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Sustainable additive manufacturing of polymers and composites: optimization of nozzle design, printing parameters, and post processing for waste to value transformation

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Additive manufacturing using fused deposition modelling (FDM) has emerged as a versatile and resource-efficient route for producing complex polymer and composite structures. However, the quality and sustainability of FDM-printed components are strongly governed by process parameters, nozzle design, and post-processing methods. This review provides a systematic analysis of these factors and their combined influence on mechanical integrity, surface finish, and dimensional accuracy. The study highlights how optimized layer thickness, build orientation, and extrusion temperature enhance interlayer adhesion and structural performance, while advanced nozzle geometries improve melt flow and minimize material waste. Post-processing techniques such as annealing, chemical smoothing, and surface finishing are evaluated for their roles in extending product life cycles and enabling recycled or bio-based polymer feedstocks. By linking process optimization to energy efficiency and material utilization, this review positions FDM as a pathway for sustainable, waste-to-value additive manufacturing. The insights presented support the development of eco-efficient design frameworks for next-generation polymer and composite processing within circular engineering systems.

KEYWORDS
additive manufacturing, filament deposition, nozzle design, print quality, sustainability, waste-to-value

1 Introduction

Additive manufacturing (AM) has transformed the landscape of modern fabrication by enabling on demand, resource efficient production of complex geometries with minimal tooling (Algarni and Ghazali, 2021). Among the various AM techniques, fused deposition modeling (FDM) stands out due to its simplicity, cost effectiveness, and ability to process a wide range of thermoplastic polymers and composites (Srinivasan et al., 2019). FDM builds components layer by layer through controlled extrusion of molten polymer, offering flexibility for both prototyping and functional manufacturing. However, achieving high-quality, repeatable, and sustainable outcomes remains a major challenge due to the strong dependence of mechanical and surface characteristics on process parameters, nozzle configuration, and post-processing techniques (Algarni and Ghazali, 2021).

Optimization of FDM parameters such as layer thickness, build orientation, infill density, and extrusion temperature has been extensively investigated to enhance bonding strength and dimensional accuracy (Srinivasan et al., 2019). In parallel, nozzle design modifications such as variations in geometry, material, and multi-nozzle systems have shown substantial influence on melt flow behavior, filament uniformity, and interfacial adhesion (KAM et al., 2020). Furthermore, post-processing strategies such as thermal annealing, chemical smoothing, and surface finishing play crucial roles in improving structural integrity, reducing defects, and refining surface quality (Ahmad et al., 2022).

While the mechanical and microstructural aspects of FDM are well-documented, their sustainability implications are increasingly drawing attention. Process optimization not only improves part performance but also reduces material wastage and energy consumption, positioning FDM as a promising tool for waste valorization and circular manufacturing (Megersa et al., 2024). Recent advances in recycled and bio-based polymer feedstocks, combined with low-energy post-processing methods, demonstrate the potential of FDM to transform polymer waste streams into functional, high-value components (Delić et al., 2024; Chakraborty et al., 2025).

Recent studies have examined the role of boron compounds and fibre-interfacial modification strategies in improving the performance of PLA-based biocomposites. Avci et al. (2024) reported that various boron additives, including zinc borate, borax-boric acid mixtures, and ulexite, alter the thermal behaviour, microstructure, and mechanical stability of PLA by acting as nucleating agents and modifying the degradation characteristics of the polymer. In another work on boron-compound-reinforced PLA/flax composites, long-term immersion (750 h) resulted in increased stiffness, where the soaked Young's modulus and flexural modulus were approximately 1.5× and 1.7× higher, respectively, than those of the untreated PLA/flax composite, indicating improved retention of mechanical properties under wet conditions (Avci et al., 2023).

Surface modification of flax fibres has also shown a significant effect on the durability and interface quality of PLA composites. Alkali treatment combined with maleic-anhydride-based coupling agents improved impact behaviour, flexural properties, and resistance to interfacial degradation during water exposure due to enhanced fibre-matrix adhesion and reduced void content (Avci et al., 2020). In PLA/TPU blend systems, compatibilization and internal lubrication have been shown to modify the mechanical and thermo-mechanical response. Avci et al. demonstrated that the addition of maleic anhydride and an internal lubricant produced a compound with tensile and flexural elongation at break roughly an order of magnitude greater than neat PLA, although tensile and flexural strength decreased by approximately 40% (Avci et al., 2022). Despite this reduction, the enhanced ductility and acceptable thermal stability suggest that compatibilized PLA/TPU systems are suitable for applications requiring increased toughness. These findings indicate that boron additives, fibre-surface treatments, and compatibilized PLA/TPU systems provide quantifiable improvements in stiffness, toughness, and moisture resistance in sustainable PLA-based composites.

Although several reviews have examined how process parameters influence the mechanical performance of FDM-printed polymers and composites, most existing works focus on isolated parameter effects or specific material systems. The present review differs by providing an integrated perspective that combines process parameter interactions, post-processing strategies, and nozzle design considerations, supported by discussion on flow behaviour and thermal-mechanical degradation phenomena occurring within the nozzle. Additionally, this work incorporates sustainability-oriented trends such as recycled polymer usage, environmentally responsible processing strategies, and material circularity, which are seldom addressed together in earlier reviews. This consolidated perspective provides a more comprehensive understanding of FDM from both performance and sustainability viewpoints, thereby differentiating the present review from prior literature.

In this review, we provide a comprehensive synthesis of the interconnected effects of printing parameters, nozzle design, and post-processing on the quality and sustainability of FDM-fabricated polymers and composites. Emphasis is placed on strategies that minimize environmental impact and enable waste to value transformation through efficient material utilization and energy conscious process design. The insights presented aims to guide sustainable additive manufacturing practices and support future innovations in eco efficient polymer processing (Chokshi et al., 2022). Although FDM is used across many sectors, a broader scope is maintained in this review to integrate process parameters, post-processing methods, and nozzle-related mechanisms within a single framework, as these factors collectively govern the overall mechanical performance and cannot be evaluated in isolation. For ease of reference, Table 1 lists the acronyms for the polymers and composites discussed in this review.

1.1 Literature search strategy and scope of review

In preparing this review, the relevant literature was identified through a structured search carried out across Scopus, Web of Science, and Google Scholar. These databases were chosen because they cover most of the peer-reviewed work in additive manufacturing and provide good depth in studies related to FDM and polymer processing. The search was performed for publications appearing between 2010 and 2025, using combinations of terms related to FDM printing parameters,

TABLE 1 **Common polymer and composite acronyms used in this review.**

Acronym	Material/Composite description
PLA	Polylactic acid
ABS	Acrylonitrile butadiene styrene
PETG	Polyethylene terephthalate glycol
PC	Polycarbonate
PC-ABS	Polycarbonate/ABS blend
PA	Polyamide (nylon)
PP	Polypropylene
PE	Polyethylene
TPU	Thermoplastic polyurethane
PEEK	Polyether ether ketone
CF-PLA	Carbon-fibre-reinforced PLA
GF-ABS	Glass-fibre-reinforced ABS
PLA-TPU	PLA/thermoplastic polyurethane blend
Bio-PLA	Bio-based polylactic acid
rPLA	Recycled PLA
rPET	Recycled polyethylene terephthalate
Biochar-PLA	PLA reinforced with biochar fillers

nozzle geometry and wear, thermal management, recycled or sustainable feedstocks, post-processing of printed parts, and waste-to-value polymer applications. Only articles written in English and offering experimental data, analytical insight, or substantial review of FDM processes were considered. Work that focused exclusively on non-FDM techniques, patents, or sources lacking technical detail on print behaviour or sustainability aspects was excluded to maintain relevance.

All retrieved papers were screened initially by title and abstract, after which the shortlisted studies were examined in full to determine their contribution to understanding the interplay between printing parameters, nozzle design, post-processing treatments, and sustainable material use in FDM. This structured approach ensured that the discussion presented in this review reflects the most pertinent findings across mechanical performance, melt flow characteristics, energy and material efficiency, and environmental considerations.

2 Influence of process parameters

2.1 Build orientation

In FDM, the orientation of the parts being built is vital as it affects their mechanical properties. Build orientation is the part's placement concerning the build plate during the modelling process. The mechanical performance of parts built in a flat orientation is consistently better than that of parts produced vertically or horizontally. This is due to the decreased internal tensions and improved layer adhesion. Megersa et al. discovered that the ultimate tensile strength (UTS) of PLA specimens was 98.16% influenced by construct orientation, with flat orientation producing the maximum strength. For instance, the build orientation significantly influences the ultimate tensile strength (UTS), contributing 98.16% to its variance. By using a flat orientation, the predicted UTS and elastic modulus were achieved with error percentages of 4.33% and 2.74%, respectively (Megersa et al., 2024). Ahmad et al. found that the construction orientation is the most important factor affecting the mechanical properties of oil palm fibre composites. This was determined through mechanical tensile and flexural testing, along with fractography analysis of the fractured samples (Ahmad et al., 2022). On the other hand, Huang et al. found that ABS specimens printed horizontally performed the best, but tensile strength and impact resistance were lowest for vertically constructed components (Huang et al., 2019). The material-dependent character of the build's orientation impact is shown by this variation. The improvement is due to enhanced interlayer adhesion and reduced porosity (Hibbert et al., 2019).

2.2 Layer thickness

Another important factor influencing the final mechanical characteristics is the layer thickness of each layer deposited during the process. Due to increased interlayer bonding and decreased porosity, thinner layers often result in higher mechanical strength and better surface quality (KAM et al., 2020; Chokshi et al., 2022; Huang et al., 2019; Shafaat and Ashtiani, 2021). Excessively thin layers, however, may result in longer printing times and more material consumption (Omar et al., 2022). When examining PLA, Chokshi et al. (2022) observed that layer height had a considerable impact on flexural strength but less on tensile strength. The necessity of optimising layer thickness for particular materials and desired mechanical qualities is shown by this variance. Furthermore, by strengthening the interfacial contact between rasters and layers, decreasing layer thickness might improve the mechanical performance of FDM-printed products (Jo et al., 2018).

2.3 Air gap

Mechanical characteristics of the FDM-printed part are also influenced by the air gap, which is the distance between neighbouring extrusion paths. The strength of the parts can be increased by reducing porosity and improving layer adhesion through a smaller air gap. On the other hand, smaller air gaps may result in nozzle blockage or inadequate material flow, which could affect the mechanical qualities and print quality (Mohamed et al., 2016a; Vosynek et al., 2018; Elmushyakhi, 2022). The effect of air gap on the dynamic mechanical properties of PC-ABS components was examined by Mohamed et al. (2016a), which has shown that air gap has a major influence on loss modulus and storage compliance. This was analysed through analytic and graphical techniques for estimation and optimization of FDM processing parameters using Q-optimal design and graphical optimization technique. Similarly, Elmushyakhi (Elmushyakhi, 2022) incorporated air gap as a criterion in their study on freeze-thaw stability, demonstrating its wide applicability. In this study, the effects of freeze–thaw cycles on the physical characteristics of FDM objects printed using the ULTEM 9085 filament is assessed. The

TABLE 2 **Effect of printing parameters on the mechanical performance of polymers and their composites.**

Process parameter	Material	Mechanical property	Effects on mechanical properties	References
Build orientation	Nylon 12	Impact strength	Y-orientation (flat) at 0° and 45° has a direct effect. Z-orientation (upright) at 90° has an indirect effect	Patti (2024)
	rPLA	Tensile and compressive strength	Superior performance irrespective of flat or on-edge orientations.	Webbe Kerekes et al. (2019)
	CFPLA		Inferior to rPLA, superior to CF-PETG. Influenced by flat and on-edge orientations.	
	PETG		Inferior to rPLA and CFPLA. Influenced by flat and on-edge orientations.	
	CF-PETG		Inferior to rPLA and CFPLA. Influenced by flat and on-edge orientations.	
	Multi-material	Tensile strength	XY orientation generally shows higher tensile strength than YX and ZX orientations.	Marabello et al. (2025)
	Metal-reinforced PLA	Compressive yield strength	Dependence on loading orientation observed for some combinations, but not all.	Kamoona et al. (2017)
	Nylon 12	Flexural strength	Build orientation is a significant process parameter affecting flexural strength.	Faidallah et al. (2024)
	PLA	Bending properties	Build orientation influencing the mechanical properties.	Königshofer et al. (2021)
Raster angle	Nylon 12	Impact strength	Parts built with raster angles of 0° and 60° demonstrated a directly proportional influence on impact strength, whereas a 30° raster angle had an inversely proportional effect. This highlights the significant impact of raster angle on mechanical performance and the importance of parameter optimization.	Patti (2024)
	ABS	Compression flexural, impact	Raster angle has a big impact on ABS's strength, stiffness, and durability in FDM. To optimize part performance and customize certain applications, it is essential to comprehend its separate impacts.	Ranaiefar et al. (2024)
	Various Materials (rPLA, CFPLA, PETG, CF-PETG)	Tensile and compressive strength	Raster angle affects both compressive and tensile strength, making it a critical component of 3D-printed composites' mechanical characteristics.	Webbe Kerekes et al. (2019)
	Multi-material	Tensile strength	Raster angle affects the properties of several materials, affecting dimensional accuracy and strength.	Marabello et al. (2025)
	PC-ABS	Storage compliance, loss compliance	Raster angle is a key parameter in FDM, influencing storage and loss compliance.	Singari et al. (2018)
	Nylon 12	Flexural strength	Raster angle and air gap are the most influential parameters affecting flexural strength.	Faidallah et al. (2024)
Printer speed	PLA	Modulus of elasticity	High speeds negatively impact modulus due to reduced layer adhesion.	Chalgham et al. (2021)
	PLA	Tensile strength	Increased speed causes anisotropy, reducing mechanical performance in the Z-direction.	Biglete and Ang (2019)
	PLA	Tensile strength	Lower speeds improve tensile strength by enhancing interlayer fusion.	Mohamed et al. (2016b)
	ABS	Tensile strength	Optimal speed enhances uniformity in mechanical properties.	Chacón et al. (2017)
	PLA	Tensile strength	Faster speeds cause voids, reducing overall strength.	Lee et al. (2007)
	ABS	Tensile strength	Low speeds allow better interlayer diffusion, increasing tensile strength.	Rankouhi et al. (2016)

(*Continued*)

TABLE 2 Continued

Process parameter	Material	Mechanical property	Effects on mechanical properties	References
	PETG	Surface finish	Faster speeds degrade surface quality, leading to increased roughness.	Dawou et al. (2016)
	Nylon	Tensile strength	High-speed printing adversely affects nylon's layer adhesion.	Lanzotti et al. (2015)
	ABS	Impact strength	High-speed printing reduces impact resistance due to insufficient bonding time.	Mohamed et al. (2016c)
	PLA/ABS	Flexural strength	Excessively high speeds reduce flexural strength due to improper layer deposition.	Tymrak et al. (2014)
	PLA	Tensile strength	Higher speeds reduce tensile strength due to weak interlayer bonding.	Turner et al. (2014)
Layer thickness	PLA	Tensile strength	Improved tensile strength with thinner layers (0.1 mm).	Megersa et al. (2024)
	PLA	Elastic modulus	Build orientation has the most significant influence, followed by raster angle. Layer thickness has less impact.	
	PLA	Tensile strength	Layer thickness, along with printing speed and infill percentage, affects tensile strength.	Sood et al. (2010)
	PLA	Impact strength	Increasing layer thickness results in higher impact strength, along with infill density.	Sun et al. (2008)
	ABS	Tensile strength	Layer thickness has a influence on tensile properties.	Huang et al. (2019)
	ABS	Impact resistance	0.1 mm layer thickness printed horizontally shows better performance, while a vertically built part has shown lower properties.	
	ABS	Impact strength	Increasing layer thickness results in higher impact strength, along with infill density. Honeycomb infill pattern performs better than rectilinear.	Sun et al. (2008)
	ABS	Tensile strength, elastic modulus, yield strength, fracture strain, toughness	Layer thickness and infill density have significant effects on tensile properties.	Shafaat and Ashtiani (2021)
	PC-ABS	Flexural strength and surface roughness	Layer thickness, build orientation and infill density, influences the strength and surface roughness.	Ahn et al. (2002)
	PEEK	Tensile, compressive, and bending strength	Layer thickness, raster angle, influences mechanical properties. Optimal properties were observed at 300 μm layer thickness and 0° raster angle.	Huynh et al. (2019)
	PEEK	Tensile properties (Young's modulus, tensile strength)	Layer thickness, along with nozzle, bed, and radiant temperatures, as well as printing speed, affects tensile properties.	Ramkumar (2019)
	PETG	Tensile, compressive, and Bending strength	Layer thickness, raster angle, printing speed, and infill percentage, affects mechanical properties.	Algarni and Ghazali (2021)
	PETG	Elastic modulus, yield strength, toughness	Layer thickness, along with raster angle and infill percentage, influences mechanical properties. PETG generally outperforms HIPS in Young's modulus and toughness.	Pawar and Dolas (2021)
Air gap	Nylon 12	Flexural strength	Air gap, along with raster angle and build orientation, significantly influences flexural strength.	Faidallah et al. (2024)
	PC-ABS	Storage compliance, loss modulus	Air gap is one of the factors affecting temperature-dependent dynamic mechanical properties.	Singari et al. (2018)
	PLA	Impact properties	Layer thickness, related to air gap, influences impact properties. Over-compression can occur with small air gaps.	Wu et al. (2015)

(*Continued*)

TABLE 2 Continued

Process parameter	Material	Mechanical property	Effects on mechanical properties	References
	ABS	Tensile strength	Air gap, along with layer thickness, part orientation, raster angle, and width, affects tensile strength.	Mohamed et al. (2021)
	PC	Tensile strength	Combined effect of air gap and raster angle influences tensile strength. Increasing contours with optimized air gap improves fracture resistance.	Adams et al. (2024)
	ULTEM 9085	Tensile properties	Air gap, raster width, angle, and contour number influence tensile properties.	Milovanović et al. (2024)
Infill density	PLA	Tensile strength	Increased at 100% infill (100.09% enhancement).	Onwubolu and Rayegani (2014)
	PLA + CF	Tensile strength	Increased at 100% infill (84.27% improvement).	
	PLA	Tensile strength (after 30 days lubricant exposure)	Decreased by 15.56%.	
	PLA + CF	Tensile strength (after 30 days lubricant exposure)	Decreased by 18.60%.	
	PLA, PLA + CF	Strain	Minor fluctuations, indicating stable elasticity.	
	PLA, PLA + CF	Young's modulus	Higher infill densities have shown improved properties.	
	ABS, PLA, PLA-CF	Compressive strength	Infill density has a significant influence.	Do et al. (2022)
	PLA	Compressive property	Crucial factor	Boppana and Ali (2024)
	PLA	Tensile property, Bending property, Surface roughness	Build direction has a significant effect.	
	PLA, ABS, HDPE	Tensile strength, hardness, impact strength	Infill density affects these properties.	Gebisa and Lemu (2019)
	ABS	Mechanical properties	Print speed has minimal effect, but higher fabrication temperature improves properties.	Hozdić and Hasanagić (2024)
	PLA	Tensile strength	Wall thickness and infill density have significant influence, increasing with higher values.	Xu et al. (2021a)
	PLA, biochar-reinforced PLA	Ultimate tensile strength (UTS), flexural strength (FS)	Infill density has shown vital influence	Umer et al. (2024)
	PLA, biochar-reinforced PLA	Impact strength (IS)	Biochar content has the most significant influence.	
	Carbon fiber	Tensile strength, flexural strength	Infill density is the most effective printing parameter.	Patibandla and Mian (2020)
	Wood PLA	Tensile strength, flexural strength	Directly proportional to infill density.	Muhamedagic et al. (2020)
	ABS (with and without electroplating)	Tensile, compressive, flexural strengths	Infill density is a key parameter.	Kharate et al. (2024)
	PLA	Tensile strength	Infill patterns significantly affect tensile strength. Concentric infill pattern had higher tensile strength (32.174 MPa), while triangles infill pattern had lower tensile strength (20.934 MPa).	Lavanya and V (2024)
	PLA reinforced with carbon fiber	Modulus of elasticity, ultimate tensile strength	Infill density is the most affecting parameter.	Zurnacı (2023)
	PLA+	Tensile test results, failure mechanism	No specific correlation mentioned between infill density and results, but process parameters like extrusion temperature, infill density, *etc.*, were kept consistent.	Sandhu et al. (2024)
	PET-G	Flexural strength	Infill density is one of the 3D-printing parameters studied.	Jasim et al. (2022)

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TABLE 2 Continued

Process parameter	Material	Mechanical property	Effects on mechanical properties	References
	CF-PLA	Natural frequency, damping	Increases with increasing infill percent. Optimal infill density for maximizing vibration characteristics is 60%.	Edinson et al. (2023)
	Glycolyzed polyethylene terephthalate reinforced with carbon-fiber	Tensile strength, Young's modulus	Increased with increasing infill densities for all infill patterns analyzed. Honeycomb infill pattern provided significant strength and stiffness.	Decker et al. (2021)
	ABS	Residual stress	Significant positive correlation between residual stress and infill percentage.	Fountas et al. (2021)
Extrusion temperature	PLA	Tensile strength	Extrusion temperature was found to be the most significant factor influencing ultimate tensile stress.	Srinivasan et al. (2019)
	PLA	Tensile strength, elastic modulus	Increasing extrusion temperature generally increases both tensile strength and elastic modulus.	Vinoth Babu et al. (2024)
	ABS	Failure strength, yield strength, compressive modulus	Lower extrusion temperatures result in more uniform features within the layers compared to higher temperatures.	Hozdić and Hasanagić (2024)
	PETG	Tensile strength	A sample with 30% (infill density), 245 °C (extrusion temperature), and 25 mm/s (print speed) exhibited better properties.	Daly et al. (2024)
	PLA	Ultimate tensile strength (UTS), elastic modulus	Extrusion temperature is a significant factor influencing UTS. An optimal extrusion temperature of 200 °C was determined for PLA.	Megersa et al. (2024)
	Tough PLA	Tensile, flexural, and compressive properties	Extrusion temperature is one of the printing parameters investigated for its impact on the mechanical properties of Tough PLA. Regression models were developed to predict these properties based on printing parameters, including extrusion temperature.	Alzyod and Ficzere (2022)
	PLA	Tensile properties	Extrusion temperature influences the tensile properties of PLA printed parts. Heat treatment improves structural strength.	Alafaghani et al. (2021)
	PLA	Tensile strength, impact strength, and flexural strength	The desirability approach and nonlinear regression were used to predict these properties with low percentage errors.	Mallikarjuna et al. (2024)
	PLA	Bending strength, stiffness, deflection at break	Extrusion temperature has the highest influence followed by printing velocity and raster orientation.	Al-Tamimi et al. (2023)
	PLA	Inter-layer cohesion, delamination energy	The influence of extrusion temperature on inter-layer cohesion were investigated	Hasan et al. (2020)
	PLA/Stainless Steel Composite	Forming quality (line height and line width)	Nozzle temperature (extrusion temperature) affects the single-channel direct writing forming quality of PLA/stainless steel composites, influencing line height and line width.	Jatti et al. (2022)
	PLA	Stiffness and strength	Nozzle temperature (extrusion temperature) significantly influences the stiffness and strength of PLA tensile specimens. An optimal temperature of 231.36 °C was determined.	Abouelmajd et al. (2021)
	PLA+	Tensile strength	Extrusion temperature, along with infill density and pattern, affects the tensile strength of PLA+ parts. The best tensile strength was observed with a triangle infill pattern.	Barile et al. (2018)
	PLA+	Tensile strength, failure mechanism	Extrusion temperature was kept constant during experiments. Crystallization due to nozzle temperature at extrusion could contribute to failure discrepancies.	Sandhu et al. (2024)

(*Continued*)

TABLE 2 Continued

Process parameter	Material	Mechanical property	Effects on mechanical properties	References
	PLA	Ultimate tensile strength (UTS)	Extrusion temperature, along with layer thickness and printing speed, significantly influences UTS. An increase in layer temperature generally leads to an increase in UTS, but it is not always the primary factor.	Liu et al. (2023)
	ABS	Tensile strength	Extrusion temperature, along with (infill density, infill pattern, print speed, and layer height), influences the quality and mechanical characteristics of the final part.	Chen et al. (2024)
	CNF/PLA nanocomposites	Tensile modulus and yield strength	Nozzle geometry and material properties affect melt flow behavior, void content, and mechanical performance of CNF/PLA nanocomposites. Different liquefier nozzle diameters were used for mechanical testing.	Yilan et al. (2023)
	ABS	Degree of fusion	Extrusion temperature, along with layer thickness, infill density, print speed, and air gap, affects the degree of fusion of adjacent tracks. The highest degree of fusion was obtained at 255 °C layer temperature.	Delgado-Prieto et al. (2023)
	Reinforced Polyamide (RPA)	Tensile and fatigue properties	Extrusion temperature, along with layer thickness and print speed, affects the mechanical properties of reinforced polyamide.	Kumar et al. (2020)

samples used in this study were printed with an air gap of–0.025 mm and at raster angles of 0°, 45°, and 90°. The results indicate that freeze thaw conditioning reduces the tensile properties of FDM samples.

2.4 Raster angle

Mechanical qualities are also influenced by the raster angle (angle of the extrusion path) concerning the build plate (Megersa et al., 2024; Huang et al., 2019). Variations in angle can result in different levels of internal stress distribution and layer adhesion. A 45-degree raster angle is ideal for increasing tensile strength. This occurs due to improved molecular diffusion and enhanced interlayer bonding during the printing process. While other studies have shown that other factors like construct orientation or layer thickness have a greater impact (Abdullah et al., 2018; Christiyan et al., 2014). According to Gao et al. (2021), the highest overall performance for PEEK samples in terms of deformation and tensile strength was obtained using a 0°/90° raster angle. It highlights the fact that the ideal raster angle depends on the material.

2.5 Infill density

The quantity of infill material in a printed component has a major impact on its mechanical qualities. Although a higher infill density often results in greater strength and stiffness, it also uses more material and takes longer to print (Ahmad et al., 2022; Rizwee and Kumar, 2024; Dezaki and Mohd Ariffin, 2020; Do et al., 2022). On the other hand, components with a lower infill density are lighter and weaker, making them appropriate for situations where weight reduction is a top priority. Ahmad et al. (2022) demonstrated that the mechanical strength of oil palm fibre composites is influenced by infill density. This was determined through mechanical tensile and flexural testing of optimised PLA prints. The results show the tensile strength of the printed specimens ranged from 0.95 to 35.38 MPa, the Young's modulus from 0.11 to 1.88 GPa, and the flexural strength from 2.50 to 31.98 MPa. In addition, build orientation had the largest influence on tensile strength, Young's modulus, and flexural strength. The optimum printing parameter for FDM using oil palm fiber composite was 0.4 mm layer thickness, flat (0°) of orientation, 50% infill density, and 10 mm/s printing speed. Rizwee and Kumar (Rizwee and Kumar, 2024) found out that the tensile strength of PLA specimens was most significantly impacted by 100% infill density and by optimising the raster angle and increasing extrusion temperature to improve layer fusion. There is a trade-off between material efficiency and strength when choosing the infill density.

2.6 Extrusion temperature

A suitable temperature for extrusion guarantees good adhesion of the layers and optimal material flow. Insufficient material flow, deformation, or poor layer adhesion can result from extremely high or low temperatures (Megersa et al., 2024; Kafshgar et al., 2021; Muhamedagic et al., 2022; Deng et al., 2018). Megersa et al. demonstrated the impact of extrusion temperature on the strength of PLA specimens. This study explored how layer thickness, raster angle, build orientation, and extrusion temperature influence the ultimate tensile strength (UTS) and elastic modulus of Polylactic Acid (PLA) specimens. The Taguchi method was employed for optimization, and analysis of variance (ANOVA) was used to assess the significance of these factors (Megersa et al., 2024). The optimal extrusion temperature for improving the toughness and strength of PLA depends on various other printing parameters. These include layer thickness, which influences adhesion between layers; print speed, which affects material deposition and cooling; extrusion temperature, which controls melt flow and bonding; infill density, which contributes to structural integrity; and raster angle, which impacts the way stress is distributed within the printed component.

Additionally, for carbon fibre-reinforced polyamide, tensile strength is less affected by printing temperature compared to other factors. This indicates that aspects such as fibre orientation, interlayer bonding, and the intrinsic properties of the composite material have a more significant role in determining its mechanical performance.

2.7 Printing speed

Layer adhesion and internal structure of the printed components are influenced by printing speed, which is the speed at which the filament is extruded and deposited. Although faster printing rates might save time, they may also affect mechanical qualities and layer adhesion because of inadequate cooling and bonding time between layers. While enhanced mechanical characteristics can be achieved by greater layer adhesion and solidification at lower printing rates, this comes at the expense of longer printing times (Ahmad et al., 2022; Huang et al., 2019; Natarajan et al., 2022). Huang et al. (2019) discovered that the quality of ABS components produced using FDM decreased when printing speed increased. Natarajan et al. (2022) found that in PLA/Acacia concinna composites, printing speed and strength were negatively correlated.

2.8 Mechanisms governing process-property relationships

The mechanical performance of FDM-printed polymers is governed by the combined effects of thermal history, polymer flow behaviour, and interlayer diffusion during material deposition. When a filament strand is extruded, the degree of molecular interdiffusion across adjacent layers is determined by its temperature relative to the polymer's glass transition and melt regimes. Higher extrusion temperatures, smaller layer heights, and reduced air gaps promote increased interfacial contact area and longer residence times above the critical diffusion temperature, enabling polymer chains to reptate across the interface and form stronger intermolecular entanglements. This mechanism directly enhances interlayer bonding strength and reduces the likelihood of crack initiation at bead boundaries (Patti, 2024).

Conversely, insufficient thermal energy, rapid cooling, or large internal voids limit chain mobility and produce partially fused interfaces that act as stress concentrators under load. Build orientation and raster angle further influence the alignment of these interfaces relative to the applied stress direction; orientations that place weak interlayer bonds perpendicular to the load path generally exhibit lower tensile and flexural strength. The extent and distribution of voids introduced by air gaps or suboptimal infill patterns also reduce the effective load-bearing cross-section, contributing to earlier failure (Webbe Kerekes et al., 2019).

Post-processing treatments such as annealing modify the internal microstructure by increasing crystallinity, relieving residual stresses, and improving dimensional stability. These thermal modifications improve stiffness and heat resistance but may also affect ductility depending on the crystallisation kinetics of the specific polymer. Surface-based post-processing methods enhance interlayer contact or heal surface defects by increasing local polymer mobility or enabling partial remelting. Collectively, these mechanisms explain the experimentally observed trends in mechanical behaviour under varying process parameters and post-processing strategies (Marabello et al., 2025). The effects of printing parameters on the performance of polymer composites is summarised in Table 2.

The reviewed studies show that parameter settings that increase interlayer contact and reduce voids generally result in higher mechanical strength in FDM parts. Build orientations that align the raster direction with the applied load minimise weak interlayer planes and therefore improve tensile and flexural performance. Smaller layer heights and zero or negative air gaps increase the bonding area and promote polymer chain diffusion between layers. Raster angles aligned closer to the load path reduce crack propagation across bead boundaries. Moderate extrusion temperatures and controlled printing speeds maintain suitable melt flow and thermal conditions for uniform layer fusion. These effects collectively explain why certain parameter levels consistently show better mechanical properties in experimental studies.

3 Effect of post-processing on properties of 3D printed polymers and their composites

Post-processing methods help improve the properties and performance of 3D printing of polymer and polymer composite materials. The main reasons can be explored as additive manufacturing progresses across several applications. Much research has been directed toward the primary limitations of 3D printed parts such as anisotropic mechanical properties, surface roughness, and dimensional inaccuracies (Papon et al., 2017). Lately, various post-processing methods have been used such as thermal treatments, chemical treatments, and surface modifications to enhance the mechanical strength, thermal stability, and functional properties of 3D-printed polymers and composites (Mwania et al., 2023). These post-processing processes have shown promising results in lowering porosity, improving interfacial bonding between print layers, and optimizing the microstructure of the as-printed parts.

Moreover, new ways for modifying the properties of 3D printed composites for applications in aerospace, biomedical, and automotive fields have been opened through the incorporation of nanomaterials and advanced polymer blends during post-processing (Ouballouch et al., 2019). Hence, a thorough understanding of post-processing parameters, material properties, and printing conditions is important to develop functionalized high-performance 3D-printed polymer composites with advanced functionality and durability.

3.1 Main significances of post-processing treatments

The primary limitations of 3D-printed polymers, including fine surface finish, internal stresses, and variable mechanical strength,

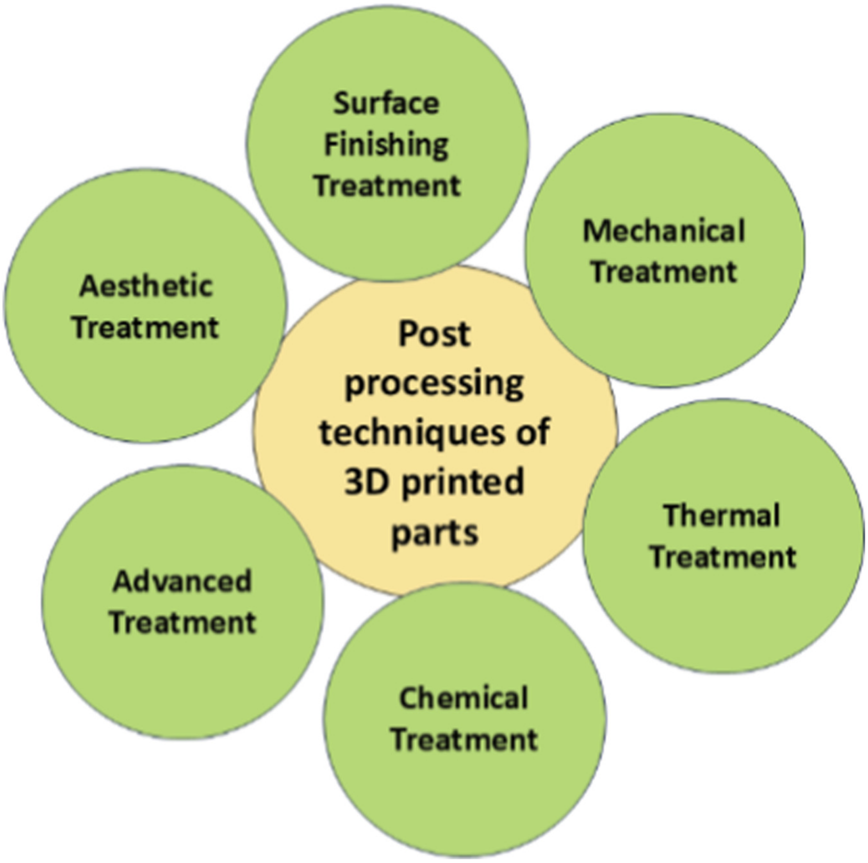

FIGURE 1
Different post-processing techniques for 3D printed parts.

have been significantly improved through post-processing techniques. Post-processing enhances surface characteristics by employing methods such as polishing and leveling, which promote durability, thermal stability, and environmental resistance through chemical coatings. Additionally, post-processing plays a crucial role in optimizing the mechanical, thermal, and chemical properties of printed parts to meet specific functional requirements.

For polymer composites, post-processing enhances bonding and load distribution, thereby improving performance in demanding applications. It bridges the gap between raw 3D-printed parts and high-quality, reliable products suitable for industrial applications.

3.2 Types of post-processing methods

Post-processing methods for 3D-printed polymers and their composites can be categorized into mechanical, chemical, thermal, aesthetic, surface finishing, and advanced treatments (Park et al., 2022), as illustrated in Figure 1. Mechanical methods, such as sanding, polishing, and machining, are commonly used to improve surface finish but may compromise the dimensional accuracy of the printed parts. Among chemical methods, techniques like vapour polishing involve exposure to solvents to achieve smoother surfaces. Thermal post-processing methods, such as annealing, enhance the dimensional stability and mechanical properties of 3D-printed parts. However, some post-processing techniques may have unintended negative effects. For instance, certain post-curing conditions might preserve dimensional accuracy but adversely impact the biocompatibility and physical properties of the material. The primary post-processing methods include chemical treatment, annealing, and vapor smoothing.

3.2.1 Annealing technique

Thermal post-processing methods are vital for enhancing the properties of 3D-printed polymers and their composites. The post thermal annealing can improve the bonding of interlaminar in fabricated polymer components (Shanmugam et al., 2021). It is broadly used, however, it has been shown to affect the thermal and mechanical properties of additively manufactured parts. Also, it explores the increment in toughness *via* better interfacial wetting. The main considerations of thermal post-processing are the resulting crystallinity and the cooling rate of the printed parts (Chen et al., 2022). When considering the poly-lactide (PLA), rapid quenching after annealing treatment can assist in maintaining its amorphous class and confirm good interlaminar toughness. On the other hand, the slow cooling results in a semi-crystalline state which can direct to minimum fracture toughness and maximum brittle behaviour (Kantaros et al., 2024). For carbon fibre-reinforced polyphenylene sulfide (CF/PPS) composites, the

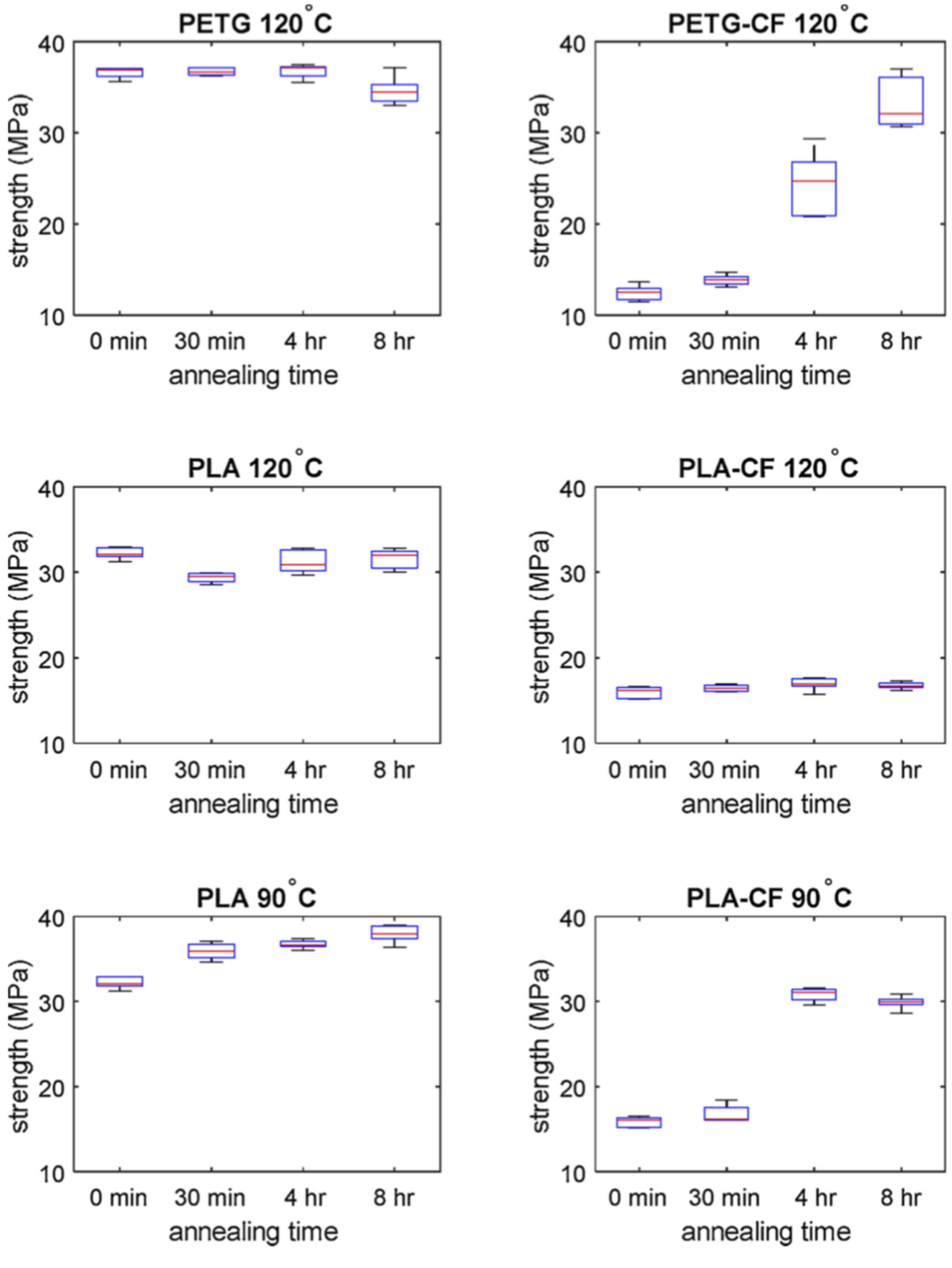

FIGURE 2
Interlayer tensile strength of 3D printed neat and reinforced PETG and PLA/CF polymer specimens subjected to annealing (Yu et al., 2023).

duration and annealing temperature influence the viscoelastic properties and degree of crystallinity (Xu Z. et al., 2021). Therefore, thermal post-processing methods are important for altering the properties of 3D-printed polymers and their composites (Mathew et al., 2023). Through changing factors such as duration, annealing temperature, and cooling rate, it is possible to optimize the thermal stability, toughness, and mechanical strength of additively manufactured parts (Birosz et al., 2024).

Annealing has been identified to improve the interlayer mechanical properties of 3D-printed short carbon fibre-reinforced PETG and PLA composites. For amorphous polymers such as PETG, the interlayer bonding is enhanced with the annealing temperature above the glass transition point. On the other hand, an effective annealing treatment can be obtained between the glass transition and cold crystallization temperatures in semi-crystalline polymers of PLA whereas, the interlayer tensile strength is reduced through the addition of carbon fibres due to increased melt viscosity. However, the appropriate annealing temperature can assist in recovering the strength of 3D-printed parts. Moreover, the annealing temperature and duration are influenced less by tensile strength compared to the layer height. Figure 2 shows the annealing treatment affects the interlayer tensile strength in PETG and PLA/CF polymer specimens. As well, the 80% of tensile properties and 73% of heat resistance of PLA components can be improved with the conditions of 100 °C for 4 h. Also, the impact energy of PLA components has shown enhancement up to three times (Yu et al., 2023). The annealing post-processing technique is concluded that it is improving the mechanical characteristics of the 3D printed parts (Stoeffler et al., 2013; Valvez et al., 2023). In contrast, the residual stresses are mitigated and explored to higher material ductility and improved surface smoothness by providing post-processing techniques for both metal and polymer 3D printed parts (Bhandari et al., 2019; Stojković et al., 2023).

Annealing has been shown to enhance the interlayer mechanical properties of 3D-printed short carbon fibre-reinforced PETG and PLA composites. For amorphous polymers such as PETG, interlayer bonding improves when the annealing temperature exceeds the glass transition point. In contrast, for semi-crystalline polymers like PLA, effective annealing occurs between the glass transition and cold crystallization temperatures. However, the addition of carbon fibres to PLA increases melt viscosity, which reduces interlayer tensile strength. Despite this, selecting an appropriate annealing temperature can help recover the strength of 3D-printed parts.

Furthermore, while annealing temperature and duration influence tensile strength, their impact is less significant compared to that of layer height. As shown in Figure 2, annealing treatments affect the interlayer tensile strength in PETG and PLA/CF polymer specimens. Specifically, PLA components can achieve up to 80% improvement in tensile properties and a 73% increase in heat resistance when annealed at 100 °C for 4 h. Additionally, the impact energy of PLA components can be enhanced by up to three times. In conclusion, annealing is an effective post-processing technique that improves the mechanical characteristics of 3D-printed parts. Moreover, post-processing techniques for both metal and polymer 3D-printed parts not only reduce residual stresses but also enhance material ductility and surface smoothness.

3.2.2 Physical methods

The functional and aesthetic properties of 3D printed parts can be improved through any one of the primary physical post-processing treatments such as surface finishing. Various methods such as polishing, sanding, and abrasive blasting can be utilized to obtain planar surfaces and minimize the layer lines to 3D printing methods (Jayanth et al., 2021). In addition to enhancing aesthetic properties, surface finishing post-processing methods also improve mechanical properties by significantly reducing surface roughness.

Moreover, the physical post-processing methods can produce an intense impact on the internal structure and properties of 3D-printed parts. Therefore, the heat treatment in NaCl powder or a closed form with pressure has been revealed to improve the physical and mechanical properties of ABS plastic samples printed using FDM. In some conditions, these post-treated samples showed properties comparable to injection-molded samples. Here, it represents the possibilities of physical post-processing to connect the gap between 3D printed and conventional manufactured parts (Stojković et al., 2023).

Hence, the physical post-processing methods are vital for optimizing the performance of 3D-printed polymers and their composites. These techniques can report common issues such as poor surface quality and reduced mechanical properties which are frequently related to additive manufacturing processes.

3.2.3 Chemical methods

Chemical post-processing methods play a crucial role in enhancing the properties of 3D printed polymers and their composites. These methods involve the use of chemical treatments to modify the surface or internal structure of the printed parts.

One of the primary chemical post-processing techniques is surface treatment which can enhance the mechanical properties and surface finish of 3D printed parts (Liu et al., 2022). This method includes the application of solvents or chemical agents to smooth out layer lines, reduce surface roughness, and improve the overall aesthetic appearance of the printed objects. Also, the chemical treatments can be used to modify the surface energy, wettability, and adhesion properties of the printed parts which is important for applications requiring specific surface characteristics (Khosravani et al., 2023).

The investigation of the impact of varnishing, coating, and polishing on the chemical and mechanical properties of a 3D printed resin and two veneering composites is shown in Figure 3. Polishing with a goat hairbrush improved surface roughness and mechanical properties for all materials. Varnishing has shown promise for improving surface roughness and wear resistance in the 3D-printed resin. However, silicone polishing and coating negatively affected the properties of materials (Liu et al., 2022).

Polishing with a goat hairbrush reduced surface roughness and increased flexural strength. For example, VITA-VCRs flexural strength is increased from 121 MPa to 145 MPa after goat hair polishing. Varnishing the 3D-printed resin reduced wear by 96% with VITA-varnish. Silicone polishing decreased the elastic indentation modulus of the 3D-printed resin by 17%. The 3D-printed resin showed a lower flexural strength compared to the veneering composites (Liu et al., 2022).

The incorporation of nano-fillers or the treatment of natural fibres with chemical agents can improve the mechanical, electrical, and thermal properties of the printed parts. Chemical treatments can be used to activate self-healing mechanisms in certain polymer composites which can provide the material to repair damage and extend its durability (Ngo et al., 2018).

3.3 Effects on mechanical properties

The post-processing techniques have significant effects on the mechanical properties of 3D-printed polymers and their composites. Annealing has been revealed to enhance the interlayer tensile strength of 3D-printed composites. For amorphous polymers like polyethylene terephthalate-glycol (PETG), the annealing at temperatures above the glass transition temperature can recover

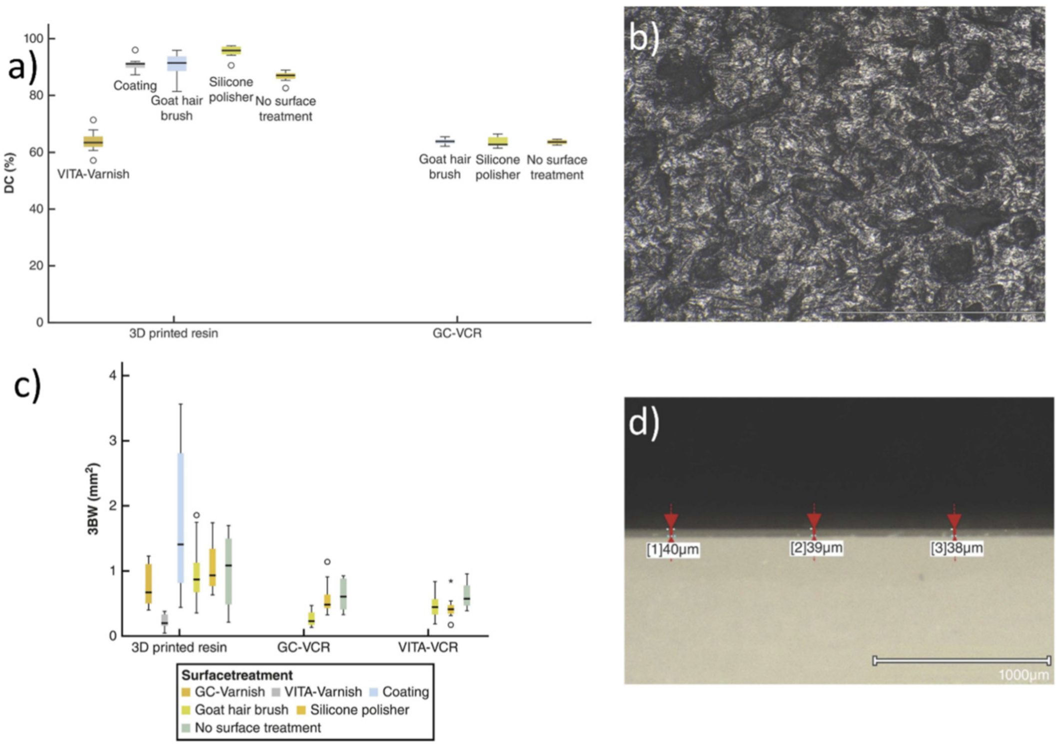

FIGURE 3
(a) Degree of conversion (DC) as a percentage, **(b)** Inhomogeneous surface with deep pits of 3D printed resin after 200,000 cycles of 3-body wear **(c)** Three-body wear (3BW) **(d)** Layer thickness of VITA-Varnish after 200,000 cycles of three-body wear (Liu et al., 2022).

the reduced interlayer tensile strength caused by the addition of short carbon fibres. In the case of semi-crystalline polymers such as polylactic acid, the recovery of interlayer tensile strength is observed when the annealing temperature is higher than the glass transition temperature but lower than the cold crystallisation temperature (Stoeffler et al., 2013). Moreover, the incorporation of carbon nanotubes (CNTs) in polyetherimide (PEI) composites has been identified to improve bond strength and reduce porosity which can give enhanced mechanical properties in 3D printed samples. The combination of CNT incorporation and annealing further improves mechanical performance and reduces warping in 3D-printed PEI samples (Vijaya Kumar and Velmurugan, 2022). This highlights the synergistic effect of reinforcement materials and post-processing techniques on the mechanical properties of 3D-printed composites (Ravi and Zagabathuni, 2026). The scale and size of 3D-printed composites also play a crucial role in finding their mechanical properties. Recent studies have shown that elastic moduli and yield strengths decrease as the scale increases. Increasing the sample size directly results in higher elastic modulus and yield strength.

3.4 Impact on tensile strength and modulus

Isostatic compaction and annealing significantly enhance the mechanical properties of 3D-printed nylon glass fibre composites. Optimal conditions (0.55 MPa and 200 °C) improved strength by over 50% (printing direction) and 100% (transverse direction) and doubled the modulus in the printing direction. These improvements result from better compaction, reduced voids, enhanced crystallinity, and fibre alignment. Compaction and annealing effectively overcome interfacial and void limitations in 3D-printed composites for improving performance (Žigon et al., 2020). Post-processing at 150 °C significantly enhances 3D printed continuous carbon fibre-reinforced composites by reducing porosity by 87% and improving interlaminar strength by 145%, without altering dimensions. The increase in thermal stability (glass transition temperature from 109 °C to 131 °C) is attributed to drying effects that reduce plasticization for enhancing mechanical performance. Post-processing effectively addresses limitations in 3D-printed CCFRC while progressing their suitability for high-performance structural applications (Ma et al., 2024).

Annealing of graphene-reinforced PLA composites significantly improved thermal stability, electrical conductivity, and mechanical properties such as tensile and flexural strength and hardness due to increased crystallinity. Functional groups remained unchanged but impact and notch sensitivity resistances decreased. Annealing enhances the key properties of graphene-reinforced PLA, highlighting its potential for advanced applications in the automotive, aerospace, electronics, and medical sectors, where the use of PLA is increasingly prevalent (Ye et al., 2022).

Moreover, the build direction of the printed parts also influences the effectiveness of heat treatment. Heat-treated and build-direction composites have shown higher tensile strength and Young's modulus than flat-build composites due to better fibre penetration and reduced porosity (Ravi and Zagabathuni, 2026).

Hence, post-processing techniques such as annealing and heat press processing can enhance the tensile strength and modulus of 3D-printed polymsers and their composites. The effectiveness of these methods depends on factors such as polymer type, reinforcement material, process temperature and build direction. By optimising these parameters, it is possible to achieve mechanical properties compared to conventionally manufactured composites. Therefore, the 3D-printed materials are progressively viable for high-performance applications.

3.5 Changes in impact resistance

Post-processing techniques can significantly influence the impact resistance of 3D-printed polymers and their composites. The layer-by-layer nature of additive manufacturing results in anisotropic properties which creates 3D printed parts exposed to delamination and reduced impact resistance. However, various post-processing methods have been explored to enhance the impact resistance of these materials. Chemical treatment has shown promising results in improving the surface quality and reducing the porosity of 3D-printed thermosetting polymers. By immersing the printed parts in solvents, it has been observed that smoother surfaces and decreased porosity can significantly lead to improved impact resistance (Muhamedagic et al., 2022). Also, thermal treatments such as annealing have been found to affect the fracture properties of 3D-printed composite structures and enhance their impact resistance. Carbon fibre reinforcements have shown a significant increase in impact resistance compared to unreinforced polymers (Kumar Jain et al., 2022). The orientation and distribution of these fibres play a crucial role in determining the impact resistance of the 3D-printed composites (Pascual-Go et al., 2021). Post-processing techniques can be used to optimize fibre orientation and distribution to enhance the impact resistance. Moreover, the development of shape memory polymers and self-healing polymers for 4D printing applications shows potential for fabricating materials with dynamic impact resistance properties that can recover after impact events (Liesenfeld et al., 2024).

The post-processing techniques have a significant role in the surface hardness of 3D-printed polymers and their composites. The layer-by-layer nature of additive manufacturing results in poor surface quality which can be improved through various finishing methods. These post-processing techniques not only enhance the surface finish but also influence the surface hardness of the printed parts. The annealing significantly enhances the impact resistance of PLA 3D printed components, with up to a threefold increase in impact energy. The infill percentage, especially at 100% plays a critical role in determining impact energy. Annealing is an effective post-processing technique to improve the mechanical performance of PLA 3D-printed parts which makes it suitable for applications requiring high mechanical integrity under load (Khan et al., 2024).

3.6 Laser polishing method

The laser polishing method is known to reduce surface properties and enhance the performance of 3D-printed nylon six polymers. This technique addresses industrial challenges by improving surface roughness, flexural strength, and tensile strength with eco-friendly polishing. Here, the experiments using response surface methodology have examined the effects of varying laser parameters on surface finish and mechanical properties. Post-polishing analysis for mechanical testing and scanning electron microscopy was compared to pre-polished samples. Multi-optimization has revealed a 20.2% reduction in surface roughness, an 8.27% increase in flexural strength and a 1.45% improvement in tensile strength. The optimal laser scanning time for samples was 0.23 min with an energy consumption of 1.58 kWh per experiment. These results prove that laser polishing significantly enhances the mechanical and surface properties of nylon 6 with a sustainable and efficient postprocessing solution. This innovative method is a promising advancement for the 3D printing industry to improve product performance and environmental benefits. Figure 4 represents the effect of laser polishing post-processing technique and their effects on a microscopic level and mechanical strength (Rithika and Sudha, 2024).

3.7 Challenges and limitations of post-processing methods

The post-processing methods for 3D-printed polymers and composites can face several challenges and limitations. One of the primary issues is the potential for reduced bonding between reinforcement and matrix materials which can result in decreased mechanical properties and structural integrity. This is particularly challenging for fibre-reinforced polymer composites where the interface between fibres and the polymer matrix is crucial for overall performance.

Surface finishing techniques categorized into chemical, thermal and physical methods have their own set of challenges. The chemical methods may change the material properties and undesirable reactions while the thermal treatments can cause dimensional changes. The physical methods such as sanding or polishing may remove too much material or create inconsistencies in the surface texture. Also, the time and cost of post-processing can be significant and compensate for some of the advantages of 3D printing.

While post-processing enhances the properties of 3D-printed polymers and composites, it introduces complexities. The challenge lies in balancing the desired improvements in surface quality, mechanical properties, and functionality with the potential drawbacks of material alteration, increased production time, and additional costs. Future research should focus on developing more efficient post-processing techniques that can maintain the integrity of the printed parts while attaining the desired enhancements. A comparative summary of the post-processing techniques discussed in this section is presented in Table 3.

4 Nozzle modifications

The nozzle design system is an important part of the FDM process, as it has a direct impact on material flow dynamics, dimensional accuracy, and overall print quality. In an FDM printer, the nozzle is the conduit through which molten polymer is extruded, and its geometry influences the material's behaviour during deposition. The technical aspects of nozzle design include parameters like channel geometry, tip diameter, internal taper angle, and thermal conductivity, all of which are important in optimizing

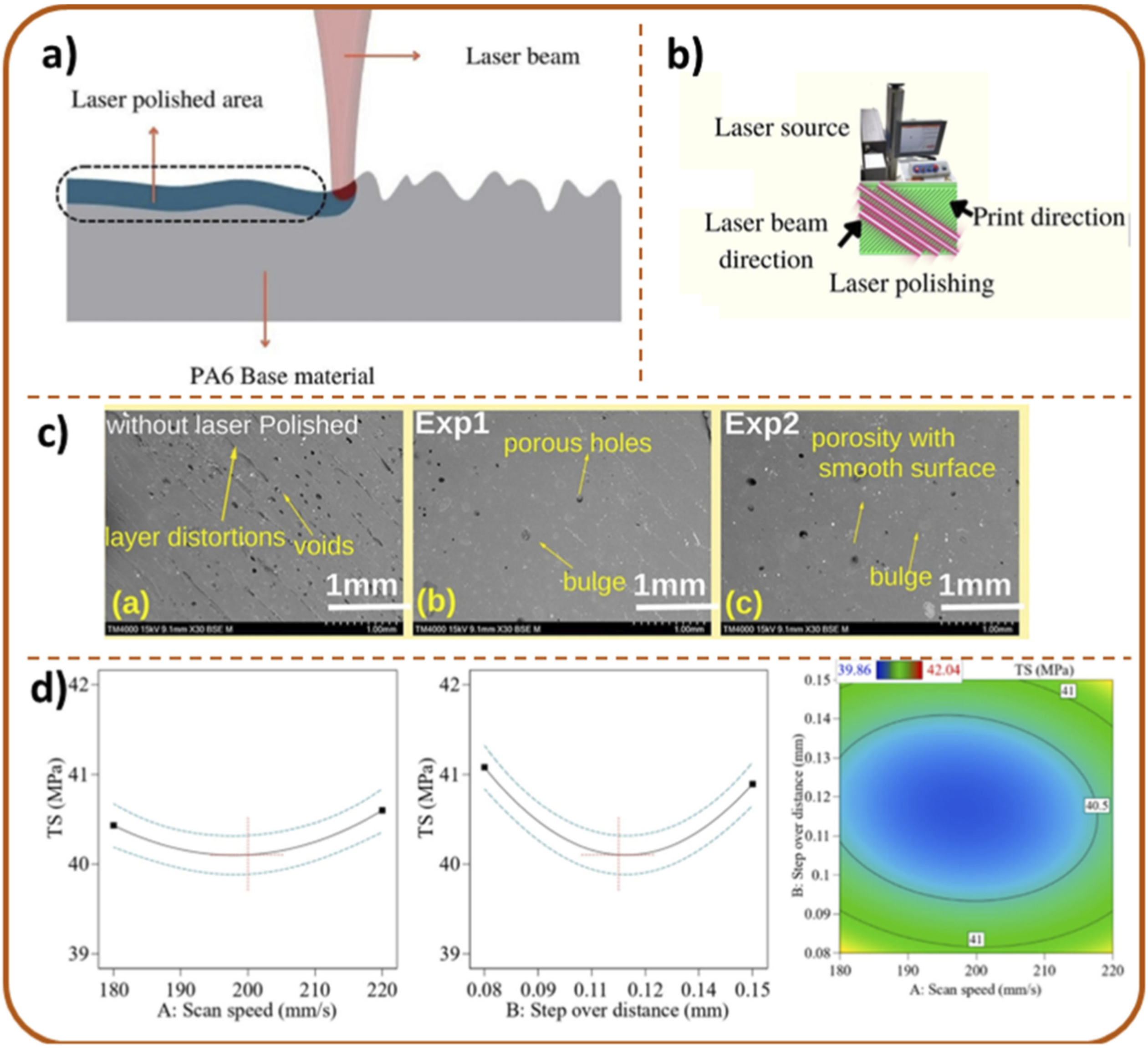

FIGURE 4
(a) The schematics of the laser polishing process (Tuli et al., 2024) **(b)** Laser polishing process, **(c)** Microscopic images of samples; **(a)** SEM image of the initial printed sample with and without laser polishing **(d)** The impact of laser scanning speed and step over distance on mechanical properties (Rithika and Sudha, 2024).

print performance. Optimized nozzle design systems are essential for achieving high precision and reliability in FDM processes. They have a direct impact on layer adhesion, dimensional accuracy, surface quality, and mechanical properties in printed parts. It is possible to improve the performance of FDM-printed components by tailoring nozzle parameters to specific material and process requirements.

Lalegani Dezaki and Bodaghi (2024) determined that a 0.3 mm nozzle diameter was optimal for open-source 3D printing with PLA after analyzing pressure drop, geometrical accuracy, and extrusion time. The study discovered that smaller nozzle diameters, such as 0.2 mm, resulted in higher pressure drops, which negatively impacted print quality. The 0.3 mm nozzle improved melt flow behaviour by minimizing pressure drop while balancing other factors, resulting in better consistency and overall part quality. These findings offer practical advice for choosing nozzle dimensions to improve FDM printing performance with PLA material.

Zisopol et al. (2023) optimized nozzle channel geometry and manufacturing parameters to enhance the dimensional accuracy of polymer strips produced through FDM printing. It was found that the strip width increased along the printing direction, and material-dependent swelling behaviour was observed, with ABS demonstrating greater swelling compared to PLA and CPE. This research highlights the critical role of nozzle channel geometry in FDM processes, providing a pathway for achieving higher precision in 3D printing. The study's integration of experimental and numerical methods offers a robust framework for optimizing

TABLE 3 Summary of post-processing techniques and their typical effects on FDM-printed polymers.

Post-processing technique	Typical materials	Commonly reported improvements	Limitations/Challenges
Thermal annealing	PLA, PETG	Increases crystallinity, improves tensile and flexural strength, reduces residual stress, improves thermal stability	Risk of distortion or dimensional change if temperature is not controlled and possible reduction in ductility
Solvent vapour treatment	ABS	Improves surface finish, reduces surface roughness, may slightly improve interlayer bonding due to local softening	Limited to solvent-compatible polymers and may cause dimensional change if exposure is excessive
Surface coating/infiltration (epoxy, resin, acrylic)	PLA, ABS composites	Fills surface pores, increases surface hardness, improves environmental/moisture resistance, may increase stiffness	Adds weight, curing time required, coating quality affects performance and reduces recyclability
Mechanical polishing	PLA, ABS	Removes surface defects, lowers roughness, reduces stress concentrators on outer surface	Only suitable for simple/accessible geometries and no improvement to internal bonding

other aspects of the FDM process, making it a valuable contribution to the field of additive manufacturing. Additionally, the findings underline the importance of considering material-specific behaviors, such as swelling, in nozzle design and process parameter selection.

Printing polymeric composites with FDM technology presents significant challenges due to the complex interaction of the polymer matrix and reinforcements, which can be fibre-based or particle-based. The size, shape, and distribution of reinforcements have a direct impact on the quality of the printed parts, with larger or poorly dispersed reinforcements frequently resulting in nozzle clogging and uneven material flow. According to studies, adding reinforcements increases the viscosity of the polymer matrix, necessitating higher extrusion temperatures and optimized nozzle designs for smooth deposition (Papon et al., 2017). Mushtaq et al. (2023) reported that the addition of natural-based fillers could lead to poor print quality due to irregularity in the particle size, and recommended for optimizing the nozzle design.

Abrasive reinforcements, such as carbon fibres and particle fillers, can cause significant nozzle wear, necessitating the use of advanced nozzle materials such as tungsten carbide. Layher et al. (2019) analyzed nozzle wear in FDM processes, focusing on longitudinal tool side wear (refer to Figure 5), which shows the profiles of a wear-free nozzle at $t = 0$ min and a worn nozzle at $t = 5{,}540$ min. A significant wear on the nozzle's external surfaces can be seen, which is attributed to abrasion caused by continuous contact between the nozzle and the deposited material. This critical issue emphasizes the need for material selection in nozzle fabrication, particularly the need for wear-resistant materials like tungsten carbide, hardened steel, or ceramic-based coatings. Furthermore, nozzle geometry optimization may reduce the localized stresses that intensify wear. There is a need for further research and development of advanced nozzle designs and materials to reduce wear in FDM processes, especially for abrasive composite materials.

Another critical issue in FDM printing nozzle design is nozzle clogging, which has a significant impact on print reliability and quality. According to studies, nozzle clogging is usually caused by uneven material flow, the presence of unmelted material, and the low molten polymer viscosity. These issues are exacerbated in composite filaments, where fibre reinforcements and fillers can obstruct the nozzle's narrow channels. Such obstructions not only disrupt material flow but also cause additional wear on the nozzle, worsening the problem and lowering overall print quality. Current FDM machines lack advanced sensing mechanisms that can monitor extrusion flow and nozzle conditions in real-time. This limitation reduces the ability to detect and mitigate clogging issues quickly, especially when printing complex geometries and high-performance composite materials.

Sukindar et al. (2016) investigated the issue of hot-end clogging, focusing on the thermal conditions that cause this fault. A 3D finite volume model of the hot end was formulated to conduct numerical simulations to supplement experimental measurements, and the two methods agreed well. The findings showed that overheating the heat barrier causes the filament's heated length to exceed the glass transition temperature, resulting in filament buckling under extruder motor force and eventual clogging. The lack of *in situ* monitoring is especially critical when processing fiber-reinforced composites, where clogging is more likely due to the abrasive and non-uniform nature of the reinforcements. In regard to this, Hıra et al. (2022) employed the Goertzel algorithm to detect clogging-specific frequencies emitted during driver gear slippage in real-time using a low-cost microcontroller. Experimental validation confirmed the approach's reliability and efficiency, making it a practical solution for timely fault identification. The use of acoustic analysis, particularly with the Goertzel algorithm, represents a significant step forward in enhancing the reliability of material extrusion 3D printing. This approach not only mitigates the risk of damage but also reduces material wastage and improves overall process efficiency.

Future research should concentrate on improving nozzle designs with optimized internal geometries to facilitate smoother material flow and reduce clogging risks. The thermal management of FDM printers should also be improved to increase their reliability and efficiency. Sharma et al. (2021) addressed the issue of overheating in the tube above the nozzle in FDM printers, which can result in material melting and extrusion failure. Using Ansys simulation software, two novel nozzle designs were proposed: one with heat sinks around the tube and one with an insulated pipe to prevent overheating. Both designs were found to be effective at maintaining optimal temperature conditions, allowing for consistent material extrusion, and broadening the application of FDM technology. Polyimide and Teflon were found to be the best materials for tube insulation and convection factor optimization, with a recommended film coefficient of 20 W/m^2 °C for forced convection in diffuser tubes. These advancements improve thermal management, increase the reliability of FDM printing, and extend the life of critical components.

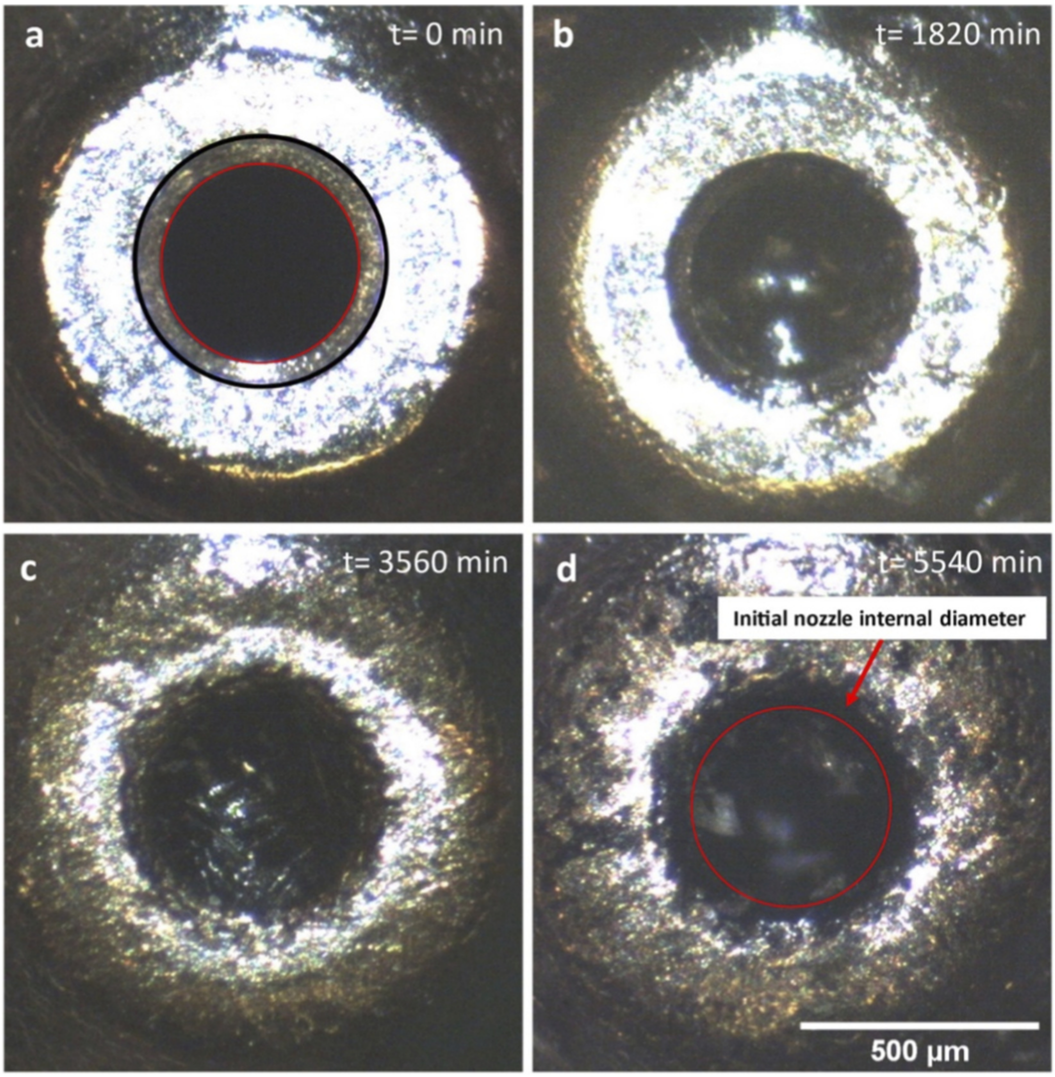

FIGURE 5
Profile comparison of FDM nozzle before and after wear (Mushtaq et al., 2023). **(a)** Wear-free nozzle at 0 min, **(b)** 1820 min and **(c)** 3560 min; **(d)** worn nozzle after 5,540 min of operation, illustrating significant abrasion due to material contact.

4.1 Additional technical considerations for nozzle design

The performance of an FDM nozzle depends strongly on the flow resistance inside the melt channel, which determines the pressure required to maintain a steady extrusion rate. For most polymer filaments, the melt can be approximated as a non-Newtonian shear-thinning fluid, in which the pressure drop increases sharply as the nozzle diameter decreases. A practical estimate can be made using the simplified Hagen-Poiseuille relationship, which, although derived for Newtonian fluids, provides a useful first-order approximation for design decisions. For example, reducing the nozzle diameter from 0.4 mm to 0.3 mm can nearly double the required pressure for an extrusion speed of 5–10 mm/s, depending on the melt viscosity of PLA or PETG. This is consistent with experimental findings in which small-diameter nozzles exhibit higher flow resistance, greater temperature sensitivity, and a higher likelihood of melt instabilities.

Similarly, the extrusion pressure varies with print speed. When the deposition velocity is increased, the polymer enters the nozzle with less residence time for heat transfer, which increases the apparent viscosity and consequently the pressure drop. In practical terms, a 20%–30% increase in printing speed may require a 40%–50% increase in extrusion force for high-viscosity materials such as fibre-filled composites. These relationships provide practitioners with a clearer basis for choosing nozzle diameters when balancing resolution, flow stability, and required motor torque.

Nozzle wear prediction can also be approached using simplified abrasive wear models. Reinforced filaments containing carbon fibres or mineral particles cause gradual enlargement of the orifice diameter. Using Archard's wear relationship, the wear volume is proportional to the product of abrasive load, sliding distance, and a material-specific wear coefficient. For a typical carbon-fibre PLA, this means that steel nozzles may show measurable dimensional change after 15–20 h of printing at moderate flow rates, whereas hardened steel or tungsten carbide nozzles exhibit significantly slower wear. Including these estimates helps practitioners select nozzle materials based on anticipated print duration and filament abrasiveness.

5 Application areas of additive manufacturing

Additive manufacturing (AM) is increasingly being adopted across medical, electronic, and automotive engineering sectors due to its ability to fabricate complex, customised geometries with reduced material waste (Bianchi et al., 2024). In the healthcare domain, AM enables the production of patient-specific bioresorbable stents and anatomically accurate tissue scaffolds, which support improved biological performance and functional integration (Taheri et al., 2022; Lambos et al., 2020). Similarly, the use of architected triply periodic minimal surface (TPMS) structures has advanced bone tissue engineering, providing enhanced porosity control and mechanical compatibility with native bone (Yang et al., 2022).

In electronic engineering, rapid developments in conductive polymer printing have enabled the fabrication of components with reliable electrical characteristics suitable for sensors, OLEDs, flexible circuits, and energy-storage devices (C et al., 2025). AM is also gaining relevance in construction and building technologies, where multi-material printing allows integration of circular-economy principles, flame-retardant fillers, and lightweight structures. Recent studies highlight the potential of bio-derived fillers and foamed geopolymers to produce sustainable, fire-resistant, and low-carbon construction materials using AM processes (Dallal et al., 2025; Yasmin et al., 2025).

Recent studies have also highlighted specific waste-to-value pathways within FDM-based polymer processing. Recycled PLA and PET waste streams have been reprocessed into usable filaments with mechanical properties sufficiently close to virgin materials for non-critical functional parts (Wakjira et al., 2025; Khan et al., 2025). Industrial and agricultural residues such as biochar, lignocellulosic powders, and fruit-waste-derived fillers have similarly been incorporated into PLA and ABS matrices to enhance stiffness, thermal behaviour, or flame-retardant performance (Soni et al., 2025; Amin et al., 2025). In addition, multiple works report that failed prints and process scrap can be re-extruded into new feedstock with only a 10%–15% reduction in tensile strength after controlled recycling cycles (Hidalgo-Carvajal et al., 2023). These findings demonstrate that AM can effectively upcycle low-value waste polymers and residual biomass into functional composites, reinforcing its potential within broader circular-economy and waste-valorisation frameworks (A et al., 2024; Gammino et al., 2025; Mania et al., 2025; Rocha et al., 2025).

In industrial environments, several of the techniques discussed in this review are being adapted for higher-volume or semi-continuous manufacturing. Multi-nozzle printers, automated filament handling, and controlled thermal environments are increasingly employed to improve production rate and consistency, particularly for functional polymer components. Process monitoring tools such as inline temperature control and extrusion-flow tracking help stabilise interlayer bonding in long build cycles. However, scale-up remains challenged by deposition-rate limitations, heat accumulation in large parts, and the need for consistent rheological behaviour when recycled polymers or waste-derived fillers are used. These considerations illustrate both the opportunities and practical constraints in translating FDM from prototyping to more industrially relevant, waste-aware manufacturing pathways.

6 Conclusion

This review highlights the significant role of process optimization, nozzle design innovation, and post-processing refinement in advancing sustainable additive manufacturing of polymers and composites. Key findings indicate that precise control of extrusion temperature, build orientation, and infill parameters enhances interlayer bonding and mechanical reliability, while customized nozzle geometries improve melt uniformity and minimize printing defects. Post-processing treatments, particularly annealing and surface modifications, further enhance component durability and aesthetic quality, contributing to extended product life cycles.

From a sustainability perspective, the interdependence of these parameters offers a pathway toward energy-efficient and waste-minimized production. The integration of recycled polymers, biodegradable composites, and eco-friendly post-processing methods represents a crucial step in closing the material loop within additive manufacturing. Future developments should focus on multi-objective optimization frameworks that couple mechanical performance with environmental impact metrics, enabling the design of processes that are both technologically and ecologically optimized.

In conclusion, optimizing FDM processing parameters and material strategies holds immense promise for waste-to-value transformation, where discarded polymers can be re-engineered into functional, high-performance components. By aligning additive manufacturing innovations with sustainable engineering principles, this work underscores the potential of FDM to serve as a cornerstone technology in the transition toward a circular and resource-efficient manufacturing ecosystem.

7 Future directions

The post-processing of 3D-printed polymers and composites is an emerging area of research with significant potential for enhancing the properties and applications of additively manufactured parts. The future trends and research directions in this field are to focus on addressing the essential limitations of 3D printing processes and growing the functionality of printed components. One key area of development is the improvement of interlayer bonding and mechanical properties through post-processing techniques. Annealing has shown the ability to enhance the interlayer tensile strength of 3D printed composites for amorphous polymers when the annealing temperature is above the glass transition temperature. Future research may explore optimized annealing protocols for different polymer composite systems and investigate other thermal treatments to further improve mechanical performance.

An interesting trend is the use of metallization as a post-processing technique for 3D-printed polymer composites. The physical vapour deposition sputtering has been applied to coat recycled glass fibre-reinforced polymers which direct to new possibilities and material reuse in different applications. This approach could be extended to other types of composites of carbon fibre-reinforced polymers and can be applied to the development of hybrid materials with unique properties.

Hence, future research in the post-processing of 3D printed polymers and composites should consider addressing key challenges such as delamination, surface quality, and mechanical properties. Innovative approaches such as annealing, metallization, and surface treatments will be crucial in increasing the capabilities and applications of 3D-printed parts. Additionally, post-processing techniques enable dynamic transformations and self-healing properties in printed structures, advancing the progressive field of 4D printing. The integration of these advanced post-processing methods with emerging printing technologies and materials will be essential for realizing the full potential of additive manufacturing in various industries.

Author contributions

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