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Additive manufacturing of polymers and composites for sustainable engineering applications

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Additive manufacturing has rapidly emerged as a transformative and inherently sustainable technology in engineering. It enables the fabrication of components with minimal or near-zero material wastage. While additive manufacturing was initially focused on metals, it now includes polymers, ceramics, composites, and biomaterials, providing an efficient platform to produce sustainable materials. This review provides a comprehensive overview of additive manufacturing techniques for non-metal materials and emphasises their potential to minimise waste, promote resource circularity, and support sustainable production. Particular attention is given to polymer-based techniques such as fused deposition modelling, stereolithography, and selective laser sintering. These techniques offer design flexibility, reduced material wastage, and compatibility with recycled and bio-based feedstocks. This review highlights the major advantages and practical applications of polymer-based materials in biomedical engineering, microelectronics, flame-retardant and conductive systems, and multifunctional composites. While most limitations are presently observed in flame-retardant systems, a comparative discussion is also provided for the other application domains to maintain balance across the sections. Additionally, emerging research on sustainable and bio-derived polymers such as PLA and PHB reinforced with carbonised biomass or eco-friendly conductive fillers is introduced to emphasise environmentally responsible pathways for developing next-generation conductive materials. Overall, this review highlights additive manufacturing as a sustainable pathway for material valorisation and innovation within waste-to-material and waste-to-energy frameworks.

KEYWORDS
3D printing, biomedical, fire retardant, conductive polymers, microelectronics applications, waste minimisation

1 Introduction

Additive manufacturing, also known as 3D printing, has revolutionised the manufacturing industry by enabling the fabrication of complex objects layer by layer, directly from digital designs (Wong and Hernandez, 2012). Initially focused on metal materials, additive manufacturing has now expanded its scope to include a wide range of non-metal materials such as polymers, ceramics, composites, and biomaterials. This shift has opened up new possibilities and applications across various industries, including healthcare, aerospace, automotive, consumer goods, and more (Vafadar et al., 2021; Han and Lee, 2020).

The versatility of non-metal additive manufacturing techniques lies in their ability to utilise the unique properties of different materials, allowing the production of parts with tailored characteristics such as flexibility, transparency, high strength-to-weight ratio, and bioactivity. Additionally, additive manufacturing offers advantages such as reduced material waste, design complexity without cost implications, and rapid prototyping, enabling faster product development cycles and customisation capabilities (Attaran, 2017; Javaid et al., 2021).

The field of 3D printing has witnessed remarkable advancements in recent years. Various 3D printing techniques have been developed, each with its unique working principles and capabilities. These techniques have found diverse applications in fields ranging from engineering and manufacturing to healthcare and design (Sahini et al., 2020; Haleem and Javaid, 2019).

Previous research works have extensively explored the potential of different 3D printing techniques and their applications. Figure 1 shows the evolution of 3D printing and its significance in various applications. Gibson et al. (2010) provided a comprehensive overview of additive manufacturing technologies, including FDM, SLA, and SLS. Their research highlighted the wide range of applications, from rapid prototyping to direct digital manufacturing, enabled by these techniques.

Bártolo and Bártolo (2011) investigated the materials, processes, and applications of SLA. They discussed how SLA, which utilises a light source to selectively cure liquid resin, is widely employed for producing high-resolution prototypes and intricate components. The author also emphasised the significant role of SLA in dental modelling and other specialised applications.

Kruth et al. (2004) provided valuable insights into SLS, a technique that utilises a laser to fuse powdered materials selectively. Their research highlighted the potential of SLS in producing complex geometries, functional prototypes, and end-use parts. They explored the process, microstructure, and properties of pure alumina powder produced through SLS.

Tammas-Williams et al. (2015) focused on EBM, a technique that employs an electron beam to melt metal powder, leading to fully dense metallic components. Their study examined the microstructure and mechanical properties of titanium alloy produced through EBM, showcasing its applications in industries such as aerospace, medical, and automotive.

Chaudhary et al. (2023) conducted a review on DLP, a technique that utilises a digital light projector to selectively cure photopolymer resin. Their research shed light on the exposure systems, materials, and applications of DLP-based 3D printing. They highlighted its significance in wearables, soft robotics, dentistry, and consumer products.

This review builds upon prior research by providing a concise overview of emerging 3D printing techniques and their applications in sustainable engineering. It examines recent advances in additive manufacturing of polymers and composites, emphasizing their role in material efficiency, design flexibility, and circular production. The insights presented aim to enhance understanding of sustainable

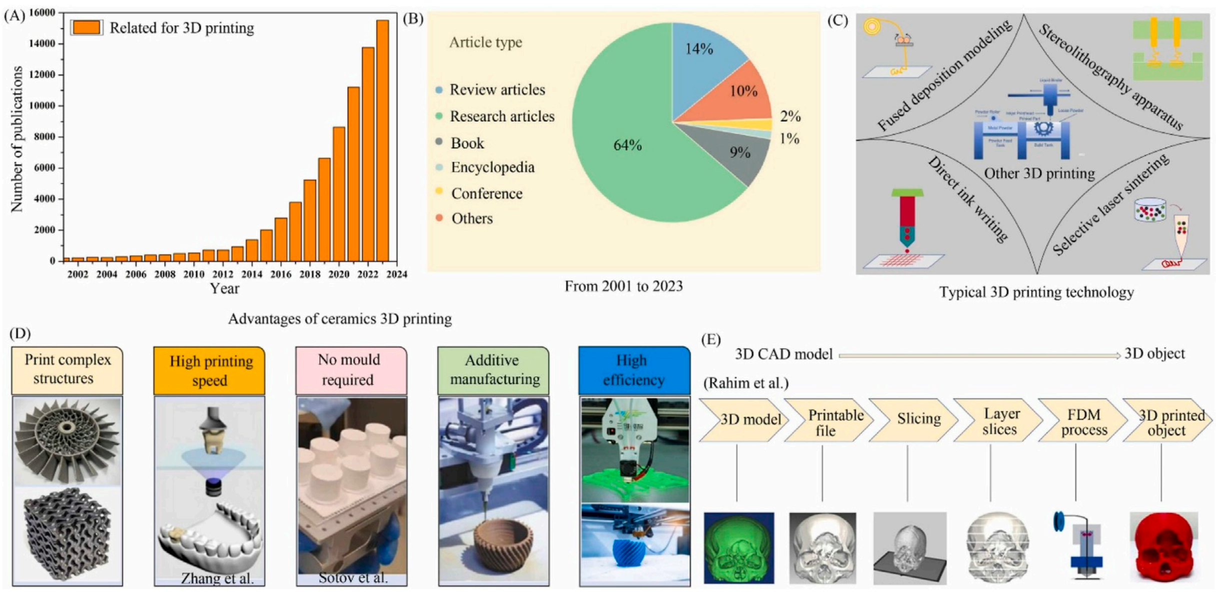

FIGURE 1
The year-wise Elsevier B.V. data on 3D printing-related works published from 2001 to 2023 **(A,B)**. Various 3D printing technologies **(C)** and the merits of additive manufacturing **(D)**. Generalised 3D printing process flow **(E)** (Wang et al., 2024a).

additive manufacturing and guide future research and innovation in this rapidly evolving field.

2 3D printing of polymers for biomedical applications

Non-metal 3D has proven particularly impactful in areas such as bioprinting, where living cells and biomaterials are used to create complex 3D structures. This technology holds promise for tissue engineering, regenerative medicine, and organ transplantation (Ahangar et al., 2019). Non-metal 3D printing also plays a crucial role in drug delivery systems, allowing for precise fabrication of personalised drug formulations and controlled-release implants. Surgical guides and instrumentation benefit from this technology as well, as it enables the production of patient-specific tools that enhance surgical precision and improve patient outcomes. In the field of prosthetics and orthotics, non-metal 3D printing has transformed the industry by offering custom-fit, lightweight, and affordable solutions. Dentistry has also greatly benefited from non-metal 3D printing, enabling the creation of accurate dental models, surgical guides, and customised restorations (Zadpoor, 2017). The technology is instrumental in medical education and training, providing realistic anatomical models for hands-on learning experiences and surgical practice (Han et al., 2019; Fairag et al., 2019). Additionally, non-metal 3D printing accelerates research and development in the biomedical field, facilitating rapid prototyping and the creation of intricate medical devices. With its continued advancement, non-metal 3D printing holds great promise for further advancements in personalised medicine, patient care, and the development of innovative medical technologies (Norman et al., 2017).

Unlike conventional subtractive manufacturing, AM allows tailoring of porosity, geometry, and mechanical properties to match biological requirements, thereby minimising implant failure due to mechanical mismatch (Koch et al., 2022). Hutmacher (2000) demonstrated that polymer scaffolds fabricated through FDM exhibited tunable pore sizes and compressive strengths, making them adaptable for diverse tissue engineering needs. Their work showed that adjusting processing parameters directly influenced structural rigidity, thereby highlighting the importance of mechanical design in tissue regeneration. This study emphasised that scaffold stiffness must be carefully matched with the target tissue to prevent premature degradation or functional failure.

Xu et al. (2006) investigated extrusion-based printing of PCL scaffolds and reported compressive moduli between 5 and 20 MPa, suitable for cancellous bone applications. They observed that porosity could be precisely controlled by altering nozzle diameter and deposition speed. The inference from this work is that mechanical engineers can fine-tune scaffold properties by coupling material selection with process control, ensuring that both strength and porosity requirements are simultaneously satisfied.

Similarly, PLA scaffolds produced *via* FDM have been widely studied. Wang et al. (2016) reported that neat PLA exhibited high structural integrity but limited osteoconductivity. By blending PLA with HA, they observed a significant improvement in bioactivity along with enhanced compressive strength, making it more suitable for load-bearing implants. This finding illustrates how combining polymers with ceramic fillers can balance biological compatibility and mechanical robustness. Also, some researchers reported that pore size and infill orientation significantly influenced the compressive modulus of the scaffold, demonstrating that design parameters in additive manufacturing directly dictate mechanical integrity. This finding highlights the role of mechanical optimisation in ensuring scaffold reliability under physiological loads (Bose et al., 2018; Khamvongsa et al., 2025).

Lee et al. investigated the mechanical behaviour of PCL scaffolds fabricated *via* extrusion-based 3D printing for bone tissue engineering applications. They reported that altering void sizes and stacking (infill) directions significantly influenced compressive and tensile strength of the scaffolds under physiological loading. For instance, they compared homogeneous designs with 0.3 mm, 0.6 mm, and 0.9 mm void sizes and gradient designs; compressive strength varied roughly by a factor of 1.4–3 × depending on location and geometry. Cubo mateo and Lorenzo (Cubo-Mateo and Rodríguez-Lorenzo, 2020) investigated the mechanical behaviour of PCL, focusing on "hidden" parameters such as layer orientation and cooling rate. They reported that scaffolds printed with alternated (0°/90°) orientation exhibited a compressive modulus of approximately 8.6 MPa, while those printed without alternation (n-ALT) had a significantly lower modulus of about 2.1 MPa.

Likewise, Wang et al. (2016) reported that neat PLA exhibited high structural integrity but limited osteoconductivity. By blending PLA with HA, they observed a significant improvement in bioactivity along with enhanced compressive strength, making it more suitable for load-bearing implants. This finding illustrates how combining polymers with ceramic fillers can balance biological compatibility and mechanical robustness. Beyond extrusion, light-based techniques offer finer resolution. Melchels et al. (2010) showed that SLA printing of PEGDA scaffolds produced feature sizes as small as 50 μm with compressive strengths of 2–10 MPa. They found that curing parameters such as exposure time governed the resulting modulus.

Hydrogel-based bioprinting has also gained prominence for soft tissue engineering. Ouyang et al. (2016) observed that alginate-gelatin blends exhibited shear-thinning behaviour during extrusion, enabling smooth deposition. Post-print ionic crosslinking improved the compressive modulus to 0.2–0.5 MPa, appropriate for soft tissue scaffolds.

Murphy and Atala (2014) demonstrated the use of hydrogel-based printing for soft tissue constructs and reported that layer thickness directly influenced tensile response and viscoelasticity of the printed gels. Mechanical analysis revealed anisotropic responses between layers, an issue commonly reported in polymer-based additive manufacturing. Curvello et al. (2019) further explored nanocomposite hydrogels reinforced with cellulose nanofibers and found a significant increase in compressive modulus compared to neat hydrogels. Their inference was that nanofiller reinforcement enables the design of mechanically robust soft tissue scaffolds while retaining biocompatibility. The load transfer between polymer chains and rigid nanofillers provided improved stress distribution, an effect that can be systematically optimised through micromechanical modelling. As illustrated in Figures 2,

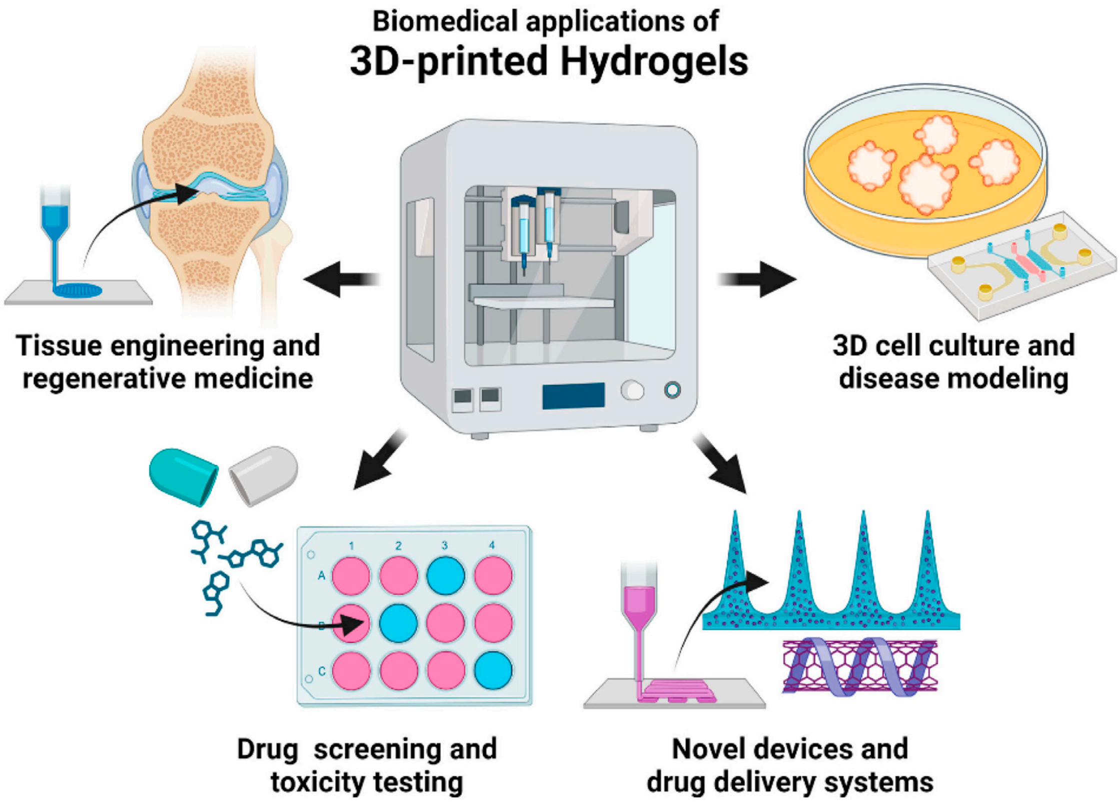

FIGURE 2
Typical biomedical applications of 3D-printed hydrogels (Barcena et al., 2024).

3D-printed hydrogels have found broad applications in biomedical engineering, including soft tissue and cartilage regeneration, wound healing, and localised drug delivery. These examples highlight the adaptability of hydrogel-based systems to mimic native tissue environments while enabling precise control over mechanical and biological functionality.

From the perspective of prosthetics, polymer-based additive manufacturing has enabled lightweight yet mechanically durable solutions. Ten Kate et al. (2017) reported that prosthetic hands produced through SLS of nylon-12 exhibited tensile strengths exceeding 48 MPa, sufficient for daily functional use. Their study also integrated finite element modelling to predict stress distribution during gripping, followed by experimental validation. In another study, Hua et al. (2022) reported the successful use of 3D-printed PLA-based stents, observing that printing orientation directly affected radial compressive resistance. Implants printed along the circumferential direction exhibited enhanced load-bearing capacity compared to longitudinal orientations.

A comparison of the above approaches reveals that each printing technique and material class fulfils a distinct biomedical area. Extrusion-based methods such as FDM and direct ink writing offer cost-effectiveness, scalability, and the ability to fabricate porous scaffolds with sufficient mechanical strength for bone tissue engineering, although their resolution remains limited relative to light-based methods. In contrast, SLA and DLP provide superior resolution and smoother surface finishes, which are particularly advantageous for applications in cartilage and dental implants. However, the photocurable resins typically employed often lack the toughness needed for load-bearing roles. Hydrogel-based bioprinting delivers the most biomimetic environment, especially for soft tissue and cell-laden constructs, but the inherent weakness of hydrogels necessitates hybrid strategies that reinforce them with polymers or ceramics. Powder-based methods such as SLS strike a balance between durability and design flexibility, rendering them promising for prosthetics and long-lasting implants, though issues of cost and powder handling persist. Collectively, the reviewed studies indicate that no single technique is universally superior, with the choice depending on the targeted tissue, the desired mechanical performance, and biological integration requirements. Hybrid approaches, for example, combining extrusion-printed PCL frameworks with hydrogel infillings are increasingly pursued to integrate mechanical robustness with biological functionality. Despite these advances, notable research gaps remain. Most investigations prioritise compressive strength while neglecting critical aspects such as fatigue resistance, viscoelastic behaviour, and long-term degradation under physiological conditions. Furthermore, computational modelling has yet to be fully utilised to complement experiments, even though it could significantly reduce trial and error in optimising implant geometry and load-bearing capacity. Finally, translation to clinical practice demands standardised testing protocols, reliable sterilisation techniques, and clearer regulatory pathways to ensure safety and reproducibility in patient-specific biomedical applications. Taken together, these studies highlight the

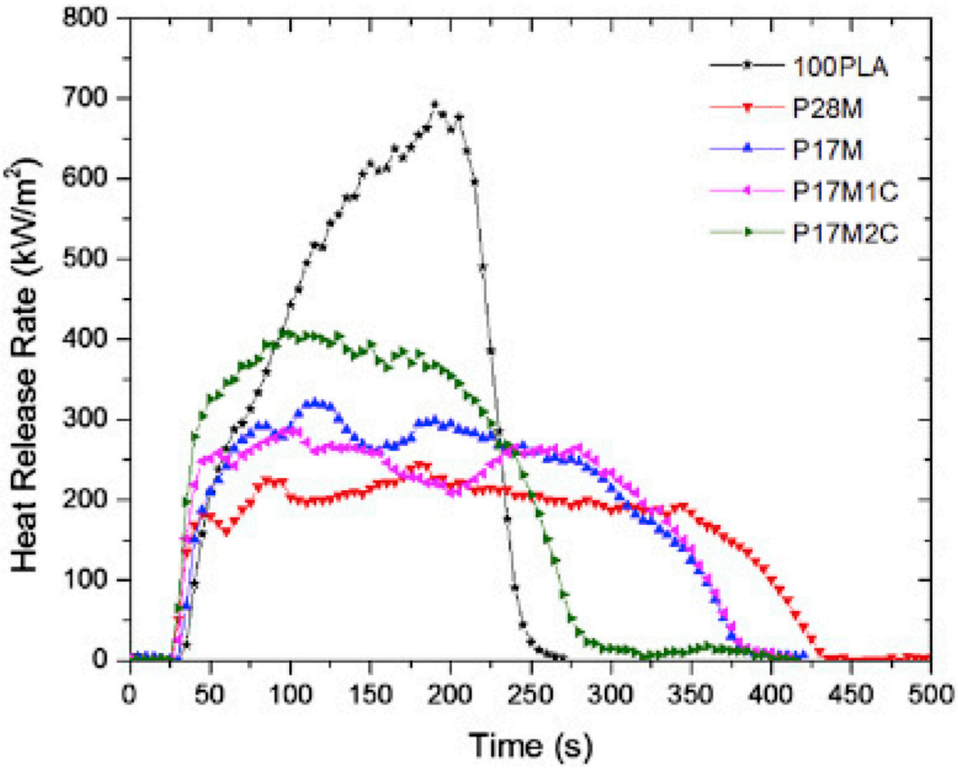

FIGURE 3
Effect of FR addition on the PLA flammability (Guo et al., 2017).

TABLE 1 Summary of 3D-printed non-metallic materials, processes, and mechanical outcomes in biomedical applications.

Material/System	Printing technique	Mechanical properties	Biomedical relevance	References
PCL	Extrusion-based 3D printing	Compressive modulus: 5–20 MPa (tunable porosity *via* nozzle/layer control)	Suitable for cancellous bone scaffolds	Xu et al. (2006)
PLA + HA	FDM	Improved stiffness and osteoconductivity	Enhances load-bearing capacity for bone regeneration	Wang et al. (2016)
PEGDA hydrogel	SLA	Feature size ~50 µm; compressive strength: 2–10 MPa	Mimics cartilage-like structures	Melchels et al. (2010)
Alginate-gelatin hydrogel	Extrusion with ionic crosslinking	Compressive modulus: 0.2–0.5 MPa	Soft tissue scaffolds; tunable rheology for printability	Ouyang et al. (2016)
Alginate-gelatin + Graphene oxide	Extrusion	Enhanced tensile strength and fatigue resistance	Improves long-term stability in soft tissue engineering	Ouyang et al. (2016)
Nylon-12 (prosthetic hand)	SLS	Tensile strength: >48 MPa	Lightweight, durable patient-specific prosthetics	ten Kate et al. (2017)

transformative potential of non-metallic 3D printing across diverse biomedical domains. Yet, the diversity of materials, printing modalities, and mechanical behaviours makes it clear that no single approach can fully meet the complex demands of clinical translation. To provide a clearer perspective, Table 1 consolidates key materials, printing processes, and their mechanical outcomes, while Table 2 outlines persistent research challenges and emerging directions. These summaries not only highlight current progress but also serve as a roadmap for future innovations in personalised, reliable, and clinically viable biomedical devices.

While the biomedical sector has demonstrated the versatility of polymer-based additive manufacturing, its potential extends far beyond biocompatible materials. In recent years, similar printing principles have been adapted for structural and functional applications, including flame-retardant and conductive polymer systems. Among these, fused deposition modelling (FDM) remains the most widely studied technique due to its design flexibility, process simplicity, and compatibility with a broad range of thermoplastics (Bugdayci et al., 2025).

TABLE 2 Research challenges and future directions in 3D printing of polymer-based biomedical materials.

Focus area	Current progress	Challenges	Future research directions
Mechanical performance	Polymers like PCL, PLA, and composites show promise in bone scaffolds and implants	Limited load-bearing capacity compared to metals; anisotropy due to printing orientation	Development of polymer-ceramic/metal hybrids; optimisation of print parameters for isotropy
Biocompatibility and bioactivity	PLA, PCL and PEG are widely used for tissue engineering	Lack of long-term biocompatibility data; limited bioactivity without modification	Functionalisation with bioactive molecules (e.g., growth factors, HA)
Surface properties	Surface modification improves cell adhesion and growth	Achieving consistent surface topography in complex geometries	Use of *in-situ* plasma treatment, laser texturing during printing
Degradation and longevity	Polymers degrade at controllable rates	Mismatch between degradation and tissue regeneration rates	Smart polymers with tunable degradation triggered by physiological conditions
Precision and resolution	Micro-extrusion and SLA enable high-resolution scaffolds	Tradeoff between resolution and print speed	AI/ML-based process control for accuracy without sacrificing throughput
Multi-material printing	Emerging techniques allow printing polymers with fillers or drugs	Poor interfacial bonding between dissimilar materials	Research into interfacial chemistry and co-extrusion mechanisms
Regulatory and scalability	Proof-of-concept studies successful	Lack of standardised protocols for clinical translation	Establishment of ISO/ASTM standards for biomedical 3D printing
Sustainability	Use of biodegradable polymers	Environmental concerns with support/waste	Recycling of support materials; bio-derived feedstocks for medical-grade filaments

3 Fire-resistant materials for FDM 3D printing

Additive manufacturing *via* FDM has expanded the use of thermoplastics in complex, customised parts across aerospace, transportation, electronics, and construction. However, a critical barrier for deploying FDM parts in safety-critical applications is the inherent flammability of most printable polymers (Aguirresarobe et al., 2024; Babu et al., 2021). Common FDM thermoplastics like PLA and ABS ignite easily and burn rapidly, failing stringent fire-safety standards (e.g., UL-94 or EN 45545; Babu et al., 2021). For instance, Figure 3 presents the HRR profiles of neat PLA (100PLA) and its modified composites (P28M, P17M, P17M1C, and P17M2C). The unmodified PLA exhibited a sharp rise in HRR, reaching a maximum of approximately 700 kW/m^2 within 150 s, followed by a rapid decline, which reflects the inherent flammability and fast-burning nature of the polymer. In comparison, all modified samples demonstrated markedly reduced peak HRR values and extended combustion durations, indicating that the additives effectively suppressed flame intensity and altered the burning dynamics. Notably, the P17M2C formulation displayed the lowest and most delayed HRR peak, suggesting superior flame-retardant efficiency, likely attributable to enhanced char formation and barrier effects (Guo et al., 2017).

This section examines the latest developments in fire-resistant FDM materials, focusing on polymer-based approaches. Three main strategies are discussed: (1) intrinsically flame-retardant polymers, (2) polymer composites with flame-retardant additives, and (3) surface treatments or coatings. For each, key findings are summarised, effectiveness *versus* limitations are evaluated, and the trade-offs in mechanical strength, printability, and fire performance are highlighted. Finally, research gaps are identified with proposed future directions, arguing that further material innovations are needed to achieve FDM parts that are both mechanically robust and fire safe.

3.1 Intrinsically flame-resistant polymers for FDM

One approach is to use or develop thermoplastics that inherently resist ignition and flame spread, without additives. High-performance engineering polymers such as PEI (e.g., ULTEM 9085; Sabic, 2024; Glaskova-Kuzmina et al., 2023) and certain PEEK (VICTREX, 2016; Ramgobin et al., 2020) grades are naturally flame-retardant, meeting UL-94 V-0 and aerospace fire standards. For instance, PEI-based filaments can self-extinguish and exhibit low smoke toxicity, making them suitable for aircraft interior parts. However, these polymers require very high processing temperatures and specialised printers, which are costly. Their use is thus limited to high-end applications. Recent research is exploring chemically modified polymers that incorporate flame-retardant elements, like phosphorus or nitrogen, into the molecular backbone. By doing so, flame resistance is built into the material's structure. For example, novel phosphorus-containing polyamides have been synthesised that char readily and self-extinguish without additives (Sun et al., 2023; Lu P. et al., 2020). Such intrinsically flame-retardant polymers promise excellent fire performance with minimal compromise to base polymer properties. The challenge is ensuring these new polymers remain printable *via* FDM, i.e., they must melt and flow appropriately and bond between layers. So far, only a few specialty filaments (like PEI blends or certain self-extinguishing nylons) are commercially available, and their mechanical properties (e.g., toughness) and ease of printing often lag behind more common materials (Wang et al., 2021; 3DGENCE).

Nonetheless, the development of intrinsic flame resistance is a promising direction. Unlike additive-filled composites, intrinsic FR polymers can avoid high filler loadings that often embrittle the material. They also circumvent issues of additive dispersion or migration over time. Going forward, rational polymer design, for example, copolymerising bio-based flame-retardant units (phosphonates, aromatic char formers, *etc.*), could yield filament materials that meet fire safety codes out of the box. Early successes in this area support the feasibility: even low concentrations of phosphorus (~1–5 wt%) in a polymer can achieve UL-94 V-0 ratings and high LOI (Babu et al., 2021). The key will be to balance these flame-retardant modifications with the thermal and rheological requirements of the FDM process.

3.2 Sustainable flame-retardant additives and composites

The most widely explored strategy is incorporating FR additives into standard thermoplastics to create composites that can pass fire tests (Teles et al., 2022). A broad spectrum of halogen-free FR additives has emerged in recent years, falling into several categories. These FR systems are considered sustainable because they reduce toxic gas release, minimise halogen-based additives, and often use naturally abundant or recyclable elements. Intumescent and mineral-based systems offer low environmental impact, while graphite, carbon nanomaterials, and organophosphates enhance fire resistance through eco-friendly, thermally stable, and recyclable composite formulations.

3.2.1 Intumescent systems (phosphorus/nitrogen)

These additives cause the polymer to form a swollen char layer when heated. A common example is APP or MPP, often used with char-forming synergists. Intumescent formulations are very effective in the condensed phase, creating an insulating carbonaceous foam that protects the underlying plastic (Hu et al., 2020). For instance, PLA composites with ~17% MPP achieved a UL-94 V-0 rating (self-extinguishing) and LOI ~29%, whereas neat PLA fails UL-94 and has LOI ~20%. The char from intumescent additives can be robust and cohesive, significantly slowing heat release. In one study, adding just 1% of a nanoclay (Cloisite 30B) with 17% MPP in PLA improved the dispersion and char integrity, resulting in an intumescent char that greatly reduced flammability (Babu et al., 2021). However, excessive additives can backfire, e.g., 2% nanoclay caused aggregation that worsened flame performance by disrupting the FR mechanism. Thus, formulation optimisation is critical.

3.2.2 Mineral fillers (hydroxides, oxides)

Inorganic additives like ATH or magnesium hydroxide release water when heated, cooling the material and diluting combustible gases. They are inexpensive and non-toxic but typically require very high loadings (30–60 wt.%) to be effective, which can severely degrade the polymer's mechanical strength and printability. In PLA, ATH at modest loading (15%–30%) did improve flame resistance but also induced hydrolytic degradation of the polyester, cutting the polymer molecular weight and embrittling the printed part (Aguirresarobe et al., 2024). High filler content also alters melt flow, often causing nozzle clogging or poor layer adhesion in FDM. Thus, while metal hydroxides are safe flame retardants, their use in 3D printing is limited unless combined with other synergists to reduce the required amount. Relevantly, Liang et al. analysed the heat resistance of PP-based flame-retardant composites using Vicat softening and heat deflection temperatures. Synergistic effect of $Al(OH)_3$, $Mg(OH)_2$, and small amounts of zinc borate improved thermal stability, with higher filler content generally enhancing these temperatures, while larger particle sizes reduced them. Uniform dispersion of the hybrid fillers within the PP matrix helped to achieve better properties (Liang et al., 2011).

3.2.3 Expandable graphite and carbon nanomaterials

Carbon-based additives are receiving attention for their ability to form protective networks. Figure 4 shows group of carbon materials used as flame retardant to improve the flame retardancy of polymeric matrix. EG flakes intumesce (expand) when heated, creating a thermal shield of graphite char (Maalihan et al., 2023). EG can be effective at lower loadings (~10 wt%), for example, a recent study coated PLA prints with a thin intumescent layer containing ~9.8% EG and APP, which adhered well and significantly improved the fire resistance of the PLA part. Internally mixing EG into filaments is also possible, though uniform dispersion is challenging. Other carbon nanofillers like CNTs and Gr can reinforce char and reduce peak heat release by creating a heat-dissipating network (Babu et al., 2021). These nanomaterials can also add mechanical strength. However, they are expensive and can affect viscosity; moreover, achieving a homogeneous mix in the filament extruder is non-trivial.

3.2.4 Organophosphates and others

Besides APP/MPP intumescents, a variety of phosphorus-based flame retardants, often in the form of organophosphate esters or DOPO-derivatives, have been developed (Vafadar et al., 2021). These can act in the gas phase (quenching flame radicals) and condensed phase to promote char. Some newer FR additives are silicone-based (forming silica-rich char) (Morgan and Kilinc, 2021; Hamdani et al., 2009) or nitrogen-based (e.g., melamine derivatives) (Grabner, 1999). Many commercial FR grades of ABS or PC use proprietary blends of these additives. For example, a flame-retardant ABS filament might contain bromine- or phosphorus-based additives that give it a UL-94 V-0 rating at 3 mm thickness (Guo et al., 2017; Geoffroy et al., 2019). The general trend in research is toward halogen-free formulations due to environmental and health concerns. Halogenated FRs (brominated, *etc.*) have largely been phased out despite their high efficacy (Mensah et al., 2022a).

In evaluating these FR composites, studies show that many formulations can dramatically reduce flammability metrics of FDM materials. Cone calorimeter tests (which measure heat release during burning) illustrate these gains. For instance, adding biochar or lignin-derived char as a filler in polypropylene was found to cut the peak heat release rate by ~70% (Babu et al., 2021). In 3D-printed PLA, effective FR additives (like APP or MPP) lead to lower peak heat release and total heat released, moving the material into safer regimes (Aguirresarobe et al., 2024). Table 3 typically shows FR composites self-extinguish faster and leave more residual char.

Crucially, researchers observed that for a given material formulation, the fire behaviour of FDM-printed samples was often comparable to that of conventionally moulded samples (Lorenzi et al., 2024). In other words, the presence of layer lines and print porosity did not drastically worsen flame spread if the material's composition had a flame-retardant. This is an encouraging finding, indicating that well-formulated FR

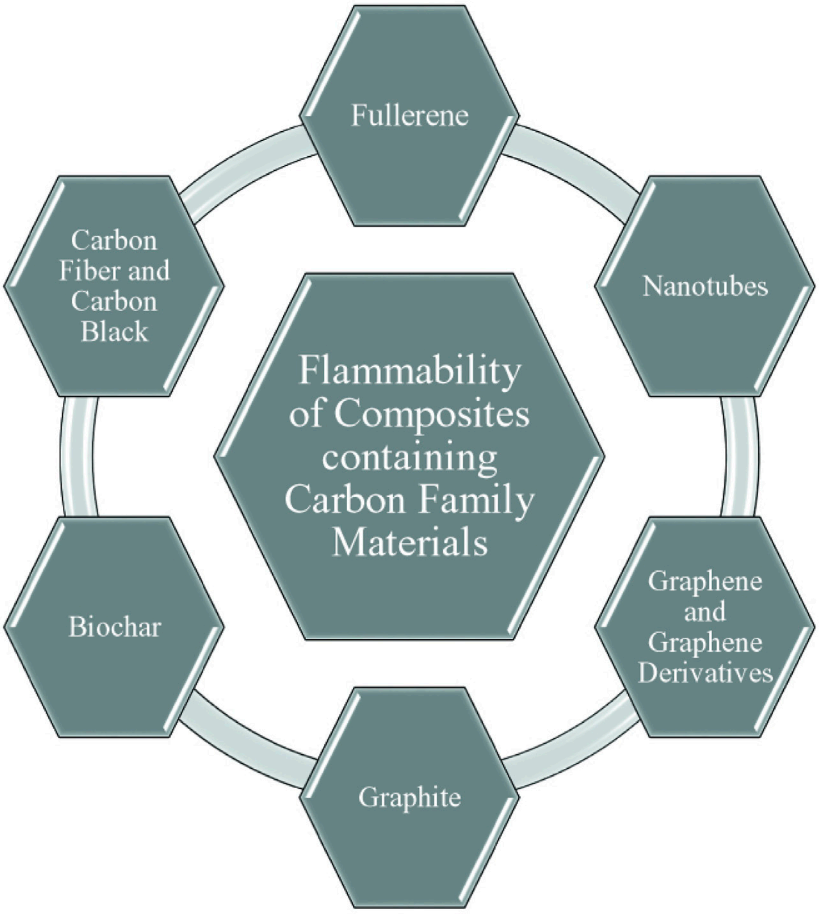

FIGURE 4
Typical carbon-based fillers used as flame retardants (Babu et al., 2020).

TABLE 3 Fire properties of FR 3D printed materials.

Material/ Composite	Flame retardant Additive(s)	UL-94 rating	LOI (%)	PHRR (kW/m^2)	Char residue (%)	References
PLA + 2% APP + 0.12% RDP	APP + RDP	V-0	26	~340	~20	Wang et al. (2024b)
PLA + 17% MPP + 1% C30B	MPP + Nanoclay	V-0	31	~240	~25	
PLA + EG@PCDAC	Expandable Graphite (Modified)	V-0	30.3	~310	~35	Chen et al. (2025)
ABS + 20% PAPP + AlPi	Phosphorus/Nitrogen IFR	V-0	30.8	~150	~40	Ghonjizade-Samani et al. (2024)
ABS + PIN coating	Phosphinate coating (surface applied)	V-0	29	~190	~30	Chen et al. (2022)
PC + 0.02% KTSS	Silylated Sulfonate	V-0	34.4	~180	~30	Lu et al. (2020b)
PEI (neat, Ultem)	None (Inherent)	V-0	47	~160	~50	Sulkis et al. (2018)

composites retain their efficacy in printed form. However, one caveat is that the porous infill typical in FDM can exacerbate flammability by allowing more oxygen access to the interior of parts (Mensah et al., 2022b). Densely printed or solid sections will perform better in fire than highly porous infill patterns.

Despite the progress, flame-retardant composites face the perennial trade-off: adding fillers or flame retardants often deteriorates mechanical properties and can impair printability. The case of PLA with EG or ATH highlights this (Perroud et al., 2022). While fire performance improves, the base polymer's molecular weight and strength can drop significantly due to thermal or hydrolytic side reactions. High loadings (e.g., >20 to 30 wt%) of any additive tend to embrittle the filament and make extrusion more difficult. Recent work seeks to mitigate these issues by using synergistic combinations of additives so that each can be used at lower amounts. For example, nano clays or graphene oxide are added in small quantities alongside primary FR additives to promote char formation more efficiently, allowing a reduction in the total filler content. Another strategy is using fibre reinforcement (glass or carbon fibre) together with flame retardants. The fibres can help restore mechanical stiffness and anchor char residue during burning. Some studies on carbon-fibre-reinforced ABS have shown improved UL-94 ratings when a flame-retardant coating is applied, with the carbon fibre skeleton helping to hold the char layer (Xu 2025). Overall, flame-retardant composites are currently the most practical solution for FDM, but optimising the formulation to balance flame retardancy and mechanical performance is complex and often specific to each polymer and application.

3.3 Surface treatments and coating strategies

Instead of modifying the bulk material, an alternative approach is to apply flame-retardant coatings or treatments to finished 3D prints. This can be especially useful for retrofitting existing materials or adding fire protection to only the surface of a part. One common method is to coat the print with an intumescent paint or varnish. These are commercially used on building materials and can also be applied to plastics. For FDM parts, researchers have developed coatings that deposit a thin protective layer rich in flame retardants. As mentioned, one study created a coating composed of APP, boric acid, and expandable graphite that could be cast onto a PLA part; upon drying, the coated part passed flammability tests that the uncoated PLA would fail (Maalihan et al., 2023). The coating swells into a charred foam when ignited, protecting the plastic underneath. The advantage of such surface treatments is that they do not require altering the filament formulation, so the part can be printed normally, and only afterwards is it made fire-resistant. This is attractive for maintaining the original polymer's printability and strength since the base polymer is unchanged.

PA6 softens quickly when subjected to flames, causing molten dripping that can accelerate fire propagation. Therefore, incorporating flame-retardant additives is essential to enhance its fire safety. To fix this, Kovács et al. applied various combinations of MgO, RP, and EG as flame retardants in PA6 and found the best combination (i.e., MgO and RP combined with EG). Further, they have used this as FR coating on CF/PA6 composites. From Figure 5, a notable synergistic effect was observed when EG was combined with either RP or MgO. A 0.5 mm thick coating with 5% RP and 5% EG lowered the composite's pHRR by 21% and by 28%. Similarly, the formulation with 5% MgO and 5% EGES100 resulted in a 27% reduction in pHRR and a 37% decrease in THR (Kovács and Toldy, 2024).

However, coatings also have limitations. They may add thickness or alter dimensions slightly, which can be an issue for tight-tolerance parts. Their durability is a concern: if the coating scratches or delaminates, the underlying plastic is exposed and flammable again. Adhesion between the coating and an FDM surface, which is often layer-rough, must be strong to avoid delamination during a fire. Encouragingly, formulations like the E.G.,/APP coating have shown good adhesion to PLA (Maalihan et al., 2023). Another surface approach is chemical infusion, where the printed object is soaked in or sprayed with a flame-retardant solution that penetrates slightly below the surface. For example, soaking a PLA print in a phosphoric acid-based solution can infuse phosphorus into the outer layers, improving flame resistance modestly. There has also been exploration of plasma deposition of flame-retardant thin films or sol-gel coatings (embedding inorganic flame retardants in a silica matrix on the surface). These techniques are still experimental but represent a growing area of research (Malucelli, 2020; Bardon et al., 2015).

Multi-material printing can be seen as a form of "built-in" surface treatment: e.g., printing a two-material part where the outer shell is a flame-retardant polymer and the inner core is a standard polymer provides a similar outcome. Geoffroy et al. (2019) demonstrated such a core-shell FDM design: a lightweight infill printed from regular ABS was encased in a shell of ABS blended with ATH or E.G., yielding a part with improved fire performance at lower overall FR additive content. This approach leverages the flexibility of 3D printing design to put the flame-retardant material where it is most needed, the surface, while keeping the majority of the part with the higher-strength base material. The result was a 30%–50% weight reduction compared to a solid FR composite part, yet with comparable flame retardancy. Such innovations blur the line between material development and structural design. They highlight how FDM's freedom in geometry can be utilised to solve material limitations.

3.4 Performance trade-offs and limitations

Achieving a balance between mechanical strength, thermal stability, and flame retardancy in FDM materials remains a complex challenge. Intrinsically FR polymers like PEI and phosphorus-modified nylons avoid the need for bulky additives but often suffer from brittleness, warping during printing, or processing difficulties due to high melting temperatures. While these materials can meet UL-94 V-0 and LOI >30%, they must demonstrate comparable tensile and impact performance to more widely used FDM polymers like ABS or PLA to gain broader acceptance (Lu P. et al., 2020; Ventura et al., 2017). Additive-filled composites-such as PLA combined with APP, MPP, or expandable graphite (EG)-have been shown to reach excellent flame retardancy, yet their mechanical properties often deteriorate at high filler loadings due to reduced ductility and increased brittleness.

Surface coatings such as intumescent paints or phosphinate-based layers provide an alternative route to flame retardancy without modifying the filament composition. While effective in forming insulating char during burning, these coatings can crack under mechanical stress or fail if fire originates internally, limiting their protective scope. More broadly, efforts to improve fire resistance, such as increasing char yield or elevating thermal stability, often result in trade-offs like reduced printability or stiffness. For instance, highly charring additives may hinder interlayer bonding or reduce

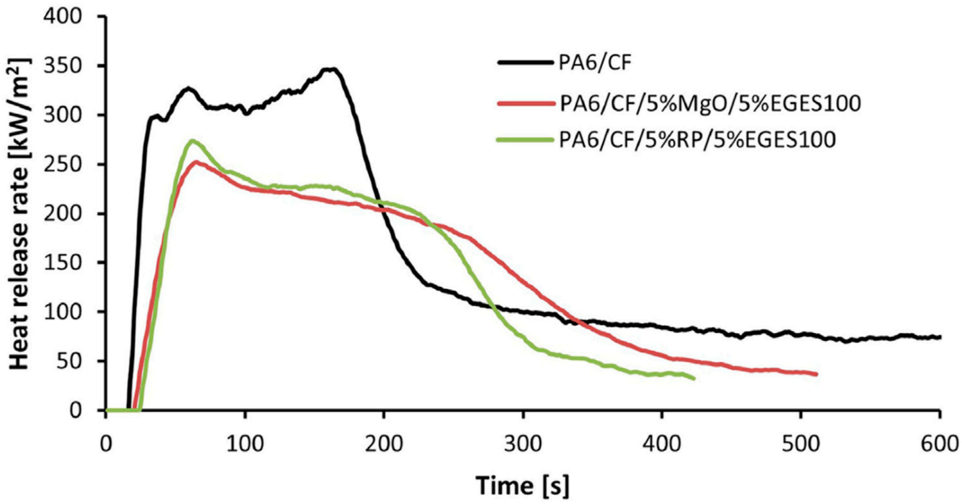

FIGURE 5
The HRR of CF/PA6 and PA6 samples with FR coating measured by mass loss type cone calorimetry (Kovács and Toldy, 2024).

elongation at break (Aguirresarobe et al., 2024). As demonstrated in cone calorimeter tests, different flame-retardant formulations leave varied residual char, reflecting differences not only in fire behaviour but also in mechanical integrity post-exposure.

3.5 Research gaps and future directions

Despite notable advances in recent years, several gaps remain in the state of the art of fire-resistant FDM materials. First, there is a need for new material chemistries that break the traditional trade-off between mechanical performance and flame retardancy. This could involve nanostructured additives that provide fire protection at very low loadings, for example, catalytic nanoparticles that promote char at 1–2% loading, or cross-linkable filaments that can be cured after printing to enhance fire resistance without fillers. Exploring bio-derived flame retardants is another promising avenue: compounds like phytic acid, tannins, or lignin have been researched as sustainable flame retardants (Chen et al., 2025) and integrating them into filaments could yield materials that are both eco-friendly and fire safe. Early studies with lignin, for instance, show it can increase char yield in polymers and reduce peak heat release (Babu et al., 2021), all while being a low-cost waste product from biomass.

Another research gap is understanding the interaction of print parameters with flammability. Most studies so far prepare standardised samples (like slabs) for fire testing, but real FDM parts can have varying infill percentages, layer orientations, and internal air gaps. Systematic investigations of how infill density or layer thickness affects flame spread would be valuable. A sparse infill might mean less fuel to burn, but as noted, it can also allow flames to penetrate and oxygen to circulate (Mensah et al., 2022b; Lopes et al., 2023). Finding an optimal printing strategy (maybe denser outer walls for protection and a sparse core for less fuel) could enhance fire performance without material changes. The core shell printing strategy mentioned earlier is one example of design mitigating material limits (Grabner, 1999); more complex multi-material designs (e.g., printing a flame-retardant barrier only in critical regions of a part) could be explored with the latest multi-nozzle printers.

From a standards perspective, current flammability tests (UL-94, LOI, cone calorimetry, *etc.*) were developed for traditional plastic specimens. Standardising tests for 3D-printed parts is a future need. Researchers have started to compare 3D-printed vs. injection-moulded samples in fire tests, generally finding similar results if the material is the same (Martins et al., 2022). But there might be unique behaviours (like delamination under flame or preferential burning along layer lines) that are not captured by standard testing of bulk material. Fire safety agencies may need to consider certifying process-material combinations for additive manufacturing (similar to how aerospace certifies specific 3D-printed materials for use in aircraft interiors). Developing predictive models for 3D print fire behaviour, incorporating material properties and print geometry, would greatly aid in designing safer parts and materials.

In terms of material innovation, reactive flame retardants that can be grafted onto polymer chains during filament production are an exciting area. These would act like intrinsic FR polymers but could start with existing commodity polymers (e.g., grafting a phosphate onto ABS). Additionally, self-extinguishing coatings that can be 3D-printed onto a part (perhaps *via* an inkjet or aerosol jet process) might allow fine control of where fire protection is applied. The future might see hybrid processes where an FDM printer lays down the structural polymer and simultaneously or subsequently deposits a flame-retardant ink in critical areas.

4 FDM printed conductive polymers

The fabrication of electrically conductive components using FDM has gained significant momentum in recent years, primarily through the development of polymer composites filled with conductive additives. Traditional FDM-compatible polymers, such as PLA, TPU, and PC, are typically insulating (Li et al., 2016).

4.1 Carbon-based fillers as conductive fillers

To impart electrical conductivity, these matrices are loaded with conductive fillers including CB, CNTs, Gr, metallic nanoparticles, and hybrid filler systems (Saberi et al., 2024; Ma et al., 2009; Yan et al., 2007; Guohua et al., 2025). The incorporation of such conductive fillers facilitates the formation of conductive networks within the polymer matrix. Achieving a well-connected conductive network, governed by the percolation threshold, is critical for enabling continuous electron transport pathways within FDM-printed conductive composites, thereby imparting electrical conductivity while maintaining mechanical integrity (Yan et al., 2023; Pejak Simunec and Sola, 2022). However, precisely reaching the percolation threshold without significantly exceeding it remains challenging, as excessive filler content can lead to agglomeration, nozzle clogging, reduced interlayer adhesion, and a deterioration of mechanical properties (Hamoud et al., 2024). Among these, carbon nanotubes and Gr have attracted particular attention due to their exceptional intrinsic electrical conductivity and ability to form percolated networks at relatively low filler loadings (Al-S et al., 2023; Gnanasekaran et al., 2017), making them ideal candidates for high-performance FDM-printed conductive composites. For instance, Yang et al. (2019), Kruth et al. (2004) investigated the effects of CNT content and processing parameters on the electrical resistivity of FDM-printed PLA/CNT composites. The electrical resistivity of pure PLA was initially measured at 1×10^{12} Ω/m^2, which decreased significantly to 1×10^6 Ω/m^2 with the addition of 2 wt.% CNT, and further dropped to 1×10^2 Ω/m^2 at 8 wt.% CNT loading. It is also important to optimise the FDM process parameters since factors such as filling velocity, liquefier temperature, and layer thickness have a significant influence on the final electrical properties. A lower filling velocity, higher liquefier temperature, and greater layer thickness were found to minimise electrical resistivity, with the lowest value recorded at 14.9 Ω/sq. It was reported that the Improved CNT dispersion and enhanced interlayer bonding under optimised conditions contributed to the superior conductivity of the printed composites. Kwok et al. (2017) reported the development of conductive polypropylene (PP)-based thermoplastic composites suitable for electrical circuit fabrication using FDM-based 3D printing. A resistivity below 10^{-2} Ω m was achieved in composites with CB loadings of ≥30 wt.%, and practical circuit printing was demonstrated with composites containing ≥25 wt.% filler, successfully operating with a 9 V battery. Stress tests under UV exposure (~0.5 mW/cm^2 for 1 month), electrical loading (12 V AC for 1 week), and thermal conditions showed low variability in resistance (<5%), confirming the stability of the composites. The electrical performance of the CB/PP composites was comparable to that of commercial Gr/PLA filaments, while offering superior thermal stability (up to 130 °C) compared to CB/PCL and Gr/PLA systems. However, the composites exhibited poor adhesion with common FDM polymers like ABS and PLA, suggesting the need for future improvements in interfacial compatibility through material formulation strategies.

The circuit is powered through a 9 V battery. The conductive track and supporting structure are shown in black and white, respectively. The conductive track was printed using conductive 29.8% CB/PP composites, and the supports are printed with nonconductive ABS. Additionally, two modules were manually assembled (right side in Figure 6) and connected through sockets and pins to form an extended 3D circuit (Kwok et al., 2017).

Camargo et al. evaluated (Camargo et al., 2022) the electrical properties of Gr/ABS composites using the four-point probe method. The results showed an average electrical conductivity of 2.46×10^{-1} $(\Omega{\cdot}m)^{-1}$, classifying the material as a semiconductor. This confirms that incorporating Gr into ABS can significantly enhance its conductivity compared to pure ABS, although the composite remains within the semiconducting range rather than reaching metallic conductivity levels.

Typically, printing parameters have a significant effect on the formation and quality of conductive networks within FDM-printed nanocomposites. Parameters such as raster angle, layer thickness, print speed, and extrusion temperature directly influence the alignment, dispersion, and interconnection of conductive fillers. Optimising these parameters is essential to achieving lower percolation thresholds, higher electrical conductivity, and improved overall performance, while poor control can lead to disrupted conductive pathways, increased junction resistance, and degraded electrical properties. In this context, Dorigato et al. (2017) reported that the electrical resistivity was strongly decreased by CNT addition even at limited filler contents (i.e., 1 wt%), demonstrating the effectiveness of nanotubes in enhancing conductivity. However, the 3D printing process itself led to a partial loss of electrical conductivity, particularly in horizontal and vertical build configurations. This reduction in conductivity during printing further resulted in a lower surface temperature increase in the printed samples, highlighting the detrimental effects of filament deposition and orientation on conductive network continuity. Sezer and Eren (2019) investigated the electrical conductivity behaviour of 3D printed MWCNTs/ABS nanocomposites. Electrical conductivity measurements showed that pure ABS exhibited typical dielectric, non-conductive behaviour; however, the addition of just 3 wt.% MWCNTs induced a transition from insulator to conductor for specimens printed at a raster angle of [0, 90], attributed to the formation of continuous conductive pathways. Further increases in MWCNT content up to 5 wt.% resulted in additional, but less pronounced, conductivity enhancement. The [0, 90] raster samples achieved percolation and conductivity at a lower MWCNT loading compared to the [−45, 45] raster samples, due to improved continuity of traces. This study confirms the critical influence of raster angle on the electrical performance of FDM-printed nanocomposites, where optimal fibre or particle alignment along the current path significantly lowers the percolation threshold and enhances conductivity. Misalignment of conductive pathways, as observed in the [−45, 45] orientation, introduces higher junction resistance and disrupts network continuity, thereby requiring higher filler contents to achieve comparable conductivity levels. Lima et al. (2025) investigated the role of infill density and infill pattern on the electrical properties of mutual capacitance sensors fabricated using FDM with conductive PLA filaments. Their study demonstrated that reducing infill density from 100% to 50% significantly increased electrode resistance (from 1.9 kΩ to 6.8 kΩ), due to increased

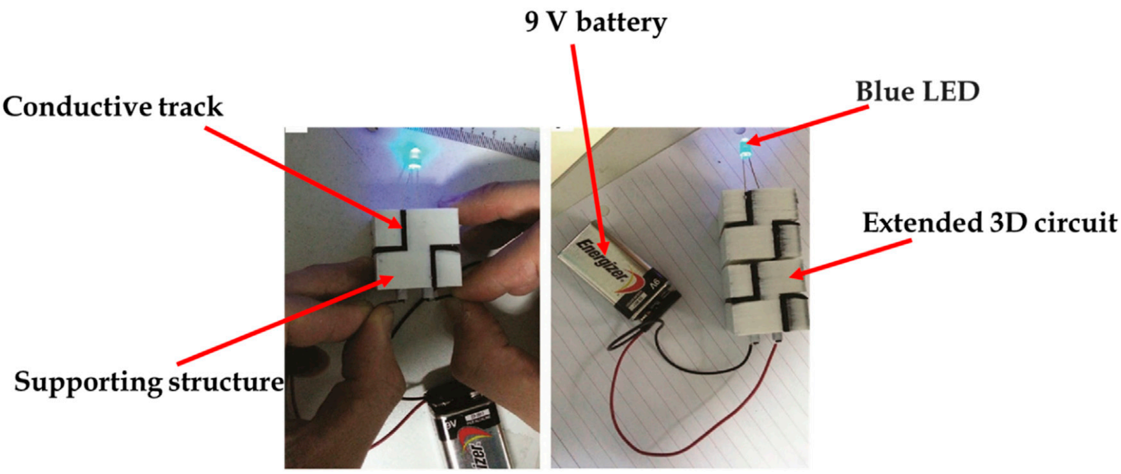

FIGURE 6
A modular 3D circuit connected to a blue LED (left) and a manually interconnected extended 3D circuit (right) (Kwok et al., 2017).

microporosity and weaker filament bonding. In contrast, variations in infill pattern at fixed 70% infill had minimal effect on resistance, although concentric patterns exhibited slightly lower resistance. Interestingly, the capacitance of the printed sensors, ranging from 0.5 pF to 2.2 pF under external stimuli, remained largely independent of both infill density and pattern. These findings indicate that material usage and production time can be optimised without degrading capacitive performance, supporting the feasibility of low-cost, customisable capacitive sensors for human–machine interface applications *via* FDM.

Sanatgar et al. (2019) reported the development of 3D printable filaments based on conductive polymer nanocomposites using a melt mixing process. MWNTs and high-structured CB (Ketjenblack, KB) were incorporated into a PLA matrix. The percolation threshold was determined to be 0.54 wt% for MWNT composites and 1.7 wt% for KB composites, as measured by the four-point resistance method. It was observed that the filament diameter remained independent of MWNT loading but increased with higher KB content. The electrical conductivity of extruded filaments exhibited a dependence on the extruder temperature at low filler contents, where conductivity decreased with increasing temperature; however, at higher filler loadings, extruder temperature had no significant influence. Additionally, the electrical resistance of the printed tracks decreased exponentially with increasing cross-sectional area, demonstrating the importance of both material composition and printing geometry in achieving optimal conductivity in 3D printed structures.

To further support the impact of hybrid carbon nanofillers on electrical and thermal properties, the study by Ivanov et al. (2019) provides valuable insights into the synergistic effects of combining GNPs and MWCNTs in PLA matrices. Electrical conductivity increased by 7–8 orders of magnitude in mono-filler systems, with MWCNTs showing a stronger effect than GNPs. Hybrid composites (PLA/3%GNP/3%MWCNT and PLA/1.5%GNP/4.5% MWCNT) exhibited synergistic effects, achieving higher conductivity than mono-filler systems due to MWCNTs bridging GNPs and limiting aggregation. Thermal conductivity improved by 181% in PLA/GNP composites but showed no synergy in hybrids because thermal transport was mainly governed by GNP content. To further highlight the importance of hybrid nanofillers in 3D-printed functional materials, Mohapatra et al. (2023) developed PLA-based composites reinforced with CNT-ZnO core-shell structures for FDM-printed TENGs. The incorporation of only 0.2 wt% CNS increased the electrical conductivity by five orders of magnitude and enhanced the output voltage from 1 V to 8.9 V. Mechanical properties were also significantly improved, with tensile strength increasing by 48.5% compared to neat PLA. The study emphasised that optimised FDM parameters such as 20% infill, 0.1 mm layer thickness, and doughnut pattern further boosted device performance. These results demonstrate that hybrid fillers not only enhance intrinsic material properties but also synergistically improve energy harvesting capabilities when combined with controlled printing strategies. Additionally, Doagou Rad et al. (2018) explored the development of hybrid PA6 composites filled with GNPs and metal microfibers. The combination of nanoscale Gr and microscale metal fillers significantly enhanced the composite properties, achieving up to 120% improvement in mechanical strength compared to metal-only composites. Thermal and electrical conductivities were also greatly improved, with post-annealing treatment yielding an additional 151% increase in thermal conductivity and 72% increase in electrical conductivity. GNPs acted as conductive bridges across gaps, facilitating denser conductive networks and contributing to improved interfacial bonding within the polymer matrix.

Compared to filler particles such as carbon nanotubes and Gr, carbon fibre-based conductive networks behave differently during FDM processing. Galos et al. (2021) reported that continuous carbon fibre filaments experienced a ~40% reduction in longitudinal conductivity after printing (from ~13,500 S/m to ~8,100 S/m) due to fibre breakage. The 3D printed unidirectional laminates exhibited ~50% lower conductivity compared to hot-moulded laminates, while transverse and through-thickness conductivities increased by approximately 13 and 3 times, respectively, due to enhanced fibre waviness. These findings highlight that while continuous carbon fibre reinforcement offers superior inherent conductivity compared to filler-based systems, the mechanical damage introduced during the FDM process-particularly fibre breakage and induced waviness-can severely degrade longitudinal electrical performance. Therefore, careful optimisation of FDM printing conditions, such as minimising filament bending, controlling extrusion pressures, and refining deposition paths, is critical to preserving fibre continuity and maximising the electrical performance of fibre-reinforced 3D printed composites. Moreover, new strategies, such as gentler feed mechanisms or *in-situ* healing techniques, may be necessary to fully exploit the advantages of carbon fibre architectures in additive manufacturing.

4.2 Metallic and ceramic fillers in conductivity enhancement

Metal-filled filaments, such as copper-PLA composites, have also demonstrated excellent electrical performance. For instance, Nassar and Dahiya (2021) investigated the fabrication and electrical performance of embedded 3D-printed circuits using a copper-based Electrify filament *via* FDM printing. They demonstrated that lateral infill orientation significantly reduced the resistance of 1 mm-wide tracks by approximately 75% compared to longitudinal infill, although this effect diminished for wider tracks. The study achieved printed track resolutions of 0.67 mm compatible with SOIC-packaged integrated circuits, using a 0.25 mm nozzle. Electrical characterisation revealed that exposed tracks could sustain higher currents (~16 mA) compared to embedded tracks (~11 mA), primarily due to improved heat dissipation. Key factors influencing conductivity included the filler content, percolation network, polymer thermal properties, oxidation during extrusion, and whether the conductor was embedded or exposed. The results highlight that although fully FDM-printed circuits currently lag traditional PCB technologies in resolution, with optimised parameters and material strategies, reliable digital data transmission and embedded circuit fabrication are achievable.

In another research, Jayanth et al. (2022) demonstrated that 3D printed CB/ABS composites achieved a maximum EMI shielding absorption of 12.95 dB at 2.4 GHz with 15 wt.% CB addition. However, this improvement in electrical properties came at the cost of reduced tensile and impact strengths. This trade-off highlights the need for optimising filler content and printing parameters to maximise multifunctional performance while minimising mechanical degradation. Their study further emphasised that although high filler loadings improve conductivity and shielding effectiveness, excessive amounts can compromise structural integrity, limiting the practical applications of such composites in load-bearing environments. Yang et al. (2024) developed CNT/PA6 filaments tailored for FDM, targeting both mechanical reinforcement and electrical functionality. The addition of CNTs significantly improved tensile strength (112% increase with 12 wt% CNT) and reduced surface resistivity by seven orders of magnitude, enabling conductive pathways essential for sensor applications. However, the study also highlights the typical trade-off: while CNTs enhance conductivity and dielectric properties, they can restrict polymer chain mobility, slightly lowering the glass transition temperature (Tg) and potentially complicating filament printability. The FDM-printed capacitive sensors achieved high sensitivity (0.0319 kPa^{-1}), fast response (60 ms), and long-term stability, demonstrating that a careful balance between mechanical integrity and electrical performance is critical for functional device fabrication. Bodin et al. (2024) demonstrated a fine-tuned approach for balancing thermal conductivity, electrical insulation, and mechanical properties in polymer nanocomposites by using AgNW@SiO_2 core–shell structures. By optimising the silica shell thickness to ~20 nm, they achieved a significant fifteen-fold improvement in in-plane thermal conductivity (3.48 ± 0.06 $W{\cdot}m^{-1}{\cdot}K^{-1}$) compared to neat PC, while maintaining electrical resistivity above 10^{12} Ω cm. The mechanical performance also benefited, as the use of the silica shell enhanced interfacial adhesion, leading to a ~20% increase in Young's modulus and recovery of tensile strength and elongation that were otherwise reduced with uncoated AgNWs. However, they observed that increasing the SiO_2 shell beyond 20 nm caused a decline in thermal conductivity (~10–15%), attributed to increased phonon scattering and modulus mismatch at the interface. This highlights the importance of carefully controlling the shell thickness to achieve a favourable trade-off between thermal transport, insulation, and mechanical integrity in nanocomposite systems.

Current applications of FDM-printed conductive polymers span several fields, including flexible strain and pressure sensors, EMI shielding materials, wearable electronics, soft robotics, and lightweight energy storage devices. For instance, Li et al. (2022) developed flexible strain sensors *via* FDM using TPU filled with 12 wt.% CB, achieving a high gauge factor of 2.653 in S-shaped zigzag designs. The sensors exhibited excellent cyclic stability (>3,000 cycles), fast response (~120 m), and low hysteresis (3%–6%). Additionally, Peng et al. (2023) developed FDM-3D printed LLDPE composites reinforced with BN@GNPs *via* ball milling, forming double networks for efficient heat and EMI management. The vertically printed part reached 3.11 W/m·K thermal conductivity and 27.8 dB EMI shielding at only 3.51 vol% GNPs. This approach enables lightweight, multifunctional parts suitable for next-generation thermal and electronic applications. The introduction of multi-material and dual-nozzle FDM printers allows simultaneous printing of conductive and insulating polymers, enabling the fabrication of integrated electronic circuits without post-assembly (Khan et al., 2025; Nazir et al., 2023; Wang Zhaogui et al., 2024). Notably, the development of 3D-printed supercapacitor electrodes using Gr-based FDM filaments has also been reported. Ferguson et al. (2025) demonstrated that chemical presoaking of conductive PLA current collectors with 6 M KOH reduced their resistance by nearly 10-fold, resulting in a five-fold increase in areal capacitance compared to untreated samples. This enhancement was attributed to improved filler network exposure, especially GNPs and carbon nanotubes embedded in the PLA matrix, which facilitated better electrochemical interfacial activity and charge transport. Looking ahead, there is a clear need for the development of next-generation conductive filaments that exhibit low percolation thresholds, high conductivity (>1 S/cm), and excellent mechanical compliance. Notably, Li et al. (2023) demonstrated that FDM-printed TPU composites reinforced with a hybrid filler system comprising MXene ($Ti_3C_2T_x$), $MnFe_2O_4$, and MWCNTs could achieve a remarkable EMI shielding effectiveness of 31.2 dB (equivalent to 99.9242% attenuation) with only 9 wt% total filler content. This performance stems from the synergistic effect of 2D–0D–1D filler interactions, which promoted the formation of a robust three-dimensional conductive network. Such architecture enabled not only efficient shielding but also high mechanical durability (tensile strength ~39.5 MPa, elongation at break ~554%) and reliable piezoresistive sensing capabilities (gauge factor up to 3.73 over 89% strain). In another study, Hu et al. (2024) further explored the electrical functionality of MXene by incorporating $Ti_3C_2T_x$-coated recycled carbon fibres into PLA matrices, achieving substantial improvements in electromagnetic shielding performance, mechanical strength, and interfacial adhesion. In parallel, sustainable strategies using bio-based polymers (e.g., PLA, PHB) reinforced with carbonised biomass or eco-friendly conductive fillers are gaining momentum to align conductive 3D printing with environmental sustainability goals.

FDM has increasingly proven its potential for fabricating complex electrical and dielectric materials with customised functionalities. Aslanzadeh et al. (2018) investigated the mechanical and electrical performance of 3D printed Nylon six parts for RF/microwave applications, demonstrating that varying infill densities and patterns can effectively tailor both mechanical strength and relative permittivity. By adjusting simple printing parameters, they enabled the low-cost, one-step fabrication of heterogeneous dielectric structures for high-frequency electronics. Similarly, Yuan et al. (2025) developed a high dielectric PVDF composite by incorporating ionic liquid (IL)-modified $BaTiO_3$ nanoparticles. Their work achieved a significant increase in β-phase content (84.01%) and a dielectric constant of 36.3 at 100 Hz, with phase stability maintained even after FDM printing. Using these materials, they fabricated a fully 3D-printed TENG with integrated friction and electrode layers, highlighting the feasibility of FDM in energy-harvesting device fabrication. Peng et al. (2025) further expanded FDM's application by creating $Ba_{0.6}Sr_{0.4}TiO_3$ (BST)/PVDF-ABS composites, achieving uniform filler dispersion and good dielectric properties. The optimised composite exhibited a dielectric constant of 18, dielectric tunability of 39.26%, and a tensile strength of 34.5 MPa, while a multi-layer capacitor with a mortise-and-tenon structure was successfully printed to demonstrate practical device performance. Xiang et al. (2020) developed highly elastic 3D-printed strain sensors based on TPU composites containing CNTs and silver nanoparticles (AgNPs). The synergistic effect between CNTs and AgNPs dramatically improved sensitivity (gauge factor up to 43,260 at 250% strain), linearity (R^2 = 0.97 within 50% strain), and stability (over 1,000 cycles). The addition of AgNPs reduced CNT aggregation, enhanced conductive network formation, and improved printability by increasing filament modulus and critical buckling pressure. Modelling based on Simmons' tunnelling theory confirmed conductive behaviour, and the printed sensors effectively monitored human motions like finger bending, wrist movement, and swallowing. Together, these studies underline that FDM, when combined with material innovations, enables the rapid and cost-effective production of advanced dielectric and energy devices with customised microstructures, offering substantial promise for applications in RF electronics, sensors, and flexible energy systems.

4.3 Future direction

Despite these advancements, achieving a balance between electrical performance and mechanical integrity remains a major technical challenge in FDM-printed conductive composites. Increasing conductive filler loading often enhances electrical conductivity and EMI shielding effectiveness but simultaneously leads to embrittlement, reduced interlayer bonding, and nozzle clogging during processing. Thus, future material development must aim to optimise this performance balance through synergistic formulations or multi-material printing strategies.

Emerging research trends suggest that multiscale hybrid filler architectures, combining nanoscale (e.g., graphene, CNTs) and microscale (e.g., carbon fibers, metallic particulates) reinforcements, could overcome the trade-off between conductivity and mechanical robustness. The use of machine learning-assisted process optimization may further enable predictive tuning of print parameters, filler dispersion, and interfacial adhesion. Moreover, *in-situ* monitoring techniques such as infrared thermography and electrical impedance mapping can provide real time feedback to ensure uniform filler distribution and defect free fabrication. Future developments in bio inspired conductive networks and self-healing polymer matrices could also address long-term reliability and damage recovery. Integrating these approaches within closed loop recycling frameworks will establish a pathway for sustainable additive manufacturing of multifunctional, high-performance composites suitable for marine, aerospace, and energy applications.

5 3D printed polymer composites for microelectronics

3D printing of various polymer composites is gaining traction in microelectronics for their capability to combine geometric complexity with functional material properties, predominantly in areas such as EMI shielding, thermal management, flexible electronics, and dielectric components (Park et al., 2022; Xue et al., 2023). Thermal or heat transfer management is vital in microelectronic devices, especially concerning surface area and enclosed environments (Nilagiri Balasubramanian and Ramesh, 2018). The advancement of information technology requires rapid-responsive electronic devices; therefore, developing high-performance polymer composites needs to be pursued. In general, polymer nanocomposites with good electrical insulation characteristics and thermal transport conductivity are preferred (Vijaybabu et al., 2023). To achieve ultra-high thermal conductivity polymer nanocomposites, it is essential to utilise state-of-the-art composite fabrication techniques and modern instrumentation. The effective improvement of thermal conductivity in polymers can be achieved through the combined use of advanced fabrication techniques like additive manufacturing and high thermal conductivity reinforcement. The role of carbon-based reinforcement is significant in enhancing the thermal conductivity of polymers and their composites (Babu et al., 2020). One way to improve the performance of electronic devices is to minimise interfacial thermal resistance between components (between the processor and the heat spreader), and another way is to enhance the thermal conductivity of individual electronic components (e.g., PCB, outer shell, *etc.*) within devices. Considering both cases, high thermal conductivity nano-fillers can be used as a reinforcement to enhance the thermal conductivity of polymer composites. For instance, Vairagade

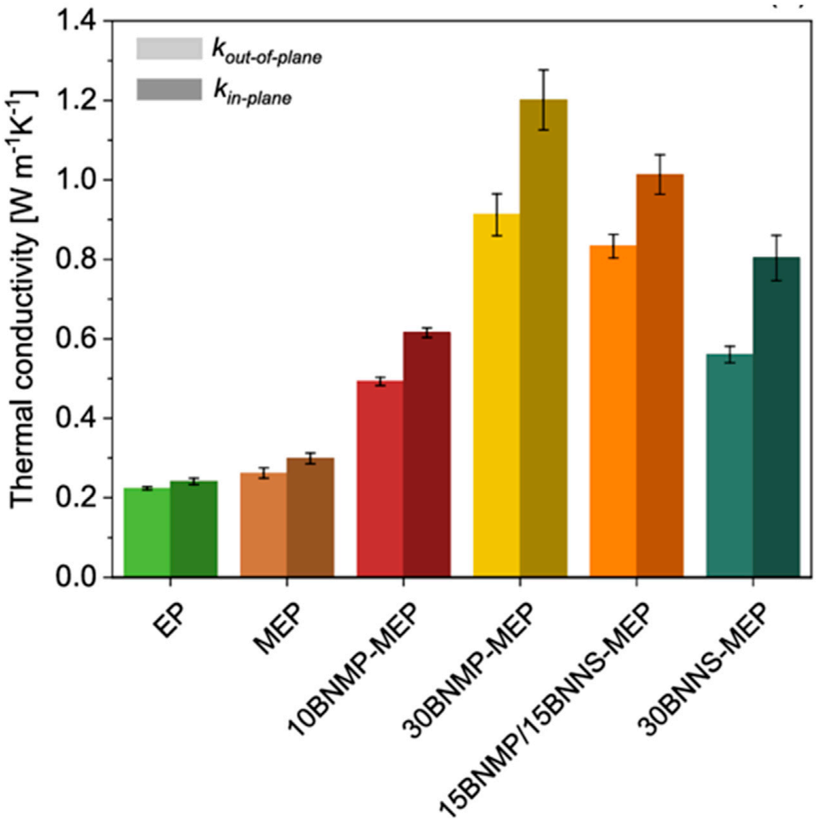

FIGURE 7
Increase in thermal conductivity of epoxy when two distinct BN fillers (Bagatella et al., 2025).

et al. (2025) utilised two different forms of carbon-based nano-fillers, namely, Gr and MWCNT, to enhance the thermal conductivity of ABS. The ABS composite exhibited a maximum thermal conductivity of 0.8 W/mK when the hybrid reinforcement consisted of 3.5 wt.% Gr and 3.5 wt.% MWCNT, which was 3.6 times higher than that of neat ABS (0.18 W/mK). This research demonstrates that the use of hybrid nano-fillers leads to a notable enhancement in thermal conductivity compared to the use of single-type reinforcements. It is important to notice that the utilisation of advanced manufacturing technology is another criterion for achieving high thermal conductivity in polymer composites. For instance, Bagatella et al. (2025) used a direct ink writing method of additive manufacturing to create a high thermal conductivity polymer composite comprising epoxy and two different types of fillers (i.e., BN microplates and BN nanosheets). They developed a 3D printable ink with high thermal conductivity and good electrical insulation, achieved through controlled orientation of BN filler. The epoxy reinforced with 30 wt.% of BN microplates showed the in-plane thermal conductivity of 1.2 W/mK (i.e. 400% higher than pure epoxy) and proved more effective than BN nanosheets (refer Figure 7). The overall interface area between the filler and the matrix is relatively higher for the nanosheet type of reinforcements compared to microplates. This is due to the higher surface area of nanosheets than that of microplates. This leads to an increased barrier effect for phonon conduction in the composites (Liu et al., 2019). Therefore, the surface area and aspect ratio can contribute to forming a good heat transport network in polymer composites (Wang et al., 2020).

5.1 Various factors on thermal conductivity enhancement

Lately, the combination of surface functionalisation with ultrasound-assisted liquid-phase exfoliation has emerged as an efficient technique for developing exfoliated h-BN. Using hydroxylated BN (OH-BN) as an intermediate, followed by ultrasonic treatment in polar solvents, yields OH-BN nanosheets containing only a limited number of hydroxyl groups on their surfaces. This technique effectively merges the benefits of mechanical exfoliation and chemical modification, offering a straightforward and scalable route to improve the dispersion of h-BN fillers in polymer matrices. For h-BN-based TIM composites, the orientation of fillers plays a crucial role in governing thermal conductivity. Consequently, constructing interconnected, directionally aligned filler networks within the polymer–particularly aligned parallel to the heat flow–has been recognised as a promising strategy to boost the thermal performance of TIMs. For instance, Su et al. prepared OH-BN and used it as reinforcement in TPU, fabricating OH-BN/TPU composites through FDM. The findings indicated that surface-functionalised (i.e., OH-BN) fillers are uniformly well distributed within the TPU through hydrogen bonding, leading to stronger interfacial adhesion between the OH-functionalised filler and TPU. At identical filler loadings, OH-BN/TPU

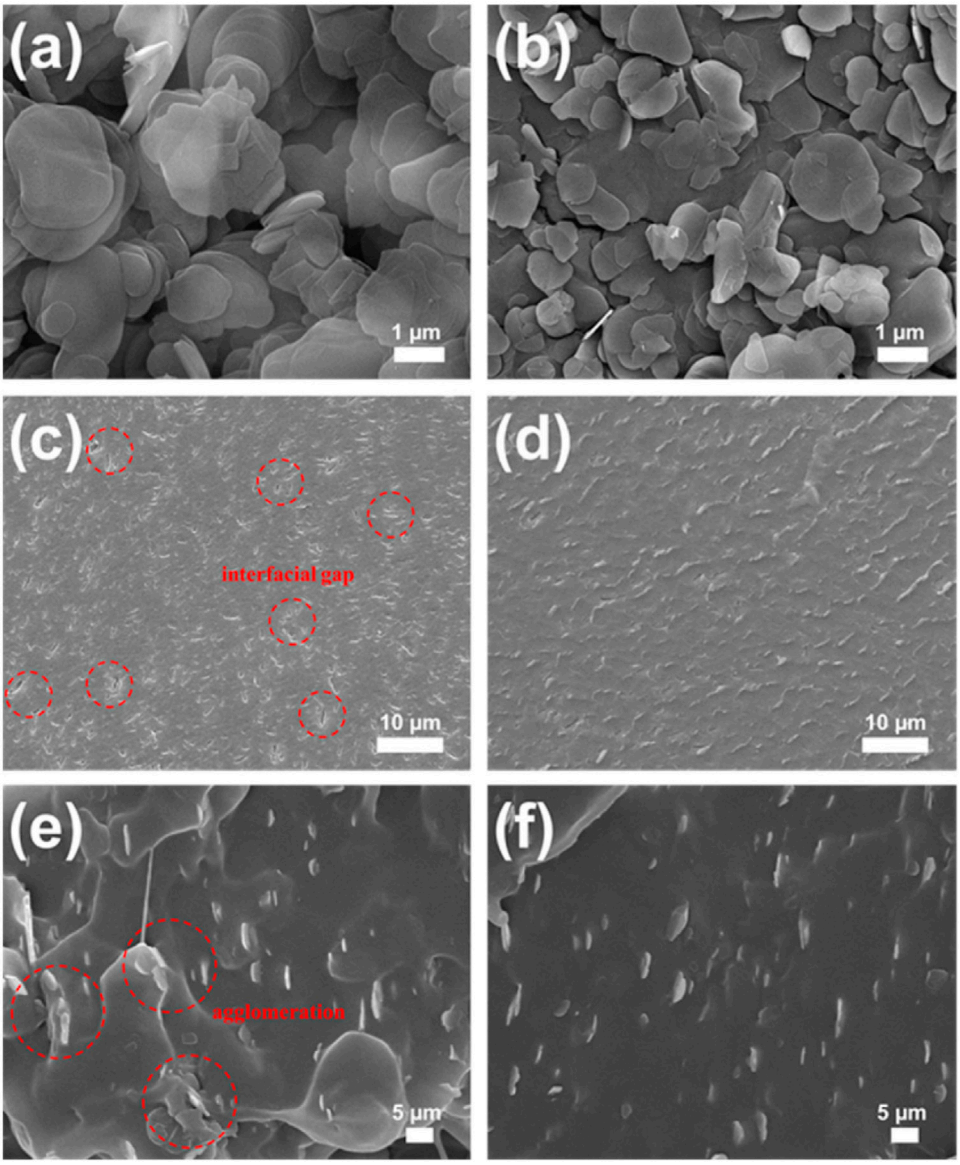

FIGURE 8
FESEM of h-BN **(a)**, functionalised BN (OH-BN) particles **(b)**, cross-profile of the h-BN/TPU filament **(c)** and OH-BN/TPU filament **(d)**, and images **(e,f)** show the cross-profile of morphologies of h-BN (10 wt.%)/TPU and OH-BN (10 wt.%)/TPU composites, respectively (Su et al., 2023).

composites demonstrated superior mechanical strength and enhanced thermal conductivity compared to those containing unmodified h-BN. In particular, at a filler loading of 10 wt.%, the OH-BN/TPU (Stand Vertical (SV)) composite achieved a thermal conductivity of 0.75 W/m.K, which is ≈ 2.5 times higher than that of the corresponding h-BN/TPU (SV) composite. The OH-BN fillers exhibited a more uniform distribution and well-aligned arrangement within the TPU matrix, resulting in the formation of an effective continuous filler network (Figure 8; Su et al., 2023).

Instead of concentrating on improving a single property, it is better to focus on simultaneously enhancing multiple properties of 3D printed polymer composites. Łapińska et al. (2025) used graphite, molybdenum disulphide (MoS_2), and siloxane reinforcements to modify the thermal properties and improve the flammability behaviour of PLA. The addition of a hybrid form of graphite (15 wt.%) and MoS_2 (2 wt.%) resulted in improved thermal conductivity (increased 40%); meanwhile, the inclusion of siloxane (2.5 wt.%) turned the PLA into an insulator (decreased 31%). Apart from the thermal conductivity enhancement, the development of high-efficiency EMI shielding polymer composites through additive manufacturing technology is another potential track (Liu et al., 2023).

For instance, Xue et al. developed an EMI shielding composite using 3D printing and showed that the developed composite has a very low reflection coefficient (R = 0.23) and good shielding performance (shielding efficiency 68 dB). Similarly, FDM printed CNT/PLA and CB/PLA scaffolds exhibited lightweight and customisable shielding structures. It was noticed that the CNT/PLA and CB/PLA achieved the shielding efficiency of ~43 dB and 22 dB at 10 GHz, respectively. Further enhanced to ~54.5 dB at the same frequency *via* polyaniline electrodeposition of CNT/PLA (Mappoli et al., 2025). Considering the flexibility and multifunctional sustainability, composites like conductive cellulose nanofibers/poly (3,4-ethylenedioxythiophene) printed structures not only deliver EMI shielding but also flexibility and sensor functions, aligning with the needs of wearable microelectronics (Amini et al., 2025).

In summary, the integration of polymer nanocomposites, additive manufacturing technologies, and sustainable reinforcements like nanocellulose presents a powerful and eco-conscious strategy for advancing microelectronics materials. Nanocellulose derived from abundant, renewable biomass sources offers outstanding characteristics such as high mechanical strength, biodegradability, large surface area, and versatile surface chemistry (Norizan et al., 2022; Ee and Yau Li, 2021). When incorporated into polymer matrices *via* additive manufacturing, it enables lightweight, mechanically robust, and functionally enhanced composites with reduced ecological impact (Finny et al., 2021; Chyr and DeSimone, 2023). Additive manufacturing streamlines fabrication by minimising material waste, energy consumption, and processing steps, thereby contributing to lower carbon footprints and supporting circular economy objectives (Chyr and DeSimone, 2023). This confluence of sustainable materials, advanced nanocomposite design, and precise 3D fabrication supports the creation of multifunctional microelectronic components combining structural complexity, tailored electrical/thermal performance, and environmental stewardship in one platform.

5.2 Research gaps and future directions for conductive polymers and microelectronics

Conductive polymers and polymer based composites offer an attractive route for flexible, lightweight, and sustainable electronic components produced *via* additive manufacturing. However, several limitations hinder their widespread application. The primary challenges include unstable conductivity under mechanical deformation, poor interlayer adhesion, and degradation of conductive pathways during repeated thermal cycles. Current formulations often exhibit trade-offs between electrical performance and mechanical strength, limiting their reliability in functional devices.

Future research should focus on developing hybrid fillers that combine metallic, carbon-based, and ionic conductive elements to achieve tunable performance. Additionally, machine learning-guided optimization of print parameters, *in-situ* monitoring of conductivity, and interface engineering through surface treatments can substantially enhance device uniformity and long-term stability. Emerging trends such as multi-material printing, 4D printing, and recyclable conductive composites also hold significant potential to revolutionize microelectronic manufacturing, aligning with sustainability goals.

6 Conclusion

Additive manufacturing of non-metal materials has become an important approach for achieving sustainable material processing and advanced product development. This review shows that techniques such as fused deposition modeling, stereolithography, and selective laser sintering have expanded the scope of additive manufacturing to include polymers, ceramics, composites, and biomaterials. These processes enable near zero material wastage, efficient energy use, and greater design flexibility, which together contribute to sustainable engineering practices.

The use of recycled, bio based, and waste derived feedstocks in additive manufacturing provides a promising route toward circular material utilization and waste valorization. The development of functional materials such as conductive polymers, flame retardant composites, and biomedical scaffolds also demonstrates the capability of this technology to create value added and sustainable products. However, further research is still needed to reduce energy consumption during printing, ensure the mechanical reliability of materials derived from waste, and develop standards for large scale industrial adoption.

Overall, additive manufacturing serves as a bridge between waste management and advanced manufacturing. It supports the transition toward resource efficient production, reduced environmental impact, and sustainable energy innovations. The continued advancement of this technology will contribute significantly to realising the principles of a circular economy and sustainable process engineering in the future.

Author contributions

PC: Writing – review and editing, Writing – original draft. VS: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review and editing. BP: Writing – original draft, Writing – review and editing. SB: Writing – review and editing, Writing – original draft. NK: Supervision, Conceptualization, Investigation, Methodology, Writing – review and editing, Writing – original draft. RM: Supervision, Conceptualization, Investigation, Methodology, Writing – review and editing, Writing – original draft.

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Glossary

ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
APP	Ammonium polyphosphate
ATH	Aluminium trihydroxide
CB	Carbon black
CNT	Carbon nanotubes
DLP	Digital light processing
EBM	Electron beam melting
FDM	Fused deposition modelling
FR	Flame-retardant
EG	Expandable graphite
EMI	Electromagnetic interference
Gr	Graphene
GNPs	Graphene nanoplatelets
HA	Hydroxyapatite
HRR	Heat release rate
LOI	Limiting oxygen index
MgO	Magnesium oxide
MPP	Melamine polyphosphate
MWCNT	Multi-walled carbon nanotubes
PA6	Polyamide 6
PC	Polycarbonate
PCL	Polycaprolactone
PEEK	Polyetheretherketone
PEGDA	Polyethylene glycol diacrylate
PEU	Polyetherimide
PLA	Polylactic acid
RP	Red phosphorus
SLA	Stereolithography
SLS	Selective laser sintering
TENGs	Triboelectric nanogenerators
TIM	thermal interface material
THR	Total heat release
TPU	Thermoplastic polyurethane