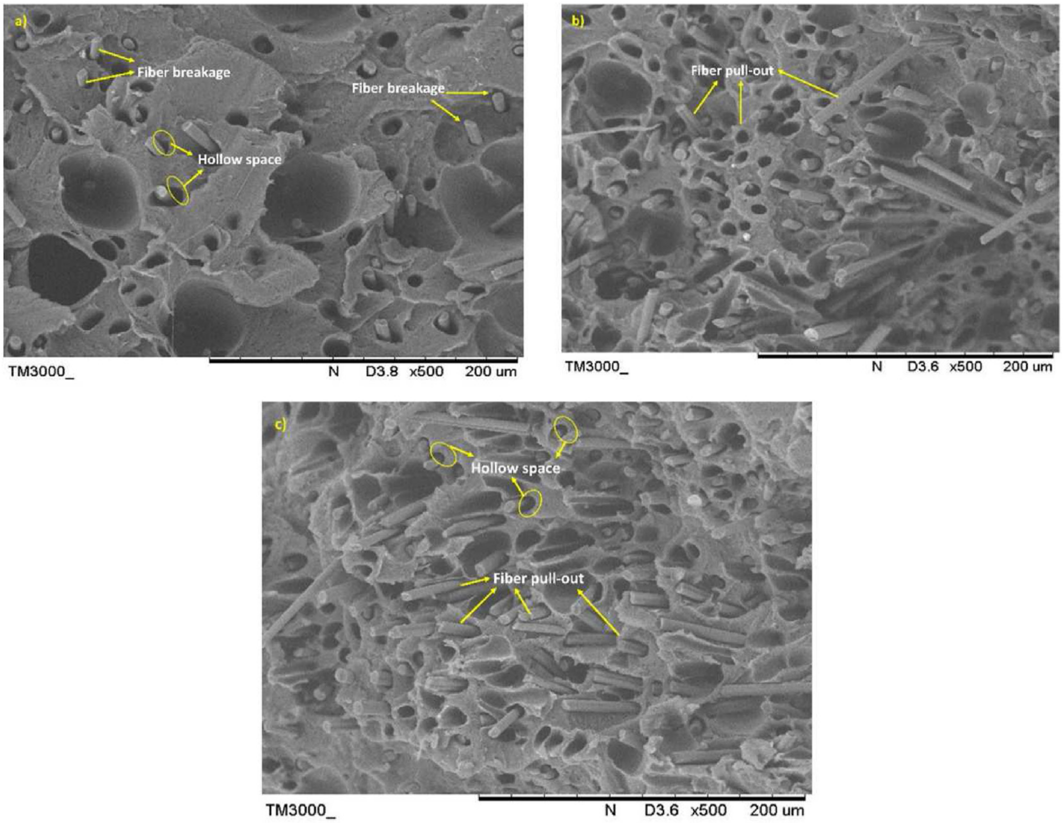

Fig. 5 – SEM pictures of the broken tensile surface of rCF/PLA filament specimens with different lengths (a) 63/10, (b) 75/10, and (c) 150/10 [53].

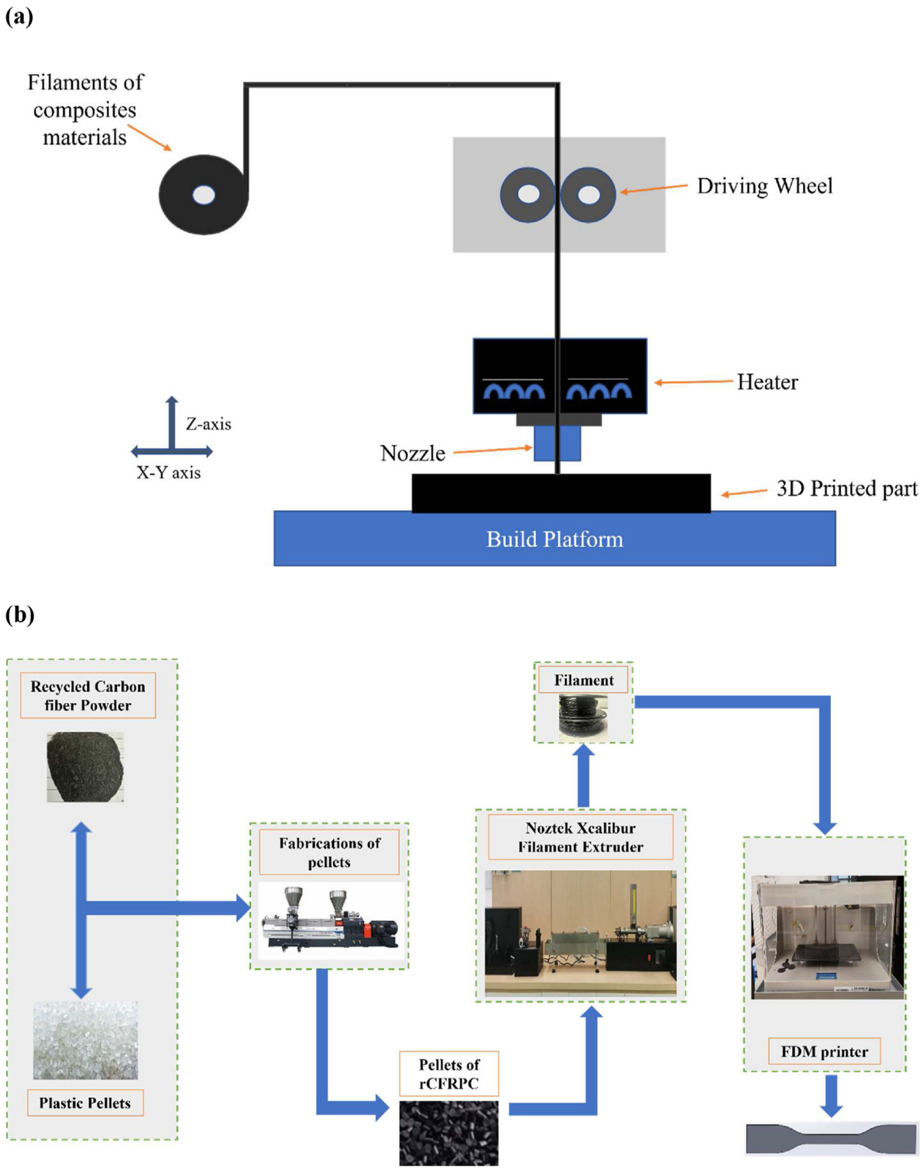

Fig. 6 – (a) AM procedure of composite materials. (b) The complete manufacturing process for the rCF (available in powder form).

performance composite materials. The method's temperature and pressure were 395 °C and 27 MPa, correspondingly. The bending strength of recovered fiber composites was 80–95% compared to vCF composites. Under supercritical circumstances, the resin elimination rates were 99.4%, 98.5%, and 97.4% after 60, 30, and 15 min. It stands to reason that the fiber layers grow more distinct as reaction times increase.

As a result, the solvent has a smaller challenge to overcome to spread to the fiber surface. But while the cross-linking thermosetting capabilities of the polymer in CFRP provide numerous benefits in terms of utilization, they are complicated to reshape [58], and also it is challenging to remelt or remold the thermosetting polymer composites, which leads to the low rate of the recycling for the thermosetting polymer composites. Because reusing back into composite materials is not feasible for most thermosetting composite materials, only their constituent components, such as reinforcement fibers and fillers or matrix resins, might be reclaimed and used as raw materials to make new composite products. In most situations, due to the poor quality of recycled reinforcement fibers, it is prohibited to employ them in the same type of applications, and poor-quality recovered composites can be utilized for low-quality applications [59].

Furthermore, 3D printing provides a new application direction for using the rCF. Therefore, a novel technique was developed in which the rCF was extracted from the carbon fiber reinforced epoxy resin composites trash using the supercritical n-butanol because the n-butanol can breakdown the epoxy matrix of the CF/EP which results in rCF with the smooth interface as well as a high residual value [60]. The reclaim carbon fiber obtained was then manufactured using the FDM printers with the polyether ether ketone (PEEK)

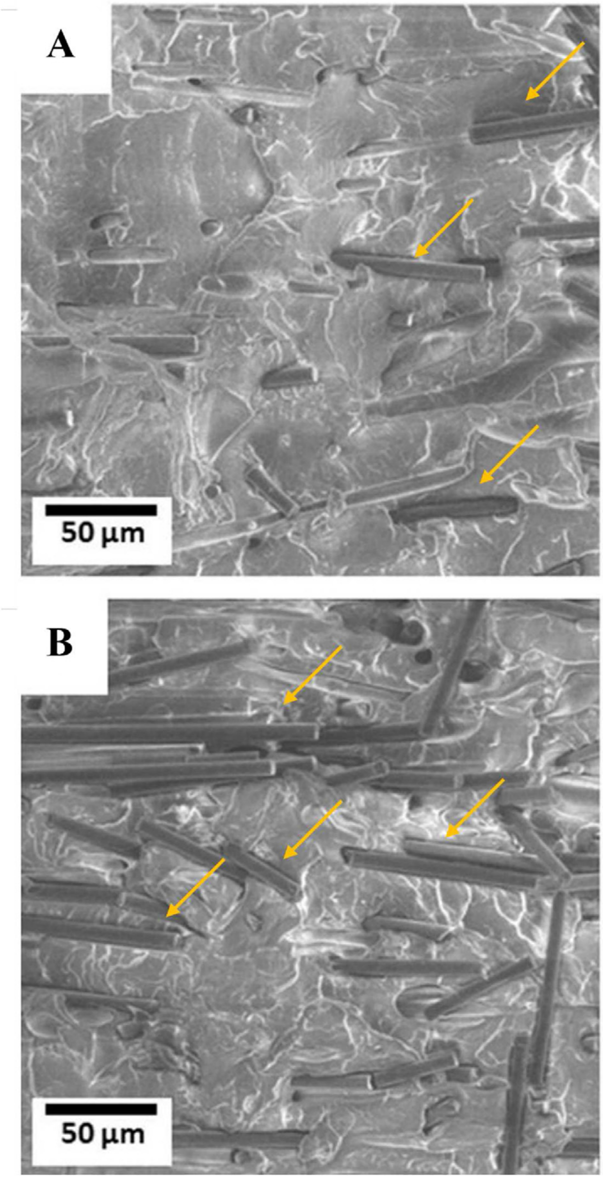

Fig. 7 – SEM micrographs of sample surface damage printed at 90°, (A) PLA/rCF5; (B) PLA/rCF10 (Yellow arrow shows the fiber pull-out) [16].

selected as matrix materials. The discontinuous rCF was milled to rCF powder using a planetary ball miller (F-P2000, Focucy). The rotational speed of the ball mill container was 500 r/min, the rotational velocity was 250 r/min, and the grinding interval was 5 min. To obtain a consistent distribution of carbon fiber powder inside the PEEK matrix, the composite filaments were ejected with two feed holes and a tapered screw. SEM was used to examine the breakage surface characteristics of the filaments. The vast quantity of holes observed that the carbon fiber was extracted from the PEEK matrix attributed to the increased tensile strength. The mechanical properties of parts manufactured using the recycled carbon fiber/Polyether ether ketone (rCF/PEEK), virgin carbon fiber/Polyether ether ketone (vCF/PEEK), and pure PEEK are shown in Fig. 9. It was concluded that experiments using fused deposition modeling generated rCF composite samples with 10% of the amount of the carbon fiber show a 17.23% rise in tensile properties over original PEEK specimens, a 10.18% improvement in flexural strength, and 96.69% rise in electrical conductivity.

3. The potential of the carbon fiber waste available for recycling

CFRC have been displacing beyond the traditional materials in high-performance applications since the 1970s because of their low weight and good mechanical qualities [63,64]. Although the majority of carbon fibers produced worldwide are currently derived from polyacrylonitrile (PAN) and pitch precursors, the pyrolysis of cellulosic fibers and the production of high-modulus carbon fibers through these processes are of significant importance in terms of fundamental carbonization chemistry [65]. Over ninety percent of the globe's commonly sold carbon fibers are now manufactured from PAN, a non-renewable petroleum-based substance [66,67]. PAN-based carbon fibers are primarily manufactured in two processes. The first stage is to create a PAN precursor, mainly consisting of monomer polymerization and manufacturing spinning liquid, which is spun more. The specification of the precursor dictates the efficiency of the carbon fiber; hence this first stage is critical in the synthesis of carbon fiber. The precursor is pre-oxidized and carbonized in the subsequent stage [68].

Carbon fiber is a highly adaptable material with significant promise in a wide range of industries. Due to its exceptional strength-to-weight ratio, carbon fiber is an excellent choice for lightweight and durable applications, including aerospace, automotive, and sporting goods industries, among others. Carbon fiber is frequently utilized for structural components in aviation because it can tolerate high temperatures and substantially reduce weight. The aircraft industry is very concerned about reducing fuel usage and Carbon dioxide (CO_2) emissions. Because of scientific and operational advancements, airline companies have achieved the goal of lowering CO_2 emissions by 70% since the 1960s and anticipate maintaining this reduction through 2050 [69]. Carbon fiber composites are utilized in the automobile industry to reduce vehicle weight, increase fuel mileage, and enhance productivity. Suzuki et al. [70] investigated vehicle lightweighting employing CFRP with thermoplastic and thermoplastic polymers, as well as rCF, and found that it reduced life cycle energy by 17%, 21%, and 25%, correspondingly. Carbon fiber is also employed in the sports goods industry to manufacture lighter, high-performance items such as tennis rackets, bicycles, and golf clubs etc.

The world consumption of carbon fiber in 2017 was 70,500 tons, an increase of nearly 11% over the past year [71]. The worldwide CFRP consumption in 2018 (Fig. 10(a)) demonstrates that aerospace, wind turbine blade, sport and leisure, and automobile industries are the most common. Furthermore, when the cost is considered, the sector-wise breakdown of CFRP leans towards the aviation industry, which accounts

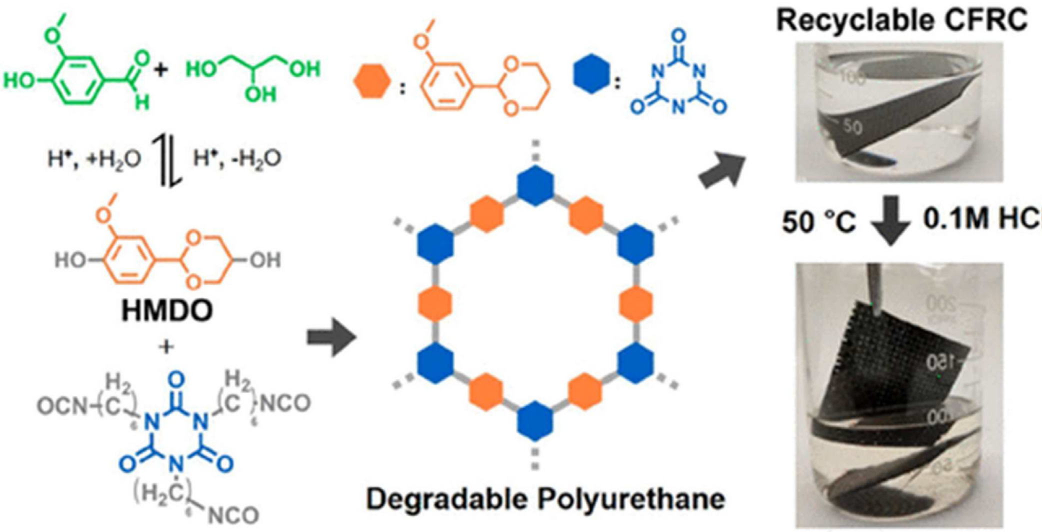

Fig. 8 – Degradable polyurethane-based carbon fiber composites production and reaction method [56].

for 73% of CFRP purchases (Fig. 10(b)). The percentage of the CFRP is less in the pressure vessel and molding compound areas. In terms of regional utilization, North America stands out as the most prominent consumer of CFRP worldwide, while Asia Pacific consumes the least among the regions, accounting for approximately 12% (Fig. 10(c)). The prepreg manufacturing process is the most utilized of the CFRP for the manufacturing of the parts which are used in the different sectors (Fig. 10(d)). The aviation industry is the most consumable application of the CFRP from the other various applications like sports, automotive [72]. For the aviation sectors, around 50% of the aircraft fabrications materials contain the CFRPC [73], and components manufactured using the CFRPC weighting around 25–30% less than those manufactured using traditional metals [74], resulting in more CFRP trash obtained from each of the aircraft. It is anticipated that 500,000 tons of composite garbage will be produced in 2050 by commercial aeronautical sector [74], as well as the cumulative of 43 million tons due to blades waste generated by 2050, producing environmental issues and emphasizing the importance of providing composite waste disposal solutions [75].

Driven by the increasing demand for lightweight materials, the utilization of carbon fiber has been steadily rising in the current year and continues to grow day by day [19,79,80]. As a result, the scientific and industrial sectors are collaboratively striving to establish a circular economy by developing frameworks for the recovery, refurbishment, and recycling of end-of-life products. The different applications of carbon fiber can lead to the immense potential of carbon fiber after its life cycle. The aircraft industry contributes 36% of the world market, followed by 24% of the world's automobile sector, primarily using high-quality PAN carbon fibers [50]. For the aviation sectors, the increasing manufacturing rate of current aircraft types with a high proportion of CFRP in their construction, such as the B787 or the A350, the global average fraction of CFRP by airplane will rise from 19.1% in 2015 to 24.8% in 2020. As a result, the average proportion of CFRP per aircraft grows by about 1% each year worldwide. It is estimated that if fabrication trash and airplane end-of-life trash are not reclaimed, the commercial airplane sector will produce around 500,000 tons of cumulated CFRP waste by 2050. The average lifespan of airplanes commercially used and manufactured using the CFRPC is 25 years [74]. By considering the average life of the aeroplane, Fig. 11 (a) depicts the growth of the amount of cumulative produced CFRP garbage by the commercial aviation industry in specific regions through 2050.

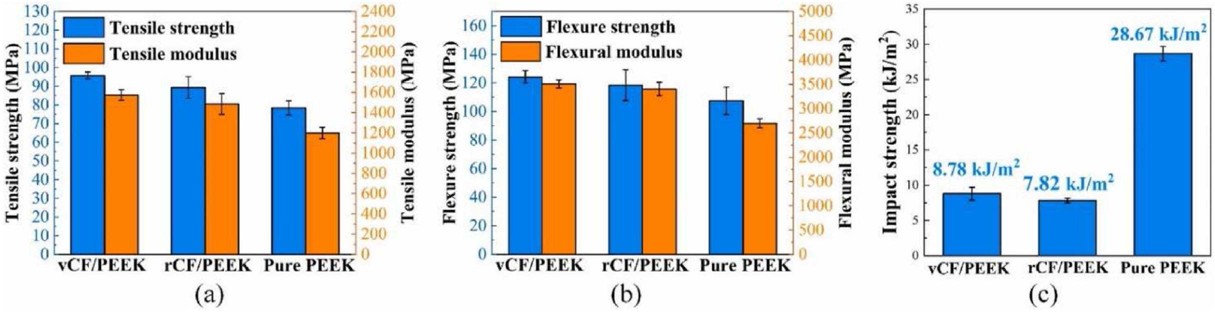

Fig. 9 – The mechanical characteristics of 3D printed rCFRP samples are as follows: (a) Tensile properties and modulus; (b) Flexural properties and modulus; and (c) Impact strength [60].

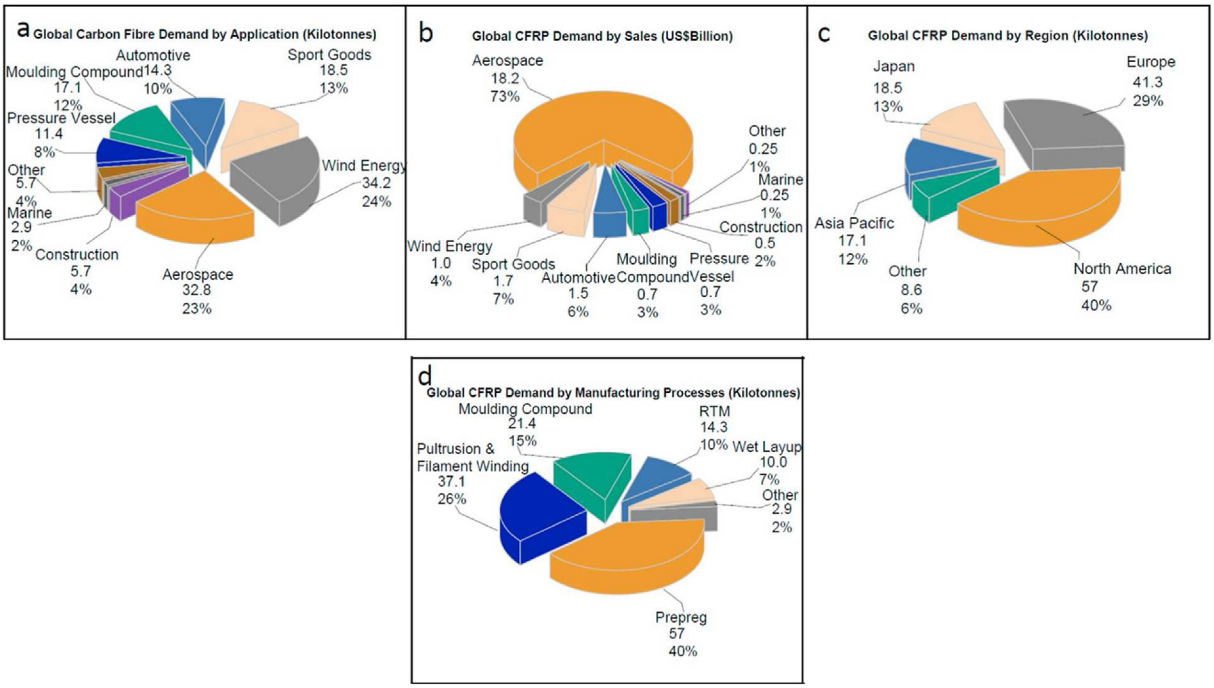

Fig. 10 – Worldwide CFRPC requirement in the year 2018 segmented by (a) Application in different sectors by quantity and percentage, (b) Trades, (c) Region, (d) Production method [72,76–78].

Most wind turbines contain three blades, whereas each blade contributes only about 4% of the overall mass of the construction (for 1–3 MW turbines). The blades of wind turbines are often built of composite materials that include thermosetting resin and either glass fiber or carbon fiber. Every year, around 10% of the waste generated by blade manufacture, or approximately 1200 tons of composite material, is generated [59,81]. As the wind power sector gains popularity and global consumption increases, the quantity of manufacturing waste also rises, particularly with the growing share of offshore wind power. The estimated waste of the carbon fiber obtained from the wind turbine sectors by considering the average age of the wind turbine is 25 is shown in Fig. 11(b). The accumulated garbage of CFRC used in the fabrication of turbine blades in Europe alone is predicted to attain 482,998 tons by 2050. According to Fig. 11(b), a huge quantity of carbon fiber will be disposed of after the 2035, and Europe has been a pioneer in the development and construction of large offshore wind turbines, which represents the significant volume of CFRP waste generated in this region by the wind power industry. Asia is a developing geographic location as well and from 2016 to 2017, China had a 27% increase in wind power electricity production [82].

4. Applications of rCF

rCF is a highly flexible material with numerous applications in various sectors that can be used to create lightweight, high-strength components for aircraft and automobiles that can reduce the weight of airplanes and automobiles. rCF is generated by recycling and reprocessing carbon fiber waste from production processes, making it a more environmentally friendly and economically feasible alternative to vCF. This substitution has the potential to enhance fuel efficiency and reduce emissions. rCF finds applications in various sectors, and the following examples illustrate its versatility across different domains.

- *Utilization of the rCF in the battery*

Savignac et al. [84] designed innovative freestanding electrodes using recycled aerospace industrial carbon fibers and LiFePO4 conductive polymers and applied them to lithium-ion batteries. The analysis revealed that when the rCF concentration was 3 wt%, the total electrode energy density was 468 Wh/kg, which enhanced the overall effectiveness of lithium-ion batteries and established a foundation for using rCF in lithium-ion batteries. The mechanical features of these fibers, which remove the requirement for the traditional Al conductive substrate, along with their electronic conductivity, make them ideal for use in battery electrodes. The utilization process of the rCF in the electrode of the lithium-ion battery is shown in Fig. 12. Cho et al. [85] created a multipurpose three-dimensional conducting rCF framework and implemented it in a lithium-ion battery current collector. After more than 250 charges and discharges at 2C, the design showed outstanding diffusivity and consistency for lithium ions during charge and discharge, with a memory-specific capacity of 148.7 mA-h/g. Furthermore, high bending and flexibility might be applied to textiles to create smart apparel.

Using vCF in the battery electrodes is unsuitable for the environment because significant energy is required to produce the vCF. The rCF has partially recovered its initial energy investment from its initial role that providing the unique opportunity to improve the Li-Ion battery performance while

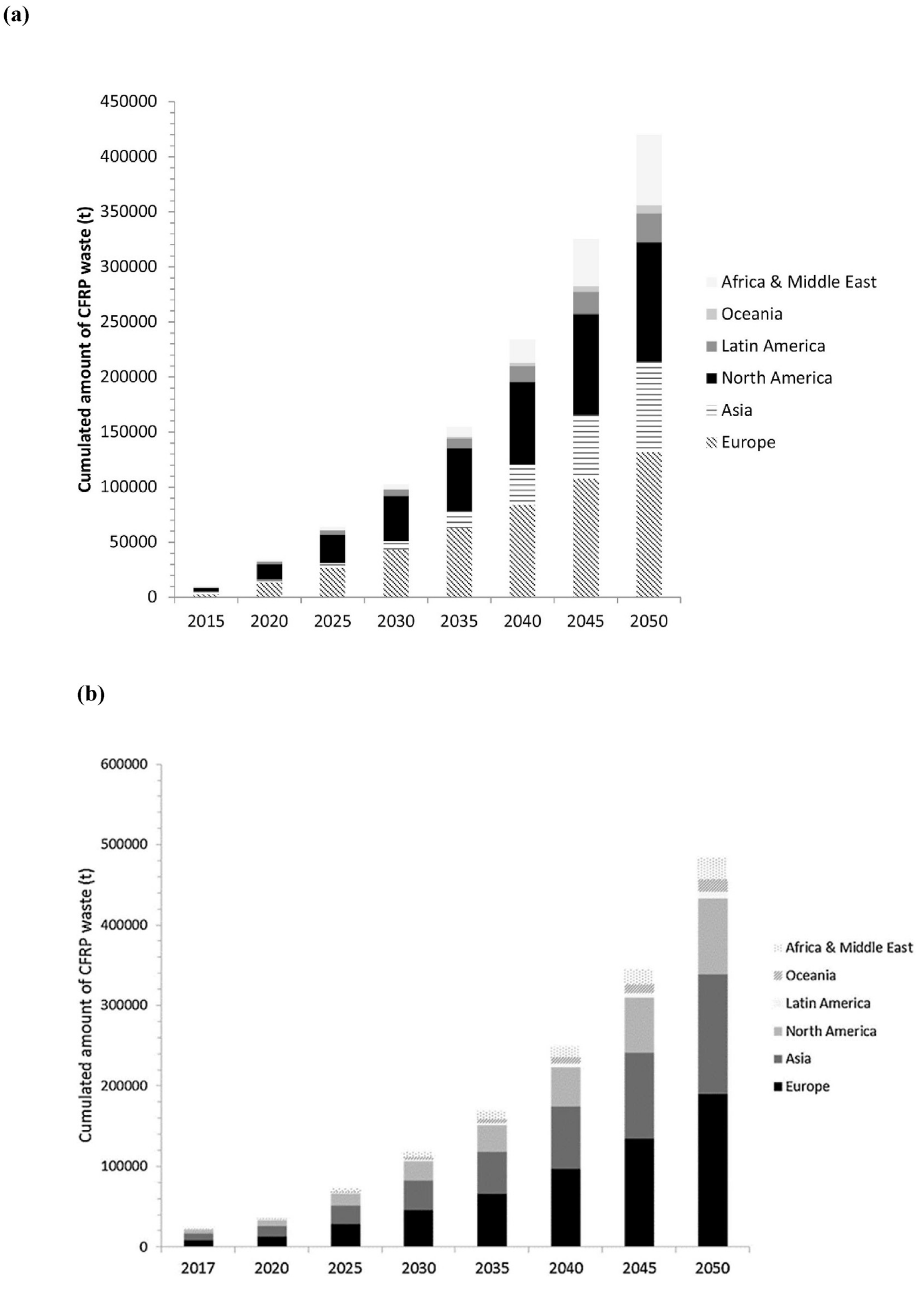

Fig. 11 – (a) The quantity of accumulated waste produced by the commercial aircraft industry by geographic region will be updated every 5 years till 2050 [74]. (b) The amount of accumulated garbage produced by the wind power industry in specific areas will be updated every 5 years till 2050 [83].

addressing a significant trash concern. The major challenge in utilizing the rCF in the battery electrodes is the pre-treatment on the surface of the rCF, which is obtained after the recycling technique. During the manufacturing process, the alignment of the rCF is essential for achieving excellent properties of the carbon fiber in the composites.

- *Applications of rCF in the Aviation and Automotive industry*

Several rCF makers say that since automobile manufacturers are unwilling to take the risk, someone must always be the initial to use innovative materials. But the manufacturers accept that extensive usage of rCF in automobiles would

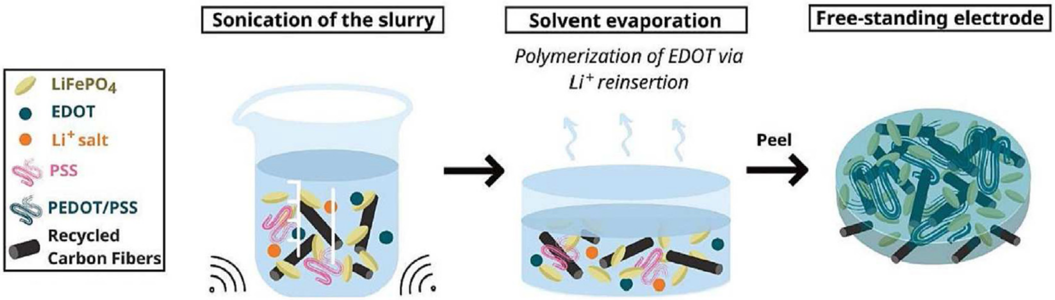

Fig. 12 – The manufacturing process of the electrode using rCF [84].

quickly exhaust the capacity of fiber recovery firms. As a result, for the present instance, they are content to participate in small-scale developments, attempting to infiltrate the automotive sector in the same manner as polymer composites, i.e., starting with less critical parts and progressing to pressure tanks [86]. BMW Group serves as an example of an automotive manufacturer utilizing rCF in their production processes. The rooftop of the BMW i3 stands as a tangible representation of the company's commitment to recycling initiatives. It is completely comprised of a carbon fiber blend. This material, which has not yet come into contact with the polymer, is reused during the pre-processing phase. Up to 95% of the materials used in the building of the BMW i3 are recoverable, and carbon fiber can be reprocessed into the manufacturing method [87,88]. ELG utilized the rCF in the headlamp of the injection molding company Sanko Gosei [89]. They replaced 30% of the rCF with 30% of the glass fiber polypropylene compound and observed that enhanced in the righty and eight percent lightweight with fewer waste materials. The headlamp, which was manufactured using the rCF is shown in Fig. 13. Lin et al. [79] created a material that is resistant to wear comprised of PEEK matrix and rCF with injection modelling to improve the weight-bearing performance and wear resistance of the matrix material in several circumstances. The friction factor and wear rate of the injection moulded 10 wt% rCF/PEEK were 0.328 and 0.44×10^{-6} $mm^3/(Nm)$, respectively, when evaluated at 1 MPa and 1 m/s with a block-on-ring tribometer. Depending on the situation, the 3D manufacturing of rCF/PEEK composites has a better frictional force (0.368) and smaller wear amount (0.113×10^{-6} $mm^3/(Nm)$) at the constant wear state than the injection-moulded rCF/PEEK, which could be related to the interface stair-stepping result and linearly ordered rCF of the 3D manufactured rCF/PEEK. Therefore, the increased mechanical qualities can encourage using 3D manufactured rCFRP products in the auto parts like the instrument panel and interior door panel, hence improving car protection [60].

Fig. 13 – Injection-moulded headlamp is manufactured using 30% rCF [89].

In the aerospace sector, rCF is progressively utilized to build lightweight, high-strength parts for aircraft. rCF makes aircraft parts like wings, airframes, and tail sections. The usage of rCF in these parts contributes to weight reduction, increased durability, and improved fuel efficiency. The aviation sector, which produces significant garbage, might be a primary source of recycled materials. The use of thermoplastics, which allow for reprocessing and rCF use, is a new aviation trend. Many thermoplastic composite substances have become employed in the manufacture of airplanes, indicating that the equipment and technology are both accessible [86].

The rCF composites employed in aviation and automotive applications provide great environmental and cost benefits compared to manufacturing the aviation and automotive sectors using new carbon fiber. The production cost of the rCF is 50% less than vCF [90]. In the aviation and automotive industries, rCF can give various benefits, including environmental advantages, reduced expenses, lightweight, and good appearance. These benefits enable rCF composites to be an appealing material for multiple applications in these industries. During the recycling process, carbon fiber is small, which is challenging to manufacture the parts with the equal length distribution of rCF in the different applications. The rCF performance is reduced compared to the vCF, which cannot be utilized in the applications of high-performance parts of the automotive and aeronautical industry.

- *Application of rCF in other sectors*

The novel composites were fabricated using the rCF obtained after lifespan. Jagadish et al. [91] employed rCF and two types of thermoelectric fillers (Bi2Te3 and Bi2S3). The power coefficient of recovered carbon fiber rises to thirty-four times with increasing filler content (Bi2Te3). The explanation was that Bi2Te3 and Bi2S3 boosted carrier mobility among rCF gaps and thus enhanced thermoelectric efficiency. Ahsan et al. [92]

investigated the effect of cyclic cryogenic processed rCF on epoxy composite wear performance. However, the friction coefficient and wear rate mentioned for industry sectors are much higher. As a result, developing rCF-reinforced polymer materials for tribological applications is of tremendous interest.

Huang et al. [62] proposed the methodology for manufacturing the rCF/PEEK composites, which significantly improves electric conductivity. The electric conductivity of the carbon fiber makes it suitable for sensing and anti-static applications [93]. Therefore, the rCF/PEEK can provide excellent electric conductivity suitable for wearble strain sensor applications. Lin and Schlarb [79] studied the tribological properties of the composites having the rCF/PEEK, which is compared to the vCF/PEEK. They investigated that the rCF is the significant reinforcement for fabricating the excellent performance polymer-based tribocompounds for use in factories that are both cost-effective and beneficial to the environment.

Wang et al. [94] created rCF composites by using NaOH to process wind turbine blade scrap and strengthen cement mortar. The addition of rCF to cementitious mortars increased their strength and volume stability. Mild NaOH (1 mol L-1) improved bonding over high amounts and untreated rCF mortars, lowering free drying shrinkage. As a result, rCF can provide essential stability to cementitious mortars while maintaining workability. In terms of electromagnetic shielding, oriented short carbon fibers can reduce surficial reflection while allowing microwaves to infiltrate, multiply reflect, and disperse within the shielding structure generated by the carbon fiber network [95]. The rCF can be combined to form an efficient multi-reflection system of EM waves, which could throw fresh insight into developing and producing EM shielding materials. Belli et al. [96] created self-sensing limestone cement mortars employing graphene nanoflakes, vCF andrCF as infill. The outcomes demonstrated that adding 0.2 vol% virgin and 0.2 vol% rCF to cement mortar improved electrical conductivity while decreasing cement mortar strength.

Using the rCF reduces the need of the vCF, which benefits the ecosystem because a substantial quantity of energy is conserved by removing the processing of vCF, and natural resources are protected. A higher length of the rCF is needed to mix carbon fiber in matrix concrete applications equally. For this purpose, one major issue is that the higher length of the rCF is required to achieve the equal mixing of the fiber, providing excellent properties.

5. Conclusion and future perspectives

This article presents a systematic overview of the rCF obtained after the waste of the CFRPC from the different sectors. The research reviewed the additive manufacturing of the rCF with the different polymers using the 3D printer, the CF potential, and the rCF applications in various sectors. Layer-by-layer manufacturing with FDM allows the rapid fabricating of complex geometries; however, component performance depends on the precise configuration of printing settings and the rCF materials used. The use of rCF as a reinforcement in polymer composites made by AM is observed. The systematic research of the rCF is a developing area in the manufacturing sector, as the recently published articles indicate. The potential of carbon fiber derived from different sectors and the wide-ranging applications of rCF in various industries are significant. Innovative and cost-effective recycling techniques are desperately required to collect and recycle valuable carbon fibers effectively.

This study on rCFRPC fabricated with 3D printers gives researchers and the manufacturing sector more excellent knowledge. Following a systematic review of the literature on the fabrication of rCF as a reinforcement in the FDM process, the following future research suggestions have been offered.

- Using the rCF with high-performance matrix materials like PEEK, Polyamide-imide (PAI), and Polyphenylene sulfide (PPS) for applications in aviation and automotive, in which recycled carbon fiber has demonstrated promising outcomes.
- The focus needs to be on creating novel and more efficient surface treatments that can enhance the mechanical characteristics of rCF. Chemical alterations, plasma treatments, and nanocoating are examples of treatments that could be used. The surface treatment will improve the adhesive bond of the rCF with the matrix material and improve the printed products mechanical characteristics, which will be utilized in high-strength applications.
- The focus is needed to develop a new recycling technique that can provide a higher length of the rCF obtained after the recycling with the economic cost and lower CO_2 emission. This will help manufacture the parts with the efficient alignment of the rCF, which can provide the higher performance that will be utilized in the applications; excellent strength is needed. By achieving the high performance of the rCF like the vCF, the utilization of the rCF as a reinforcement in the matrix materials increased for application in the different sectors.
- Fiber alignment techniques are being developed and offer the potential for converting rCF into CFRP with high fiber volume fractions for high-value usage [97]. Future research will focus on regulating rCF characteristics by systematically studying aligning fiber process factors and precisely controlling the rCF deposition routes to ensure the appropriate fiber alignments. Achieving the desired alignment of the rCF in the printed specimens can improve the printing specimens' mechanical strength. The references [44,45,98] provide the appropriate alignment process which is used for increasing the mechanical characteristics. The references proposed a methodology for aligning the rCF in the polymer matrix for manufacturing the specimens using the 3D printing technique. The alignment process provides the isotropic properties of the samples manufactured using the rCF-reinforced polymer composites in the FDM, leading to excellent mechanical properties.
- Scaling of rCF after recovering from this procedure is still a research area that can be a big way to improve the functionality of goods made from these rCF. Chemical sizing can be studied to eliminate interfacial defects such as initial fiber/matrix debonding and interlaminar structural failure. The role of chemical sizing in rCF surface quality,

an essential factor for optimal interfacial adhesion, may be influenced.

- The exceptional performance of the FDM specimens manufactured using rCF depends on the suitable choice of manufacturing parameters during printing. The printing parameter of the FDM printer's directly influence the mechanical properties of the manufactured specimens. The proper selection of printing parameters provides excellent strength for the manufactured part. The printing parameters, such as printing temperature, raster angle layer height, infill percentage, and printing speed, directly impact the mechanical properties of the created samples. It would be better if the relationship between printing parameters and mechanical qualities of produced parts could be fully understood, allowing AM to customize high-performance material parts using the rCF.
- Several defects are generated during the AM process. Recognizing how these faults emerge can result in ways to reduce or eliminate them. This, in turn, will allow for improved qualities and accelerate the approval procedure for these recycled carbon fiber materials.
- To enhance the quality of rCF, scientists could investigate new recycling procedures or modify current ones. Approaches such as cryogenic grinding or chemical recycling might be employed to produce high-quality fibers with better mechanical qualities.
- The use of cellular structure modeling and topology optimization simplifies the process considerably to manufacture 3D printed recycled CFRP composite materials with configurable mechanical properties while maintaining lightweight.
- The study will concentrate on enhancing the mechanical characteristics of parts printed using the FDM method to solve the remaining shortcomings of the present techniques while also investigating further new potential strategies for achieving more excellent performance. Further research on process improvement techniques for various engineering and high-performance polymers will be required to fulfill multiple commercial applications.
- Further research should focus on the variable mechanical characteristics of rCFRPC and the effect of varied loading situations, such as damp heat, on mechanical characteristics.
- Surface and topological deformities should be carefully addressed by establishing hybrid systems for pre-processing, on-printing, and post-processing for manufactu-ring of rCF with the various matrix materials.

Declaration of competing interest

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

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