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REVIEW ARTICLE

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A review on material extrusion additive manufacturing of polycarbonate-based blends and composites: Process-structure–property relationships

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Abstract

Polycarbonate (PC) is a valuable engineering polymer with numerous technical characteristics like desirable mechanical properties, high heat resistance, chemical resistance, optical clarity, and electrical insulation capabilities. Therefore, it finds extensive use in aerospace, automotive, consumer goods, optics, medical devices, and electronics. Materials extrusion additive manufacturing offers several advantages, such as customized geometry, minimal material waste, cost-effectiveness, and ease of material modification. Accordingly, PC has recently emerged as a robust and durable additive manufacturing material. This review aims to investigate how printing parameters in materials extrusion additive manufacturing affect the properties of PC and PC-based materials, with a specific emphasis on mechanical properties. The main drawbacks associated with pure PC filaments, like high print temperatures, warping tendencies, and a propensity to retract during printing, are also discussed. Considering the significant demand for developing PC blends and composites tailored for application in material-extrusion additive manufacturing, the influence of different types of fillers, including polymeric, metallic, and ceramic, on improving the mechanical behavior is then reviewed. This paper explores the diverse applications of additively manufactured PC parts, especially within advanced areas like aerospace, electrical engineering, and medicine. Lastly, prospects and challenges are presented in the review.

Highlights

- PC is a key engineering polymer for extrusion 3D printing.
- Printing parameters affect the quality and strength of polycarbonate parts.
- Various fillers adjust polycarbonate-based composites' mechanical properties.

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- High temperatures, warping, and retraction are major 3D printing challenges.
- 3D-printed PC composites can be used in a variety of applications.

KEYWORDS

additive manufacturing, material extrusion, mechanical properties, polycarbonate, process parameters

1 | INTRODUCTION

In recent years, Additive manufacturing (AM) has emerged as a modern fabrication technique that allows for the quick and efficient production of complex geometries, contrasting with traditional subtractive manufacturing methods.[1,2] Also, parts are produced layer by layer, providing a customizable manufacturing method.[3,4] This approach offers enhanced flexibility and reduced investment costs, making it particularly valuable for modeling and rapid prototyping applications.[5,6] AM techniques can be categorized into seven main types: Sheet Lamination, Binder Jetting, Directed Energy Deposition, Powder Bed Fusion, Vat Polymerization, Material Jetting, and Material Extrusion.[7,8] Material Extrusion (MEX) is a widely utilized AM method known for its cost-effectiveness, versatility, simplicity, and high geometric accuracy.[9–11] In MEX, thermoplastic polymers are fed into an extruder, melting and depositing layer by layer to create the desired shape. Fused deposition modeling (FDM) employs prefabricated filaments with fixed diameters as the feeding material, patented in 1989.[12,13] While a variety of plastics can be used with FDM, the most commonly used filaments are polylactic acid (PLA)[14] and acrylonitrile butadiene styrene (ABS).[15,16] Although other filaments such as thermoplastic polyurethane (TPU),[17] acrylonitrile styrene acrylate (ASA),[18] polyamide (PA),[19] polypropylene (PP),[20] polyetheretherketone (PEEK),[21] PEI (polyethyleneimine)[22] and polycarbonate (PC) offer superior properties, they are more challenging to print and require advanced printers.

PC is a family of amorphous thermoplastic polymers known for their impressive mechanical strength, optical transparency, thermal stability, and impact resistance.[23,24] GE and Bayer initially patented PC as Lexan and Makrolon, respectively.[25] PC has become a fundamental material among engineering plastics.[26] Generally, polymers with a recurring carbonate group in their polymeric backbone are classified as part of the PC family; Bisphenol-A PC (BPA-PC) is the most widely produced and utilized variant.[27,28] This polymer is primarily produced via interfacial polymerization,[29] although other methods, such as melt-polycondensation[30] and solid-state polymerization,[31] are available that are more environmentally friendly.[32] Newer types of this polymer with aliphatic backbones, such as tri-methylene carbonate PC (TMC-PC)[33] and isosorbide PC (ISB-PC)[34] are also synthesized via ring-opening polymerization[35] or polycondensation[36] that provide biodegradability, biocompatibility, recyclability, food-safe properties, and UV resistance[37–40] while reducing the consumption of fossil resources by eliminating aromatic precursors like BPA.[41,42] However, these advantages come with a trade-off, as aliphatic PCs exhibit inferior thermal stability, service temperature, and mechanical properties.[43,44] Despite these drawbacks, the advantages of aliphatic PCs have sparked significant interest and research in recent years.[45–47]

PC is considered a vital engineering plastic,[48] and the most common PC manufacturing methods include injection molding, compression molding,[49] pultrusion, extrusion,[50] and milling.[51,52] Traditionally, CNC-subtractive manufacturing methods, such as milling, in applications requiring exceptional precision, like PC dental crowns or optical lenses, were used.[53] The FDM technique not only offers the flexibility and reliability of subtractive manufacturing methods but is also more capable of producing complex geometries.[54]

The earliest confirmed reports of using PC in AM can be traced back to the early 1990s.[55,56] Sandia, for example, developed the Sinterstation 2000, an SLS (Selective Laser Sintering) machine capable of fabricating PC parts primarily used for investment casting patterns.[55] By 1999, SLS was used to produce functional parts.[57] Nevertheless, this method was not widely used due to the limited availability of raw materials, complex operations, and high costs.[58] Another widely studied and practiced AM method for PC is Stereolithography (SLA).[59] In SLA, a photosensitive polymer is employed as the starting material, and controlled light/UV projection triggers polymerization or cross-linking reactions. Among these methods, Fused Deposition Modeling (FDM) has received the most research attention due to its simplicity, availability of starting materials, and cost-effectiveness. Crump originally patented FDM in 1989[60]; nonetheless, it was not until the early 2000s that printers capable of printing PC parts, such as the Stratasys®, were introduced to the

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market.[61] Initially, the main challenge with FDM was dealing with the high temperatures required for printing PC parts. Historically, FDM was primarily used for modeling and rapid prototyping,[62] and its quality was lower than conventional methods.[63] However, recent advancements in FDM technology, material production, and the incorporation of fillers and additives have significantly improved these deficiencies, enabling the production of functional FDM PC parts in specific industries.[64] More recently, newer methods such as Fused Particle Fabrication (FPF) and Fused Granule Fabrication (FGF) have been employed, eliminating the need for filaments by allowing the starting material to be directly inserted into the printer without additional processing steps.[65] This facilitates the printing procedure and significantly increases the printing speed, making them ideal for Large Format Additive Manufacturing (LFAM). Large-Format Additive Manufacturing is also a relatively new method that fabricates large single-piece components, expanding the applications of AM.[66–68] For the Material Extrusion (MEX) technique, both filament-based (FFF) and granule-based methods are used; however, FGF (fused granular fabrication) offers significantly higher deposition rates—up to 200 times compared to FFF methods.[66]

Over the past few years, there has been significant research interest in the additive manufacturing of PC. The performance of additively manufactured PC is significantly influenced by the relationships between process, structure, and property, as the processing conditions directly influence the microstructure and, consequently, the final properties of the 3D-printed parts. Therefore, it is essential to provide a comprehensive review that explores recent progress, practical considerations, and challenges from an engineering and materials selection perspective to benefit the scientific community. The central perspective of this paper, as shown in Figure 1, is cause and effect. The paper first analyzes the effects of

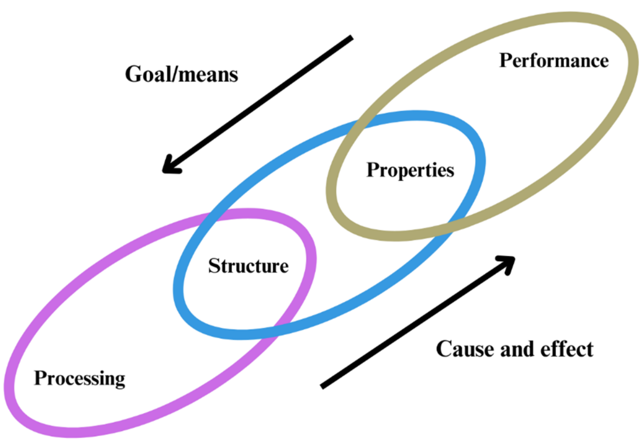

FIGURE 1 Material science paradigm.

printing parameters on PC properties, particularly focusing on mechanical properties. The second part examines various polymeric, metallic, and ceramic fillers and their impact on the mechanical properties of 3D-printed PC coupons. Finally, the paper focuses on the applications of additively manufactured PC, particularly in high-tech industries such as aerospace, electrical, and medical. Exploring these applications could highlight the practical uses of PC in industries that require advanced technological solutions. Over and above, challenges and prospects in FDM 3D printing of PC are explained to provide a clear overview of technical considerations and the promising outlook of material-extrusion additive manufacturing of PC in the modern world.

2 | EFFECTS OF PRINTING PARAMETERS

The formation of defects is more likely in parts produced by the FDM method than in other manufacturing techniques like compression molding.[69] The integrity of FDM specimens is determined by the strength of weld lines, which is influenced by the printing conditions.[70] Understanding how each parameter affects the quality of printed parts and optimizing them is crucial to producing high-quality parts with minimal material waste and high dimensional accuracy.[71,72] Moreover, due to the dependence of the material's flow behavior on these parameters, dimensional accuracy is also strongly dependent on printing parameters.[73] The Printing parameters can be divided into two categories: 1) FDM machine parameters, such as bed temperature, nozzle temperature, chamber temperature, and nozzle diameter, and 2) working parameters, including raster angle, raster width, printing speed, infill ratio, and build orientation as depicted in Figure 2.

In addition to the printing parameters, the characteristics of the starting material, such as mechanical, thermal, electrical, rheological, and optical properties, as well as the crystallinity content, significantly influence the final properties.[74] For polymers with a high glass transition temperature (T_g), such as PC, the inter-diffusion of polymer chains becomes more complicated, negatively impacting the strength of the weld lines; however, tuning the printing parameters or using core-shell filaments with a lower T_g, like HDPE or LDPE shell can help mitigate this issue.[75,76] Crystallinity also has an effect, and polymers with higher crystallinity suffer from shrinkage and warpage, and achieving a high dimensional accuracy is challenging.[77] Crystallinity also plays a role, as polymers with higher crystallinity tend to suffer from shrinkage and warpage; on the other hand, the bonding

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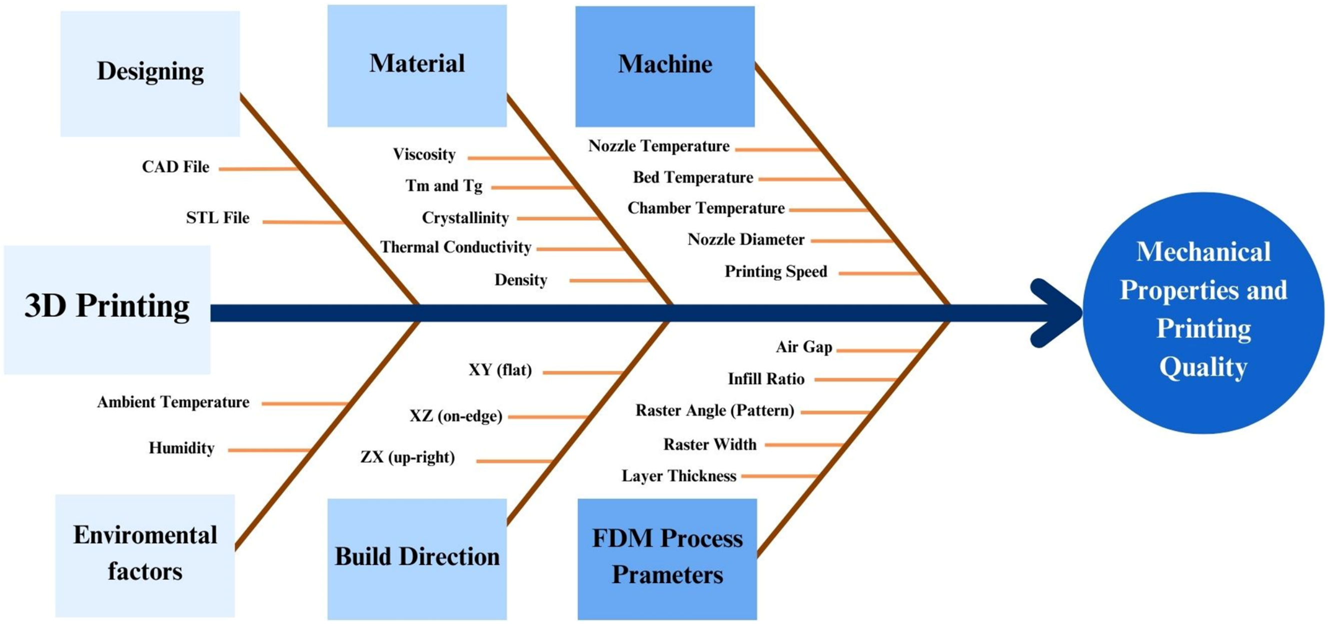

FIGURE 2 Parameters involved during the fused deposition modeling (FDM) printing procedure.

strength of semi-crystalline polymers is more robust due to the formation of cross-crystallites.[78–81]

Figure 3A shows a representation of an FDM 3D printer during the manufacturing process and some related printing parameters. Figure 3B,C schematically depicts the raster angle of printing parts and different build orientations. The mechanical characteristics of FDM samples are strongly affected by the bonding strength of rasters since they have lower mechanical strength than the material itself; this leads to anisotropic behavior. Based on Figure 4, different raster angles lead to a specific failure mechanism. In Figure 4A, the raster angle of 0° is exhibited; it can be seen that in these samples, the failure is primarily through the exfoliation of rasters caused by inadequate bonding strength.

Moreover, raster angles of 45° and 90° are also shown in Figure 4B,C. The highest tensile strength is usually observed in a raster angle of 0°, and the failure of these samples is through the breakage of filaments. Different raster angles are depicted in Figure 4, and generally, the most practiced raster angles are +45/−45 and 0/90, as can be seen in Figure 4D,E. Nonetheless, other raster angles are also used for special needs and purposes. It was observed that samples printed with a raster angle of +45/−45 exhibited the highest stiffness; the yield strength and mechanical behavior of these samples were also more robust. The failure mechanism of samples with raster angles of +45/−45 and 0/90 is depicted in Figure 4D,E. In samples with a raster angle of +45/−45, the failure is justifiable by the breakage of filaments, while both filament exfoliation and breakage are observed at a raster angle of 0/90. In contrast, printing with a raster angle of 0/90 is inferior in terms of stiffness and, in turn, demonstrates a more brittle mechanical behavior.[73,83–85] In samples with a raster angle of 0/90, half of the layers have significantly lower load-bearing capacity, leading to lower mechanical properties and stiffness. Figure 4B,C presents a schematic representation of the raster angles. The results align with previous research on other materials, such as ABS.[86] Furthermore, with increasing raster angle, samples fail more from their strands than their weld lines, as shown in Figure 4.[84] Typical fabricated build orientations include XY, XZ, and YZ, each offering specific advantages and disadvantages. Also, these build orientations are schematically illustrated in Figure 3C. Build orientation is a substantial factor in determining the direction of the applied load relative to the weld lines. The XZ printing direction is attributed to the highest mechanical properties, with XY and YZ being next, YZ exhibiting the poorest behavior of all three build orientations.[73,87] Besides, dynamic mechanical studies proved that with increasing build orientation angle, 0° being the XY orientation and 90° being XZ, on the one hand, the storage modulus of samples tends to decrease; on the other hand, their loss modulus shows an increasing trend.[88,89] Therefore, XY parts have more energy-storing potential, while XZ parts have more energy-dissipation potential.

Impact strength is also strongly related to the raster angle and build orientation of printed samples.[90] Printing with raster angles parallel to the notch deteriorates the toughness of samples, and minimal impact strength will

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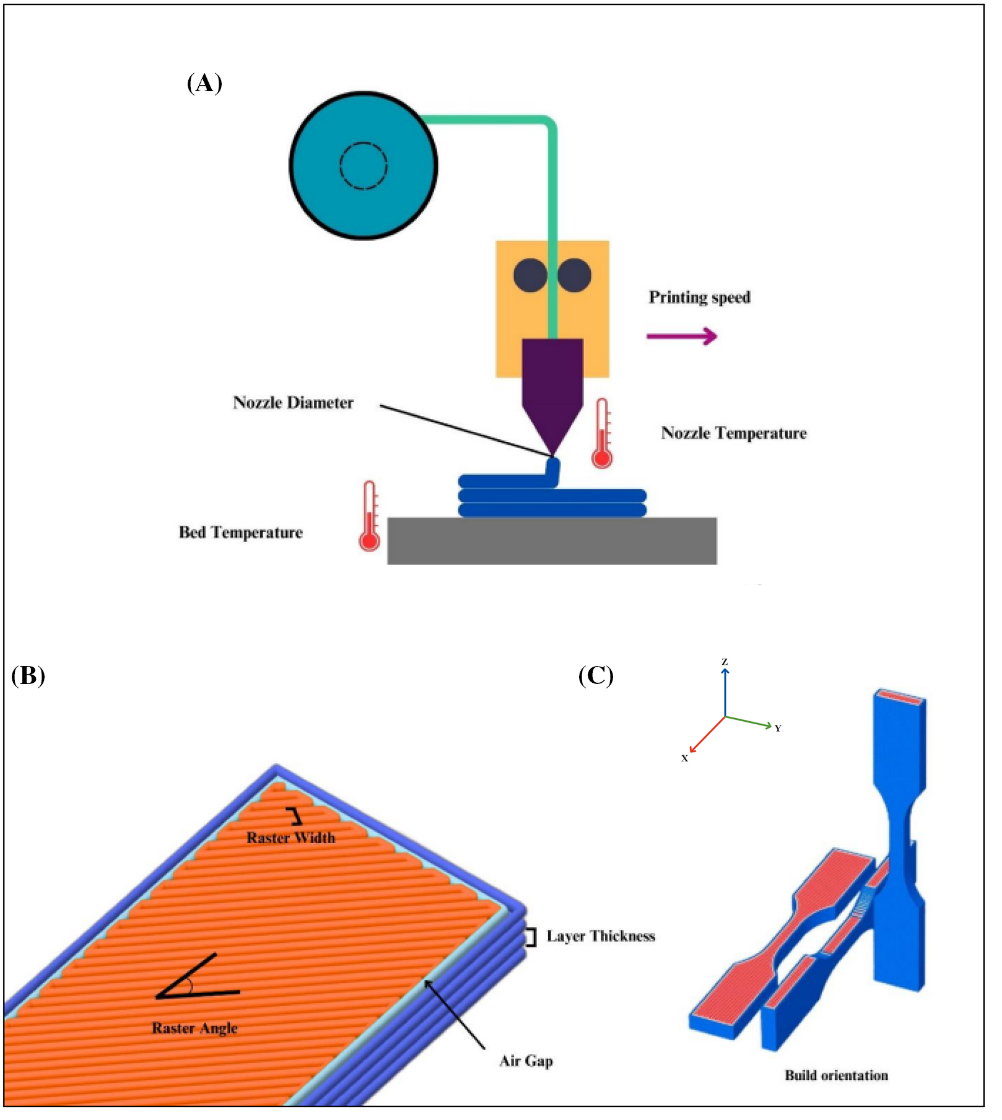

FIGURE 3 Fused deposition modeling (FDM) printing parameters: (A) nozzle diameter, printing speed, nozzle temperature, and bed temperature. (B) Layer thickness, raster angle, air gap, and raster width. (C) Different build directions.

be observed as a result. Printing in XZ orientation also has similar results. In contrast, YZ printing offered the best build orientation due to the superior impact strength of samples printed in this build. In addition, samples printed with a raster angle of +45/−45 had the highest impact resistance because of the high energy-consumption crack propagation procedure, which led to the crack deflection.

Based on previous studies, reducing the layer thickness resulted in improved mechanical properties.[73,89,91] This is mainly due to the fact that more heat flux is transferred to the deposited materials, and therefore, an enhanced bonding between layers will be observed. However, in another attempt,[89] increasing the layer thickness first decreases the mechanical strength and then increases it; this could be as a result of increased cooling time consequent to increased deposited material or, as suggested by Mohamed et al.,[89] as a result of reduced distortion and printing-induced defects. More interestingly, they observed an increase in the storage modulus, loss modulus, and mechanical damping with increasing layer thickness, which is a controversial result compared to previous studies. Their claim, however, is supported by morphology studies; scanning electron microscopy (SEM) micrographs proved more abundant imperfections, delamination, and tearing by reducing the layer thickness.

Negative airgap values improve mechanical strength by reducing defects and porosity,[88,89] while positive airgap reduces mechanical response. However, decreasing airgap beyond a threshold deteriorates printing quality and properties.[89]

Nozzle diameter impacts printed part quality and dimension accuracy. For filaments with solid particle fillers, small nozzle diameters can cause clogging, interrupting printing, and introducing unnecessary expenses.[92]

Generally, as the nozzle temperature increases, samples exhibit an improvement in mechanical strength because of enhanced interlayer diffusion and weld line

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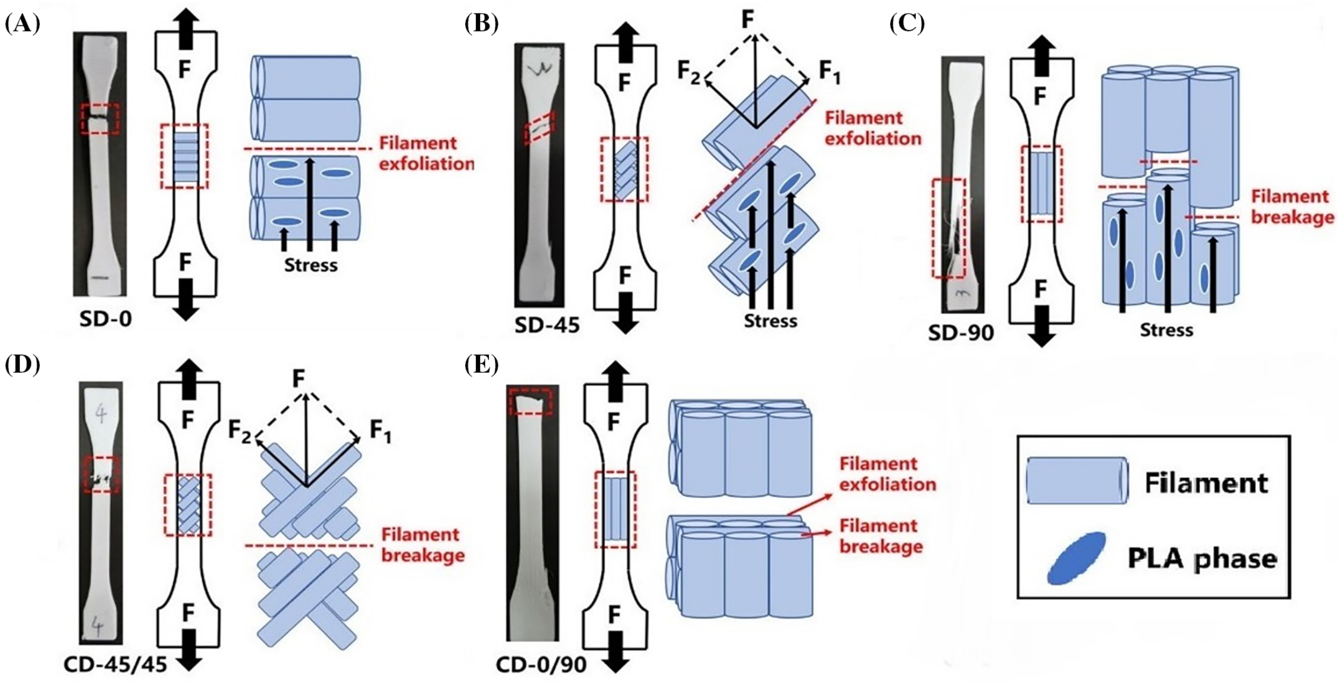

FIGURE 4 Effects of different raster angles on the tensile behavior of polycarbonate (PC) at a (A) 0-degree raster angle, (B) 45-degree raster angle, (C) 90-degree raster angle, (D) +45/−45 raster angle, and (E) 0/90 raster angle.[82]

quality.[89,93,94] However, excessively elevating the nozzle temperature can negatively affect the material's flow properties. Therefore, the trade-off temperature between good layer adhesion and flow properties should be selected. For instance, Vidakis et al.[93] observed that mechanical properties first increase with increasing nozzle temperature and then tend to decrease. The range of 250–300°C is considered suitable for the nozzle temperature in 3D printing of PC, but this range could change because of additives and fillers.[95]

Printing speed impacts part finish and adhesion but adversely affects mechanical properties.[96] Increased speed reduces elastic modulus and tensile strength because of improper melting and filament slippage, leading to defects and misprinting.[91,96–98]

For instance, an increase in the addressed defects for samples with short carbon fibers as reinforcing agents was perceived.[96,97] However, controversial results were observed regarding the mechanical properties of pure PC filaments. While increasing the printing speed increased tensile properties in the literature,[97] another indicated the opposite.[96]

The size and printing path of samples also have noticeable effects on the final properties of printed products. It was observed that mechanical properties tend to decrease just by increasing the size of samples.[78] The observed behavior is mainly attributed to the increased time it requires for the nozzle to deposit new strands adjacent to previous ones, which cools down the material and negatively impacts the diffusion of adjacent layers. Consequently, poor weld lines lead to inferior mechanical behavior compared to samples with smaller sizes. In PC's case, the mentioned problem is more severe due to its relatively high glass transition temperature and amorphous nature.

FDM printers are divided into two subcategories of open and closed chambers, with the ability to control chamber temperature designed to reduce the adverse effects of the temperature gradient during the printing procedure. The effects of open and closed chambers on the appearance of PC samples proved the necessity of printing PC under the controlled environment of closed chambers.[83,96] During the printing sequence, deposited layers start to cool down, and thus, a temperature gradient starts to exist between adjacent layers; subsequently, this promotes warpage and deflection and impairs high-quality and dimensionally accurate printing.[99] It was figured out that just by increasing the chamber temperature from 30 to 90°C, the temperature gradient decreases from 5.4°/mm to nearly half the value of 2.7°/mm. This reduction was effective in producing more flawless and less warped samples, but the mechanical properties of printed samples with a raster angle of 90° also tended to be enhanced due to decreased misaligned beads.[83] However, the mechanical response of traverse samples showed little to no improvement, which shows the inability of

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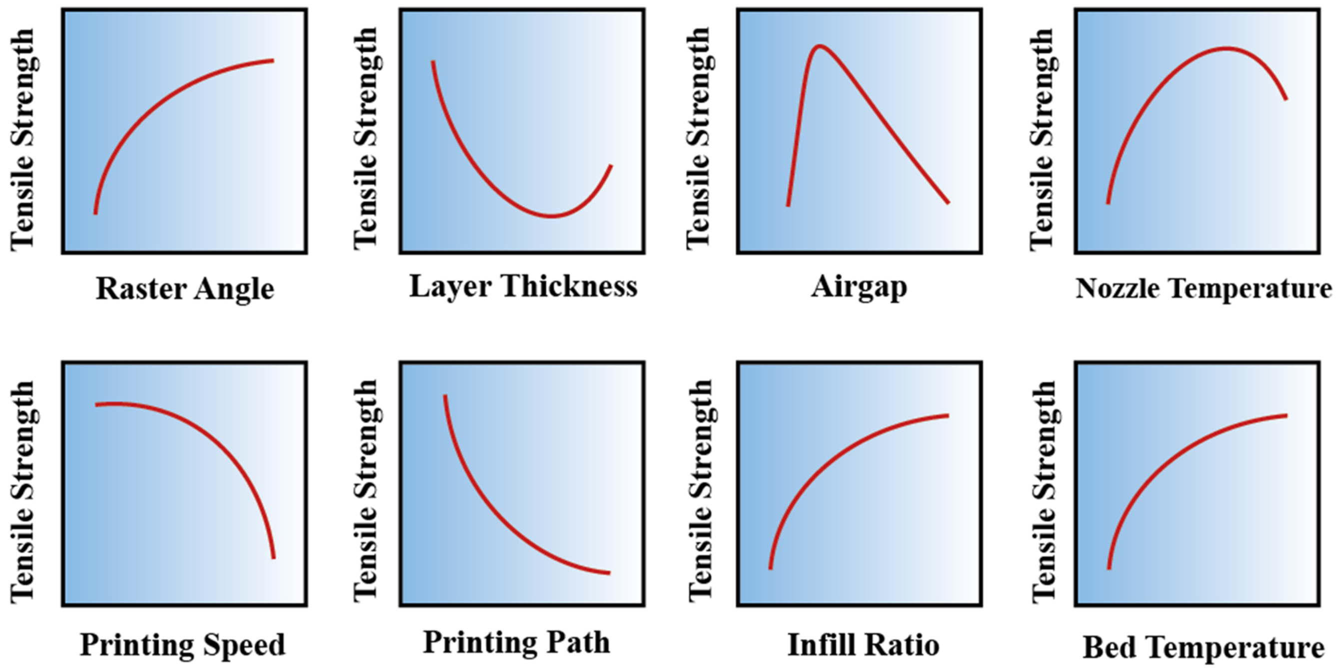

FIGURE 5 Proposed schematic curves representing the influence of chosen factors on the tensile strength of additively manufactured polycarbonate (PC).

chamber temperature to improve the inter-layer adhesion. Moreover, the addition of short carbon fibers (SCFs) complicates the warpage problem amid differences in the coefficient of thermal expansion between additives and matrix. Nevertheless, closing the chamber during printing was figured out to be effective in reducing harmful warpage in both non-reinforced and SCF-reinforced samples.[96]

The effects of ambient humidity on the quality and properties of PC during printing were also studied by Fang et al.[83] PC is a hygroscopic plastic with a high moisture absorption tendency, so it is essential to dry the PC before processing it. Generally, PC filaments are dried at temperatures as high as 120°C for at least 6 h. However, extending the drying time to 24 h is highly recommended; otherwise, PC is prone to void formation and, in severe cases, hydrolysis.[100]

In Figure 5, the influence of the aforementioned printing parameters on the tensile strength of additively manufactured PC is schematically displayed. Also, in Table 1, the typical range for PLA, ABS, and PC printing parameters is tabulated. In general, it can be observed that the temperature requirements for printing PC parts are much higher. For instance, while the nozzle temperature for printing PLA parts is limited to 180–230°C, it is common for PC samples to have nozzle temperatures of up to 300°C. Similarly, higher bed and chamber temperatures should be employed to achieve optimal printing quality.

3 | POLYCARBONATE FORMULATION

Although neat PC parts possess good properties, many endeavors have been carried out to improve different properties, most notably the mechanical aspect of PC filaments. Several additives have been compounded with PC, factoring in ceramic, metallic, and natural nanoparticles; several polymeric blends have also been fabricated using PC as a constituent element. The primary motivation of this practice is the improvement in the processability, mechanical, and thermal properties of printed PC parts.

3.1 | Polycarbonate blends

Research on PC blends is as old as the PC itself, and many other polymers have been blended with PC. However, due to the relative modernity of FDM, the number of studied PC blends is limited to ABS, PLA, and PETG. Except for the PETG,[112] the other two polymers are immiscible with PC, and in the case of melt blending, separate phases will be formed, reducing the mechanical properties. Consequently, introducing a compatibilizer such as a block or grafted polymer in most cases seems necessary.[113–115]

The chemistry mechanisms of compatibilizers in polymer blends involve interfacial activities that can be

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TABLE 1 Comparison of printing parameters between polycarbonate (PC), polylactic acid (PLA), and acrylonitrile butadiene styrene (ABS).

Material	Nozzle temp. (°C)	Chamber temp. (°C)	Bed temp. (°C)	Printing speed (mm/s)	Ref.
PC	230–300	>100	40–145	5–50	[73,78,90,101–104]
ABS	220–270	60	40–110	30–110	[86,105,106]
PLA	180–230	60	25–65	30–90	[90,107–111]

modified by reactive and nonreactive interactions.[116] The main objective of compatibilization is to reduce the interfacial tension between the immiscible polymer components, leading to improved properties in the blend.[117] The specific chemical mechanisms can vary depending on the type of compatibilizer used and the nature of the polymer blend. Reactive processes result in copolymer formation, while nonreactive methods bridge polymer interfaces.[116] As depicted in Figure 6A, diblock copolymers consist of two chemically distinct blocks, while triblock copolymers consist of three blocks, with the middle block different from the outer two blocks.[118] Chain extension increases polymer chain length, and interfacial adsorption reduces interfacial tension.[119,120] The addition of block copolymers as compatibilizers in polymer blends can provide several advantages, including improved mechanical properties, increased toughness, better phase morphology, as can be seen in Figure 6B, and cost-effectiveness, making it suitable for a wide range of applications.[117,118]

Compatibilizers for PC/ABS blends and similar solutions can also be used for PLA. These additives include maleic anhydride-grafted ABS (ABS-g-MAH), Styrene-Isoprene-Styrene (SIS), ethylene-butyl acrylate-glycidyl methacrylate (PTW), ethylene-methyl acrylate copolymer (EMA), and maleic anhydride-grafted styrene-ethylene/butylene–styrene copolymer (SEBS-g-MAH).[82,112,121,122]

The largest body of research has been conducted on PC and ABS blends owing to their popularity and achieved properties. It has been noticed that blending PC with ABS yields higher mechanical properties and enhanced processability compared to a neat PC.[89,123–126] For instance, Kannan et al.[124] reported a significant increase in the tensile properties of 3D-printed PC with the addition of ABS, attributed to the anti-plasticization effect formed by the chain mobility property of PC. Although the exact composition was not reported, the printed sample exhibited a tensile strength of 43 MPa and a tensile modulus of 1800 MPa, which were higher than the tensile properties of both PC and ABS alone, and the tensile strength and elastic modulus were also respectively 16% and 41% higher than those of PC. The rationale behind these enhancements was mainly due to the anti-plasticization effect, which restricted molecular movement and improved tensile strength and elastic modulus. However, considering the inferior tensile properties of printed PC (36 MPa), the role of other parameters, including improved layer adhesion and printability, cannot be undermined. Furthermore, SIS was added to the PC/ABS blend to improve compatibility, and consequently, better impact strength and elongation at break were obtained; nevertheless, tensile strength, elastic modulus, and hardness values decreased. The rheology analysis confirmed the role of SIS in improving the extrudability and printability of the blend.[82] Additionally, Kumar et al.[127] investigated the effects of varying PC loading from 10 to 50 wt% on the tensile strength of the PC/ABS blend. Increasing the PC content from 10 to 30 wt% and then 50 wt% brought about the improvement of tensile strength from 40 to 47.1 and 47.4 MPa, respectively. Similarly, blending PC with PLA improved tensile strength, and in the case of the blend with 50 wt% PLA, the tensile strength was enhanced from 61.1 to 63.7 MPa.[82] Owing to the elastomeric nature of PTW, the phase interface gaps between PC and PLA were filled, leading to improved mechanical properties and reduced warpage. As a result, incorporating 20 wt% PTW into the blend containing 40% PLA enhanced the impact strength by approximately nine times.[82] This shows a significant improvement in the impact strength of PC/PLA blends that lack any other additives since the impact strength was sharply detracted as a result of blending. The morphology of injection molded PC/PLA samples, printed PC/PLA, and printed PC/PLA/PTW are shown in Figure 6C–F. It can be observed that the morphology of the injection molded sample is less directional, which leads to more isotropic behavior. Also, the introduction of PTW resulted in a more uniform distribution of PLA phases throughout the PC.[82] Aside from the mechanical aspect, other properties of PC are also altered by blending. For instance, PC/PLA blends demonstrate improved layer adhesion due to the lower T_g of PLA.[82] In the case of PC and PETG blends, the highest mechanical properties were observed in the sample with 75 PC and 25 wt% PETG.[112] Morphological analysis revealed excessive void formation in the former samples and improved layer packing in the latter, which was the main contributor to the observed behavior.[126] The PC75/PETG25 sample had an impact

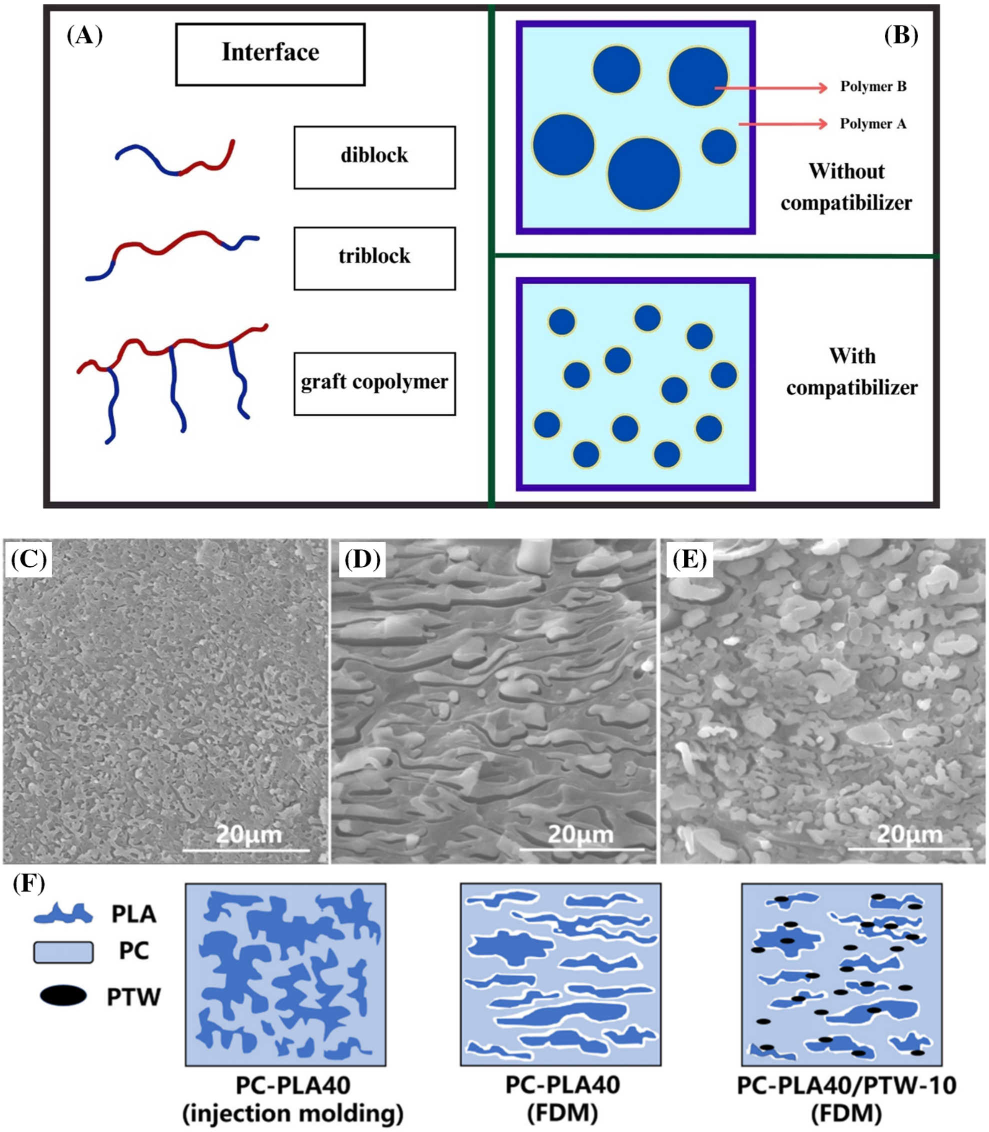

FIGURE 6 (A, B) schematic of mechanisms of compatibilizers and effect of compatibilization on the morphology of polymer blends cryogenically fractured morphology of samples. (C) Injection molding sample based on polycarbonate (PC)-PLA40. (D) Fused deposition modeling (FDM) sample based on PC-PLA40 and (E) PC-PLA40/PTW-10. (F) Schematic of the PLA phase distribution in the PC matrix.[82]

strength of about 4.5 kJ/m^2, higher than other printed samples.[112] Additionally, PETG proved to be highly effective in reducing the warpage of PC samples. For example, with 75% PC, a severe warpage with more than 2 mm deformation was observed. The addition of PC to PETG in variable proportions affects thermomechanical properties, reducing warpage and leading to significant improvements compared to pure PETG. According to the tan δ analysis, a remarkable shift from 90°C in pure PETG to 120°C in a 50/50 PETG/PC blend indicates potential miscibility.[112] Table 2 presents a summary of the mechanical properties of PC blends.

3.2 | Polycarbonate nanocomposites

Incorporating nanoparticles and fibers into PC can potentially modify its mechanical, thermal, and printability characteristics. Typically, nanoparticles are added to enhance these properties. However, it is important to note that in some cases, particles tend to clump together, leading to inferior mechanical properties; this necessitates studying the optimal filler percentage and the use of proper surface modification. Hence, researchers are studying the effects of nanoparticles and fibers on PC, and below is a brief overview of the common defects associated with each filler.

Pure PC usually exhibits brittle failure with localized plastic deformation zones; it elongates 1%–5% before breaking. Figure 7A displays the fracture surface of pure PC. A high-quality specimen should have minimal printing defects like holes and delamination. However, due to the abovementioned challenges in printing PC, it is possible to observe samples with defects, as shown in Figure 7A. Additionally, Figure 7B presents the side surface of a printed pure PC sample, demonstrating acceptable layer fusion without any defects or interruptions in

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TABLE 2 Mechanical properties of polycarbonate blends.

Blend	Measurement type	Yield Stress (MPa)	Strength (MPa)	Modulus (MPa)	Strain (%)	Impact strength (KJ/m^2)	Ref.
PC/ABS	Tensile		51.03				[127]
		19.83		2530	1.12		[128]
			44				[124]
		38.9	44.7	2200	2.78		[129]
		55.52		990	5.97		[130]
			44	1800			[124]
			42.4	1899			[131]
			32.39 (Not annealed)				[132]
			38.99 (Annealed)				[132]
	Flexural		43.19 (Not annealed)				[132]
			66.17 (Annealed)				[132]
PC/PETG 75/25	Tensile		41.2	1990	2.7		[112]
	Flexural		67.1	2230			[112]
PC/PETG 50/50	Tensile		40.3	1900	2.8		[112]
	Flexural		64	2150			[112]
PC/PLA 60/40	Tensile		46				[82]
	Toughness					27	[82]

the printed pattern. When other fillers are introduced to PC, its behavior undergoes slight changes.

In some cases, the incorporation of nanoparticles leads to the formation of agglomerates, which decrease the mechanical properties of PC samples. SEM micrographs in Figure 7C,D depict agglomerates of aluminum nitride (AlN) in PC. The size and distribution of these agglomerates depend on processing steps, nanoparticle type, and filler loading. Generally, as the weight percentage of nanoparticles increases in the matrix, more agglomerates form, thereby reducing the effectiveness of the filler in PC. Moreover, nanoparticles can also alter the flow behavior of PC, resulting in defects in printed samples. Reduced flowability due to nanoparticles often leads to misprinting, particularly at higher filler loadings. These defects are visible on the side surface of printed specimens, as shown in Figure 7E,F.

Furthermore, the formation of voids increases, resulting in samples with reduced quality. Figure 7G illustrates an instance where changes in the flow behavior of PC result in samples with numerous voids. These defects appear to affect the tensile and impact properties of PC primarily.

Ceramic fillers are known for their hardness and reinforcement effect on polymers. They have been extensively studied because of their low coefficient of thermal expansion, thermal conductivity, and electrical resistance, which is attributed to the absence of free electrons.[135] So far, only a few ceramic fillers have been added to 3D-printed PC parts. The effects of Aluminum Nitride (AlN),[133] Titanium Nitride (TiN),[136] Silicon Carbide (SiC),[134] Titanium Carbide (TiC),[137] and nano-silica (NS)[138] have been investigated. Most of these fillers had negligible effects on the thermal properties of PC parts. In addition, except for NS, other ceramic fillers slightly reduced the thermal stability of PC. Aside from that, incorporating these particles proved to be effective in enhancing the mechanical properties of PC. Compared to AlN, TiN is a more effective additive, as it demonstrated a significantly superior interface with PC and, as a result, a more robust filler-matrix interaction; TiN exhibited no signs of agglomeration while also not hampering impact, hardness, and flexural properties, unlike AlN.

TiC has contributed the greatest improvement in tensile properties among all reviewed ceramic additives; it was figured out that TiC induces polar-polar interactions with the PC matrix, simultaneously boosting the material's tensile strength and elongation at break.[137] SiC and NS were not as effective as other fillers. More specifically, as vividly depicted in Figure 7G, SiC acted somewhat as a foam-making agent, bringing about abundant voids within the PC-based printed parts, leading to the

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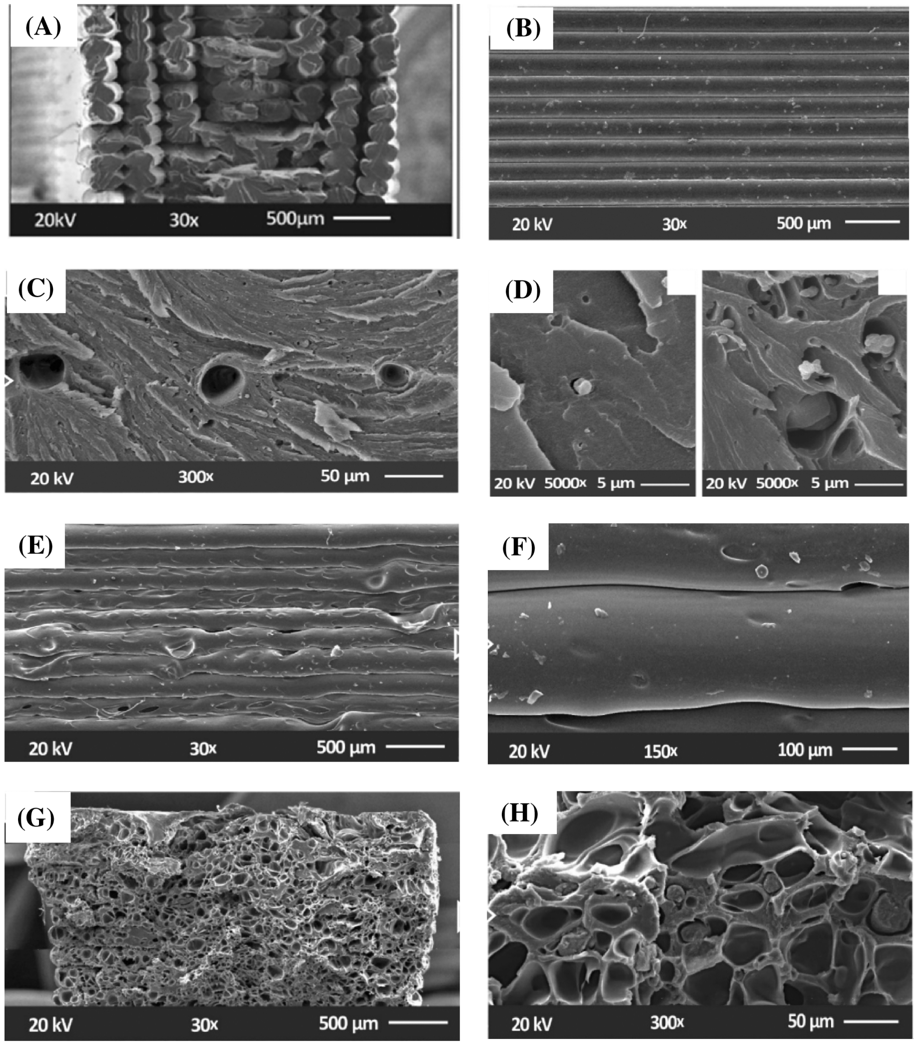

FIGURE 7 (A) Fracture surface and (B) side surface view of neat polycarbonate (PC) tensile sample. (C) Fracture surface of AlN/PC sample with agglomerates. (D) 5k× magnification view of AlN agglomerates.[133] Side surface view of SiC/PC samples at (E) 30× and (F) 150× magnification. scanning electron microscopy micrographs of the fracture surface of the prepared PC/SiC nanocomposites at (G) 30× and (H) 300× magnification.[134]

deterioration of mechanical properties. The performance of NS particles was much worse; this is the side effect of the poor layer adhesion, attributed to the addition of NS.[134] Similar results with bentonite were also observed. The incorporation of this ceramic filler, despite good dispersion and lack of evident agglomeration, decreased the tensile strength of 3D-printed PC. Therefore, the observed reduction is attributed to the reduction in layer adhesion.[139]

Interestingly, a somewhat different trend in the flexural properties was observed. While SiC particles performed lower than average in the tensile properties, they contributed the highest enhancement for the flexural and impact properties. TiN and TiC performed relatively closely. Their nanocomposites exhibited a marginally lower flexural strength than SiC-incorporated parts; however, the flexural modulus enhancement was negligible. Additionally, AlN particles deteriorated the flexural properties of PC, and the highest observed improvement in the impact strength corresponded to the sample with 2 wt% filler loading with only a 3.8% increase. By taking the morphology analysis into perspective, in all fillers, cases of particle agglomeration were detected. Though the exact number of agglomerates varied from filler to filler. Also, increasing the weight percentage led to more abundant agglomerates in general. The relatively low performance of AlN nanoparticles was mainly addressed by poor filler-matrix interaction that not only led to agglomeration but also resulted in an adequate filler network unable to form either; this was also the case for NS particles, in which, as previously outlined, poor layer-layer interfaces were perceived, which necessitate the presence of a compatibilizer not only in this case but also in other similar cases suffering from the mentioned issue.[133,134,136–138] The only upside in incorporating NS was improvements in printability and shear thinning behavior, which enhances the processability of PC.[139]

Aside from the addressed ceramic additives, Tungsten powder was added to PC, resulting in alterations in the material's mechanical, thermal, rheological, and electromagnetic properties.[140] Adding tungsten improved the impact resistance of PC, with the impact strength increasing from 32 J/m in the neat PC sample to 45 J/m in the sample with 5 wt% tungsten inclusion. Morphology

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analysis showed that introducing tungsten particles did not harm the PC, as crack initiation occurred on layer interfaces rather than on tungsten particles. Rheology analysis indicated increased viscosity in the PC matrix. The main focus of this study was to improve the radiation shielding capabilities of PC, which are discussed in detail in Section 4.

Cellulose Nanofiber (CNF), a natural wood-based filler, was also investigated for its effects on printed PC.[141] It is considered an environmentally friendly option for enhancing the mechanical properties of plastics. The addition of 0.5 wt% filler loading resulted in about a 10% enhancement in tensile strength from 62 to 70 MPa, but a higher filler loading of 1 wt% decreased the tensile strength to 54 MPa. Similar trends were observed for flexural strength, initially increasing from 91.2 to 94.2 MPa before dropping to 68.6 MPa. Remarkably, the impact strength improved in the sample with 0.5 wt% CNF, reaching 18.2 kJ/m^2 compared to 16 kJ/m^2. Morphology analysis revealed discontinuities in the sample with 1 wt % CNF, indicating signs of filler agglomerations and nozzle clogging (discussed in Section 2). Additionally, due to the unstable nature of CNF at elevated temperatures, the thermal stability of PC was also adversely affected. However, it is noteworthy that the degradation rate was decreased, possibly due to the relatively high degradation energy requirements of CNF.

Carbon fillers comprise carbon atoms in the bulk of their structures and have recently been extensively used for their unique electrical, thermal, and mechanical properties. Herein, the effects of different carbon fillers, including carbon fibers,[142–145] carbon nanotubes (CNTs),[61] and graphene (G)[128,146] in the PC, are discussed. CNTs demonstrated a superior reinforcing performance compared to short carbon fibers (SCFs). Nonetheless, the literature survey on carbonic fillers suggests they were not among the most effective reinforcing agents for printed PC-matrix composites. Continuous fibers, unlike short fibers, can transfer and retain loads within their unbroken strands, thereby reducing the load applied to the polymer. This ability, combined with their orientation, results in composites made with continuous carbon fiber (CCF) exhibiting higher strength levels.[147] In general, 3D-printed CCF PC composites showed significant improvements in tensile strength, modulus, and stiffness-to-weight ratio.[148] The most significant increase in the elastic modulus corresponded to the CCF bundles inserted inside the PC samples during the printing sequence, and an elastic modulus exceeding 3 GPa was observed. Similar results for flexural strength were also observed with the use of CCF, with bending strength increasing to almost 600 MPa. This is nearly six times the original flexural strength of 3D-printed PC. Another study achieved tensile strength of around 1300 MPa.[149] These findings highlight the immense potential of CCF as a reinforcement material for high-performance applications.[148]

On the one hand, SCF increases thermal stability. The increased degradation temperature is a result of the hindrance of polymer chains. The degradation temperature significantly decreased at higher carbon content compared to pure PC because of heightened porosity and fiber accumulation in specific areas, illustrated in Figure 8A–C. Figure 8D shows the strengthening mechanism of crack pinning around two fibers. However, the ground for the fall in tensile strength remained inconclusive. According to the literature, G also proved effective in the thermal stability of PC, which was mainly attributed to increased heat dissipation rates. SCFs were also effective in this regard, and adding 5 wt% of this material enhanced the thermal stability of the PC. Based on Figure 8E–H, the embedded CF occupied the print surface without any gaps, thus reducing porosity and consequently enhancing strength.[142,144,150]

The box charts in Figure 9 provide a comprehensive overview of tensile, impact, and flexural properties associated with each filler added to the PC matrix. Regarding Figure 9A, it is evident that ceramic fillers notably enhance the tensile strength of printed PC parts. Interestingly, carbonic fillers display a wide range of tensile strength, while natural fillers exhibit slightly higher tensile strength than polymeric blends. However, there is a noted discrepancy in the expected improvement of tensile modulus by ceramic fillers due to calculation errors and unreliable data, as depicted in Figure 9A. Regarding impact properties, carbonic fillers were found to give higher impact strength compared to ceramic fillers (Figure 9B). Still, more data must be collected from different fillers and polymeric blends for better comparison. Figure 9C highlights that ceramic fillers generally yield the highest mean flexural strength, followed by natural fillers and polymeric blends. Additionally, the flexural modulus of polymers varies widely, making direct comparisons challenging due to various influencing factors, such as compatibilization.

Various mechanical characteristics have also been observed in other thermoplastic-based 3D-printed composites. For instance, incorporating carbonic fillers, including carbon fiber, graphene, and CNT, into ABS and PLA can result in a wide range of mechanical properties.[151–153] Specifically, both decreases and increases in tensile strength, tensile modulus of elasticity, flexural strength, and flexural modulus of elasticity compared to the neat ABS have been reported with increasing graphene concentration.[153,154] The incorporation of ceramic and natural fillers has improved the tensile and flexural properties of 3D-printed composites in a similar way.[155–157] However, it was demonstrated that at higher filler concentrations, polymer

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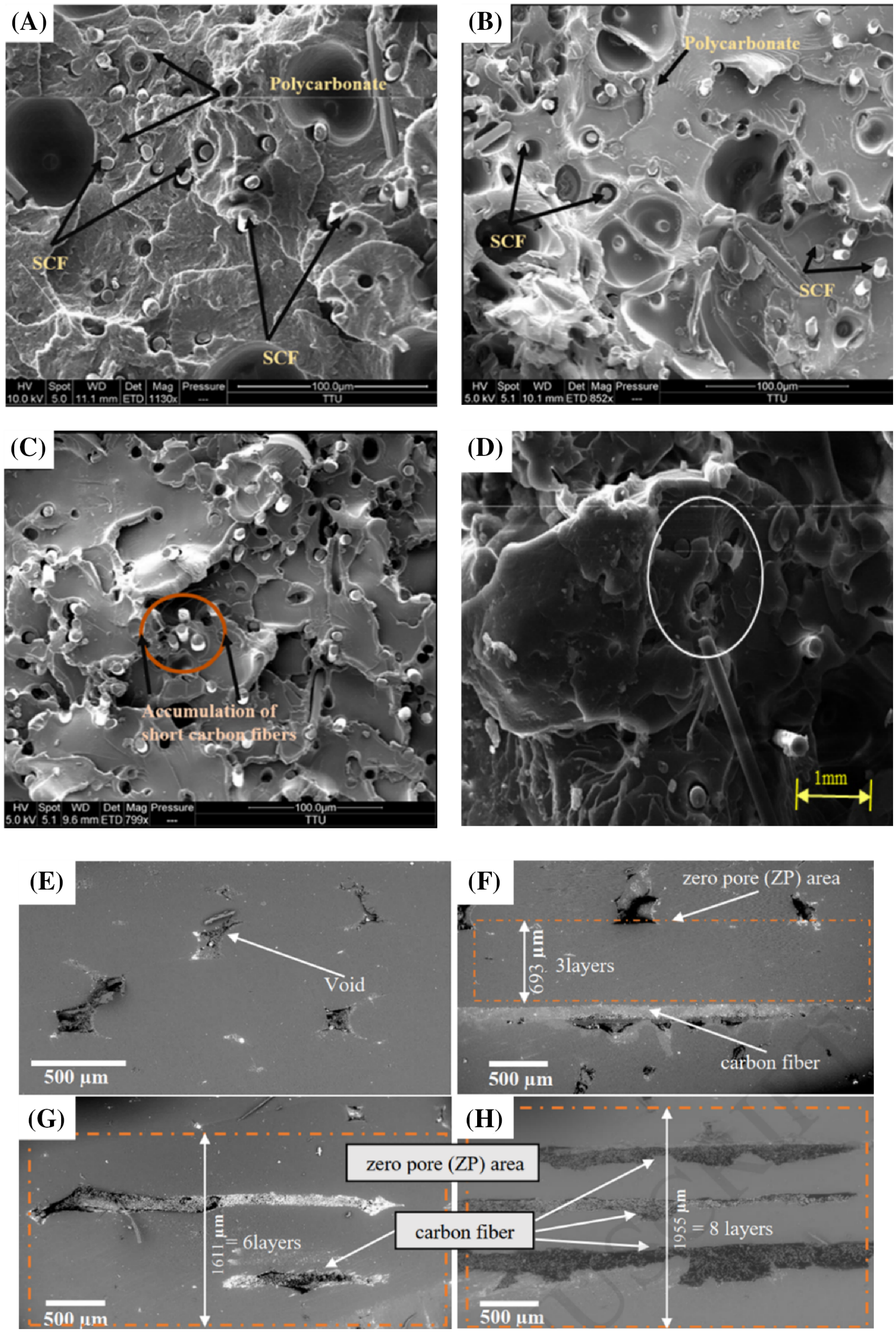

FIGURE 8 Scanning electron microscopy (SEM) images of (A) 97% PC/3% SCF, (B) 95% PC/5% SCF, and (C) 90% PC/10% SCF.[142] (D) Crack Pinning strengthening mechanism in PC/SCF filaments.[150] SEM images of (E) unfilled PC, (F) PC reinforced with a single bundle of CCF, (G) PC reinforced with two bundles of CCF, and (H) PC reinforced with three bundles of CCF.[144]

chains become immobilized. This immobilization results in significant stress concentrations at agglomeration points, which in turn induce fracture points and subsequently reduce the composite's mechanical properties. In terms of tensile strength, 3D-printed PC composites can achieve up to 80 MPa. Although this is lower than PA and PEEK, which range from 50 MPa to 90 MPa and 70 MPa to 100 MPa respectively, PC composites have a higher tensile strength than PLA and ABS. Regarding elastic modulus, PC surpasses ABS and PA, but falls behind PEEK and PLA. PC also has better processability compared to PA and PEEK, considering the temperature requirements for printing these polymers. However, printing PLA or ABS is much easier than PC. Due to its amorphous nature, PC is less prone to shrinkage and exhibits better dimensional stability than PA or PEEK, and is comparable to ABS. Semi-crystalline polymers like PA or PEEK, with high crystallinity content, often face challenges in achieving good layer bonding, resulting in poor mechanical performance from inadequate printing practices. On the other hand, despite requiring higher printing temperatures than ABS or PLA, PC is less likely to encounter these issues.[158–160]

The flowability of other 3D printed thermoplastic composites is also influenced by blending and creating composite filaments. Typically, increasing filler content

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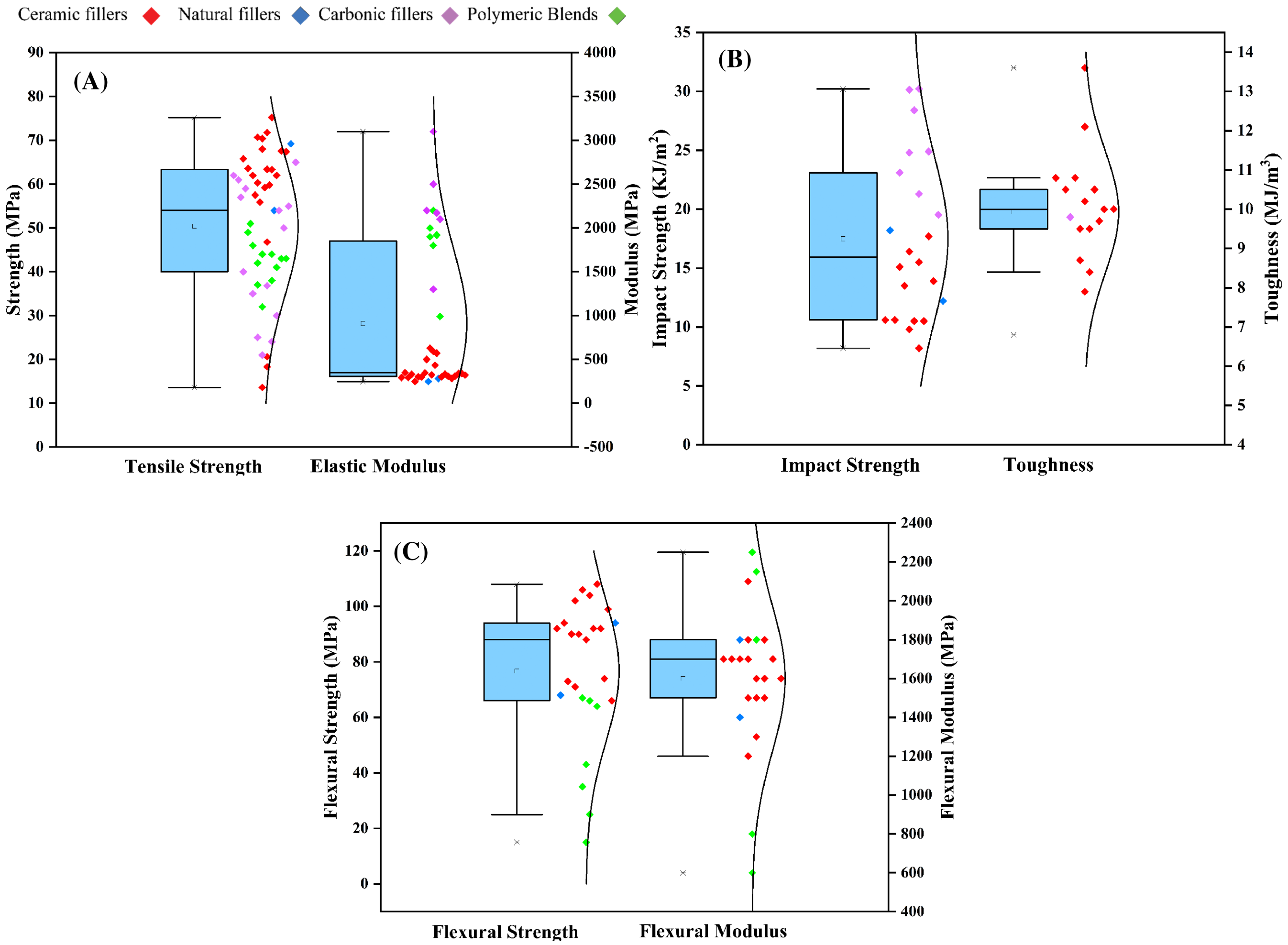

FIGURE 9 Box diagram reporting ranges for mechanical properties of printed polycarbonate: Box diagrams for (A) tensile strength and tensile modulus, (B) impact strength and toughness, and (C) flexural strength and flexural modulus.

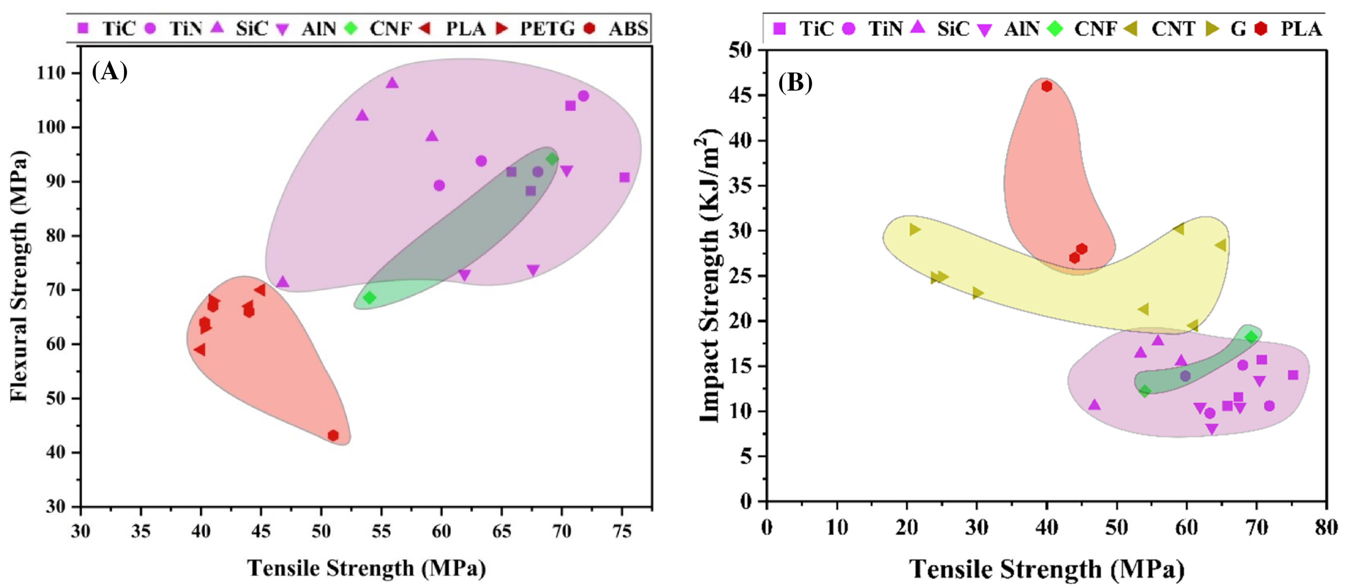

FIGURE 10 Box diagram of (A) tensile strength and (B) impact strength of polycarbonate (PC) materials per their formulations.

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reduces flowability and increases viscosity, likely due to the restricted mobility of polymeric chains caused by solid fillers.[157,161,162] However, for thermoplastics with a low mold flow index like ABS, blending with an elastomer can enhance its elastic behavior and simultaneously improve printability.[1]

For wrapping-up purposes, the Ashby charts provided in Figure 10 are appropriate materials. The optimal loading of ceramic fillers, primarily composed of nitride and carbide fillers in PC additive manufacturing, induced a brittle flexural behavior in printed PC parts, resulting in significantly high flexural strength due to their relatively non-deformable nature. This behavior led to expected superior flexural strength values in the printed parts filled with ceramic fillers compared to those containing other additives. However, this behavior also had repercussions on impact resistance (toughness). The noticeable brittle behavior of composite parts containing ceramic fillers, coupled with their sensitivity to filler agglomeration (more pronounced without a proper compatibilizer), adversely affected their impact strength.[163–167]

In contrast, the toughening effect (impact-modifying) of ABS within the PC matrix, attributed to its dual-phase structure, significantly reduces the impact of external forces by dissipating their energy. Consequently, the miscible printed PC/PLA models avoided catastrophic rupture.[168] As a result of this comprehensive investigation, the PC/PLA blends showcased exceptional impact performance compared to all printed PC-matrix composites.

4 | APPLICATIONS

The desired properties of PC make it suitable for a variety of applications, such as safety goggles, greenhouses, bulletproof glass, and automobile headlights.[169] Additive manufacturing techniques are widely employed in applications that necessitate the rapid production of highly customized parts because of their unmatched flexibility compared to traditional methods.[170]

4.1 | Aerospace and energy applications

The aerospace sector is making increasing use of additive manufacturing. For instance, approximately 70% of NASA's Mars Rover thermoplastics used were fabricated by FDM.[171–173] Among the thermoplastics, PC is an attractive choice due to its excellent mechanical and thermal strength, making it a suitable choice for wind tunnel models requiring smooth surfaces, low drag, and robust properties to withstand high-velocity airflow.[170]

3D-printed PC models are a viable alternative to traditional metallic wind tunnel models, providing superior dimensional stability and performance when coated with chromium.[174,175] Declining space cargo costs have driven a rise in small CubeSats, which require radiation shielding as well as electromagnetic and thermal properties. PC and ULTEM 9085 are suitable materials, with Tungsten-doped PC improving X-ray shielding.[176] PC-based filaments with carbon nanotubes exhibit piezoelectric properties, enabling real-time monitoring of wing part deformation. PC has also reduced production time and costs for aircraft wiring conduits compared to cast aluminum using LFAM techniques.[177]

3D-printed PC models using LFAM have also been employed to fabricate wind turbine blades for the energy sector. In 2014, researchers printed a blade measuring 1.7 by 0.2 meters, enabling the study of minute changes in wind.[68]

4.2 | Medical applications

PC's widespread medical usage has been limited due to health issues associated with Bisphenol-A exposure, such as diabetes, miscarriage, and thyroid problems[178–185]; Bisphenol-A-free polycarbonates (BFPs) have been developed through thermal and photopolymerization methods to address the mentioned issue.[186] BFPs demonstrate good thermal stability and are suitable for autoclaving surgical instruments. The microscale continuous-optical printing (μCOP) system shows promise for BFP use in flexible biosensors and actuators.[187] Additionally, considering the biocompatibility, high optical transparency, and flexibility of BFP, it claims to have a bright future in biomedical applications such as microfluidic devices, cell growth and proliferation, and organ-on-a-chip.

In an experimental study conducted by Dong et al.[188] on printing lower limb prosthetic sockets using PC compared to PLA and PA, PC possessed superior key properties such as better tensile strength (46.06 MPa), Flexural strength (80.38 MPa), and elastic modulus (2033.01 MPa) compared to PA and PLA; however, PC's substantially low elongation at break is a drawback as a primary material for lower limb prosthetic sockets.[144]

Additively manufactured models give the edge to be highly customized depending on specific demands; in light of that, Tichy et al.[189] investigated the possibility of utilizing PC to fabricate dental crowns and the release of BPA. In another study, FDM technology was exploited to fabricate vertebral models, as depicted in Figure 11A.[190] These highly educational models give medical students hands-on feelings regarding different body parts. PC models were also acceptable compared to ABS as the most performed material. Although some should be carefully fabricated, they can be used as the starting material for these applications. Thus, the results of this study paved the way for producing cost-effective and highly accurate vertebral models.

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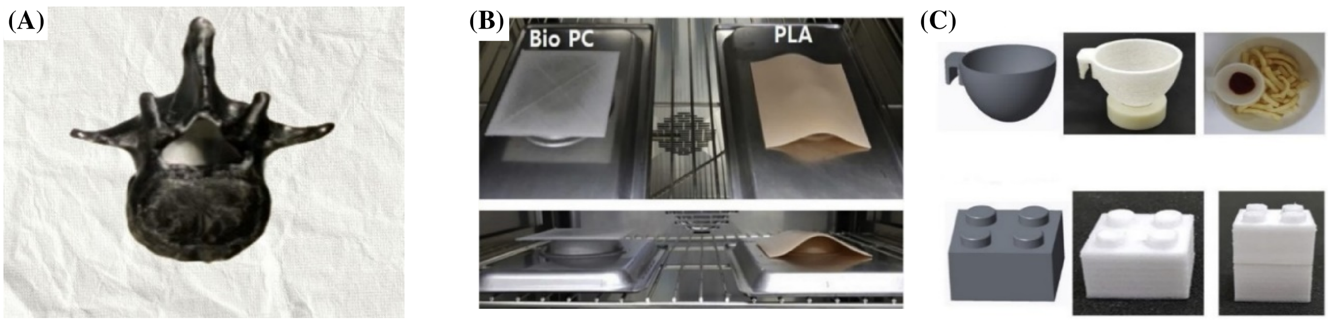

FIGURE 11 (A) Polycarbonate (PC) vertebral model for educational purposes,[190] (B) bio-based polycarbonate during UV aging tests, and (C) household applications of bio-based polycarbonate.[191]

4.3 | Electrical, optical, and functional applications

PC possesses a significant foothold in electrical and optical applications since there are few plastics with the optical transparency and reflective index of PC. For instance, G. Zubel et al.[192] fabricated solid-core Plastic Optical Fiber (POF) and Bragg gratings drawn from an additively manufactured PC preform. A previously studied and tested method called drill and draw was used to make POFs, and PC offered unprecedented advantages over other commonly used POFs. More specifically, besides its optical properties, PC possesses a relatively high T_g of around 140–150°C among plastics, which gives a high operational temperature of around 125°C. For instance, the highest operational temperatures of other commonly used plastics for POFs, Topas 5013S-04, Zeonex 480R, and PMMA, are 110, 100, and 92°C, respectively. The entrapment of air bubbles inside the printed part, thus hampering the transparency, was the main impediment to this study. The team tackled this issue by optimizing the printing parameters and then post-processing fabricated sections at 130°C for 4 weeks to further remove the air bubbles between thread lines and improve layer bonding. It can be claimed that there is considerable potential in fabricating fiber optics using FDM, as the printed fibers showed no signs of undesirable characteristics.

Aside from optical properties, PC also has an acceptable dielectric constant, and traditionally, many parts like electrical housings and switches are made of PC and blended with ABS. However, higher dielectric constants required for electromagnetic applications can be achieved by adding metal oxide fillers like TiO_2 modified with silane for improved dispersion.[193] Incorporating Fe_3O_4 can embed ferromagnetic properties for electric motor housings. For insulating PC parts, injection molding is the preferred method of fabrication. Additively manufactured parts face challenges like surface roughness because of their layered nature. Notably, surface and bulk inhomogeneities lead to excessive electric buildup, causing premature electric breakdowns and failures.[194]

4.4 | Other applications

PC applications are not limited to those mentioned above. PC possesses superior properties, making it an excellent replacement for parts traditionally made of PLA. Reich et al.[195] fabricated molds for low melting point thermoplastics injection using recycled PC as starting material to build various molds as a more sustainable solution for discarded polycarbonates. This work helps fabricate hard-to-print or abrasive composites that may otherwise damage the production apparatus. In addition, they managed to utilize this method to fabricate and replace damaged household parts. For example, they successfully printed the head of a floor steamer that cost around 20 times less while offering similar functionality to the user. Another proposed application is a blade of a custom-made ice scraper for clearing frozen outdoor parts like car windows.

In recent studies in line with sustainable development and eco-friendly plastics, Je Park et al.[191] used bio-based ISB-PC to 3D print household parts. The main incentive of this research was to introduce a more sustainable and robust solution for parts typically printed using PLA. As can be seen in Figure 11B bio-based PC has superior UV resistance compared to PLA. Although PLA parts will deflect and deform at temperatures higher than 70°C, bio-based PC parts can retain their shape at temperatures as high as 114°C. Hence, PC parts can be easily sterilized at elevated temperatures. Besides, taking the low thermal stability of PLA into perspective, PLA parts will have a relatively low limited life cycle, which is not the case for PC parts. Printed parts can be used for various household applications, such as cookie cutters, spoon holders, sauce bowls, dog bowls, toy blocks, and cell phone holders, as shown in Figure 11C; however, their applications are not necessarily limited to these examples.

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5 | CONCLUSION AND PROSPECTS

PC has excellent potential in FDM 3D printing. Throughout this investigation, it was observed that by carefully selecting the printing parameters and the usage of additives, a wide range of properties and applications can be obtained. However, there are some challenges that should be resolved. Achieving good bonding strength in PC parts is challenging, and probable solutions include lowering the T_g using plasticizers or blending, using core-shell filaments that have a shell with a lower T_g, and post-processing treatments. The main challenges in LFAM are shrinkage and dimensional stability. However, advancements in material grades are addressing these issues. For example, in 2017, Sabic introduced special PC grades under the brand name Thermocomp, which offer high dimensional stability.[68,196]

Polymeric blends and nanoparticle inclusions can modify the physical, mechanical, and chemical properties of 3D-printed PC. Still, the number of studied systems is somewhat limited compared to polymers such as PLA or ABS, which leaves an excellent margin for future research. Additionally, the effects of surface treatments and compatibilizers should be investigated.

Warpage is another problem associated with printing PC samples. It negatively affects parts both mechanically and aesthetically and should be minimized. Unlike semi-crystalline polymers, this warpage comes primarily due to high thermal stresses caused by the temperature gradient between consequent layers.[165,166] Like bonding strength, lowering the glass transition temperature could benefit PC by reducing the warpage. Increasing the heat transfer between adjacent layers is a solution practiced in other plastics like ABS and PP, which suffer from a similar problem. In addition, annealing above the glass transition temperature for short periods leads to reduced warpage. In addition, for future work, developing computational models with the ability to predict and optimize the mechanical properties of 3D printed parts based on printing parameters might be a good idea.

Advancements in soft robotics and electronic devices within the manufacturing industry may face obstacles due to challenges in traditional single-material additive manufacturing, such as balancing shape flexibility and structural strength. To overcome these challenges, next-generation machines could be developed as multi-3D systems, which involve using a combination of technologies to create 3D, multi-material, multifunctional devices. These systems could, for example, print PC alongside other thermoplastics like shape memory polymers. This approach will enable the on-demand production of smart devices with adjustable stiffness and integrated components, offering significant advantages to the automation industry.[197–199]

In recent years, the excessive use of plastics and other synthetic materials, which are notoriously difficult to dispose of, has raised significant ecological concerns. This growing awareness has shifted global attention towards adopting sustainable materials and embracing a circular economy (CE) model, emphasizing recycling and resource efficiency.[200] Utilizing recycled thermoplastics is an effective way to tackle sustainability challenges.[201] However, one of the predominant challenges regarding the use of PC is recyclability. PC is non-biodegradable, and its wastes pollute the environment for decades. Little research has been conducted on using recycled PC as the starting material for 3D printing. Doing so offers several advantages, including mitigating the negative impacts of PC waste on the environment, providing a cheap starting material for engineering applications, and having better printability than a previously unutilized PC due to its rheological properties. However, recycled materials are more brittle, have lower tensile properties, and are aesthetically less appealing. Incorporating waste fillers and fibers into the recycled PC matrix can significantly improve the composite material's mechanical properties and address circular economy concerns, along with expanding its suitability for a range of applications.[201,202]

Researchers and industry professionals should continue exploring and optimizing PC exploitation, considering the impact of printing parameters, additional materials, and fillers on the final properties of the manufactured parts. This comprehensive understanding will contribute to further enhancing the capabilities and applications of additively manufactured PC parts, opening up new opportunities for innovation in the field.

AUTHOR CONTRIBUTIONS

Nima Rashidi Mehrabadi: conceptualization, writing – original draft, writing – review & editing. **Gholamreza Pircheraghi:** conceptualization, supervision, writing – review & editing. **Ali Ghasemkhani:** conceptualization, writing – original draft, writing – review & editing. **Parsa Hosseinpour Sanati:** writing – original draft, writing – review & editing. **Alireza Shahidizadeh:** writing – original draft, writing – review & editing. **Alireza Kaviani:** conceptualization, writing – original draft, writing – review & editing. **Suprakas Sinha Ray**: writing – review & editing.

CONFLICT OF INTEREST STATEMENT

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

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DATA AVAILABILITY STATEMENT

No data were used for the research described in the article.

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