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REVIEW ARTICLE

Three-dimensionally printed elastomeric materials: Matrix innovation, functional expansion, and advances in multifield applications

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Abstract

Additive manufacturing (AM; commonly known as three-dimensional [3D] printing) has gained widespread adoption across diverse fields owing to its high precision, capability to directly fabricate complex geometries, and support for personalized customization. Elastomeric polymers, which combine excellent elastic recovery with multifunctional properties, have converged with 3D printing to establish the emerging field of 3D-printed elastomers, thereby overcoming limitations of traditional manufacturing in design freedom and functional integration. This review systematically surveys advances in 3D-printed elastomers over the past five years. It focuses on the characteristics and suitability of mainstream processes, including material extrusion, material jetting, and photopolymerization, and provides detailed classifications of polyurethane-based, silicone-based, polyolefin-based, and bio-based matrix materials. The design and processing principles, core breakthroughs, and current technical bottlenecks of functional elastomers are comprehensively outlined, while summarizing demonstrated applications in biomedicine, flexible electronics, soft robotics, industrial manufacturing, and consumer products. Nevertheless, key challenges remain for 3D-printed elastomers, including balancing competing material properties, reconciling process throughput with dimensional precision, ensuring reliability in extreme environments, and enabling large-scale manufacturing. The review concludes by outlining future directions, such as the design of dynamic and adaptive polymer networks, the development of green and sustainable materials, and convergence-driven interdisciplinary innovation, thereby providing guidance for future research and industrial translation.

Keywords: Additive manufacturing; 3D-printed elastomer materials; Matrix materials; Multifunctionality; Multi-application fields

1. Introduction

Additive manufacturing (AM; also known as three-dimensional [3D] printing) is a transformative rapid prototyping and production technology widely recognized as a foundational pillar of the Fourth Industrial Revolution.[1] Unlike conventional manufacturing, AM employs computer-aided design (CAD) data to instruct 3D printing systems in precisely depositing materials layer by layer, thereby enabling the fabrication of geometrically complex structures.[2] Continuous progress in material innovation has expanded the application of AM across diverse sectors, including architecture,[3-5] medicine,[6-8] electronics,[9,10] and aerospace.[11-13] These applications are enabled by the distinctive capabilities of AM—high precision, direct fabrication of complex architectures, and adaptability for personalized customization—which position it as a powerful and versatile advanced manufacturing paradigm.[14]

Elastomers are polymeric materials capable of undergoing reversible deformation under an external load and rapidly recovering their original shape and volume once the load is removed.[15] Exhibiting diverse functionalities such as adhesion,[16] self-healing,[17] insulation,[18] and ionic conductivity,[19] elastomers have achieved widespread adoption in industries including automotive,[20] electronics,[21] medical devices,[22] and wearable technology.[23] In recent years, rapid advancements in 3D printing have facilitated the integration of elastomeric materials into this manufacturing paradigm, giving rise to the emerging field of 3D-printed elastomers. Compared with conventional manufacturing techniques, 3D-printed elastomers provide notable advantages in tunable material properties, enhanced design freedom, increased production efficiency, and expanded application possibilities.[24]

Owing to the inherent chemically cross-linked network structure of conventional elastomers, they are essentially unsuitable for direct 3D printing, and three clearly defined types of elastomer-based printable systems are actually utilized in 3D printing according to different forming mechanisms, including un-crosslinked precursor materials that undergo thermal or photo-induced crosslinking after printing to form elastomers, polymer solutions that achieve solidification through solvent evaporation, and thermoplastic elastomers that are processed via melt extrusion upon heating and maintain excellent elastomeric properties after cooling, among which typical thermoplastic polyurethane (TPU) belongs to the thermoplastic elastomer system rather than the polymer solution system, and such clear classification can effectively avoid confusion in material types and processing principles. To optimize the printability, processability, and post-printing performance of these systems, the precursor materials or thermoplastic elastomer substrates are often modified via chemical or physical strategies. Numerous research groups have reported high-performance 3D-printable elastomer systems developed from diverse matrix systems based on the above printable types. A primary challenge in the development of 3D-printable elastomers lies in enabling the fabrication of complex geometries while concurrently preserving robust mechanical strength, elasticity, recovery behavior, and stable functional characteristics. Despite growing research efforts on 3D-printable elastomers, comprehensive systematic reviews with critical analysis of technical bottlenecks remain limited.

This review aims to critically examine recent advances in 3D-printed elastomer materials from the past five years and to offer comprehensive insights into their functional variants. Special emphasis is placed on anticipated applications of diverse functional 3D-printed elastomers across multiple domains, core breakthroughs of material design and processing, and inherent technical bottlenecks of different material systems. Finally, this review analyzes prevailing challenges in 3D-printed elastomer materials and presents perspectives on future development pathways with clear connections to current research trends.

2. Overview of 3D printing technology

2.1. General workflow of 3D printing

The general procedure for 3D printing fabrication is illustrated in Figure 1b and can be summarized as follows:[25] (i) designing a three-dimensional model using CAD software; (ii) exporting the model in STL (STereoLithography) file format; (iii) slicing the digital model with software compatible with the selected printer; (iv) printing successive two-dimensional layers in accordance with the slicing data and printhead trajectories defined by G-code; (v) constructing the full three-dimensional object through incremental movement along the z-axis; and (vi) removing the printed part from the build plate, eliminating support structures, and performing post-processing to produce the final component.

2.2. Classification of 3D printing technologies

Since its emergence in the late 1980s, 3D printing has diversified into multiple process categories to meet material- and performance-specific requirements. American Society for Testing and Materials (ASTM) International classifies AM technologies into seven categories—powder bed fusion, material extrusion, material jetting, binder jetting, vat photopolymerization, sheet lamination, and directed energy deposition (Figure 1a).[26] For elastomeric materials, the most widely used AM processes fall into three

categories: material extrusion, material jetting, and vat photopolymerization. Table 1 provides a comprehensive comparison of the manufacturing processes most commonly used for 3Dprinted elastomers. Each method has distinct advantages and limitations; process selection for research or production should be guided by application-specific printing requirements and material attributes.

2.3. Comparison of 3D-printed elastomer materials with traditional elastomer materials

Within elastomeric materials, the continued maturation of 3D printing processes has driven rapid advances in 3D-printed elastomers. Compared with conventional fabrication routes (e.g., chemical cross-linking, physical blending, and bio-based processing), 3D-printed elastomers provide notable advantages in design freedom and geometric complexity, production throughput and speed, mass customization, tunable material properties and compositional diversity, and environmental sustainability (Table 2). Meanwhile, traditional mold-based manufacturing still maintains irreplaceable dominance in large-scale industrial production, featuring ultra-high continuous production efficiency, stable product consistency, low marginal cost for mass output, and mature quality control systems, which are difficult for current 3D printing technologies to match in standardized bulk manufacturing scenarios. Collectively, these comparisons reflect the complementary development of 3D-printed elastomers and traditionally manufactured elastomers, rather than a simple substitution relationship.

2.4. Emerging advanced 3D printing technologies

Beyond the conventional 3D printing processes mentioned above, a series of emerging advanced 3D printing technologies have recently emerged, which effectively break through the limitations of traditional printing in terms of structure, function, efficiency, and precision, and have become key driving forces for the development of 3D-printed elastomers.

2.4.1. Integrated printing

Integrated printing realizes the one-step integrated

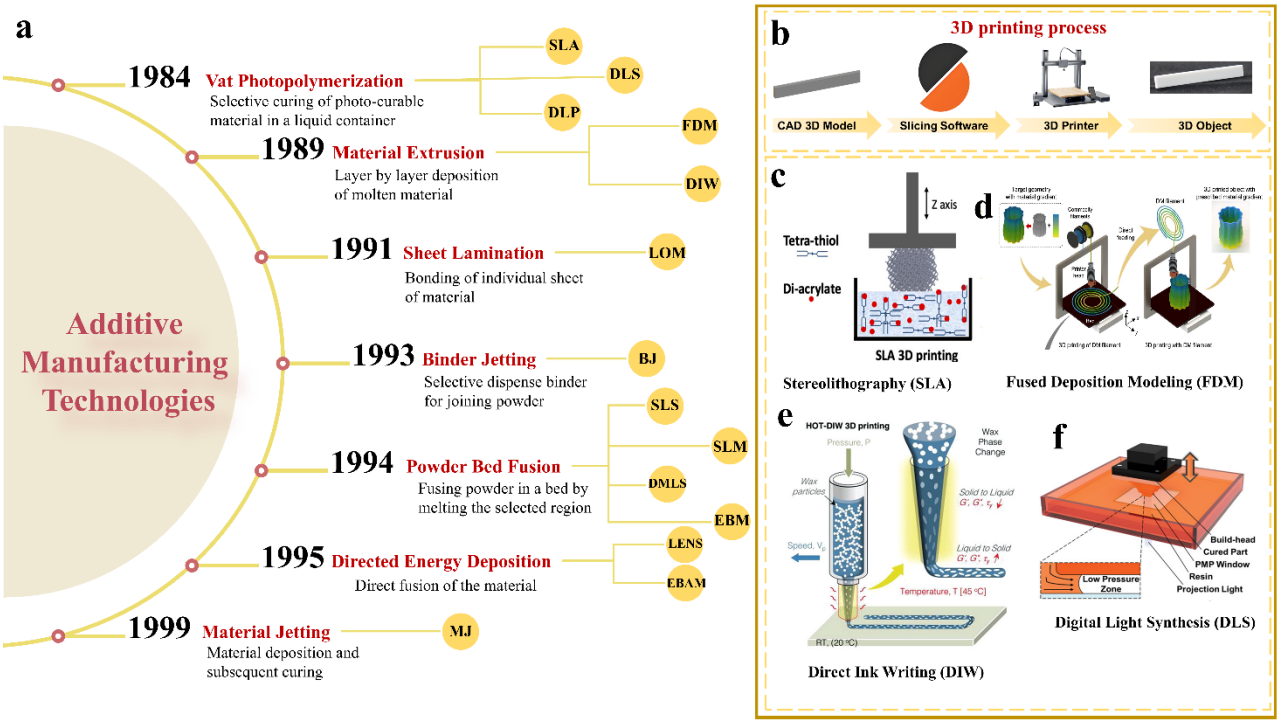

Figure 1. Overview of 3D printing technologies: classification, workflow, and representative process. (a) Classification and representative processes of 3D printing technologies. (b) Manufacturing workflow of 3D printing technologies. (c) Schematic of stereolithography (SLA) operation. Reprinted with permission from Shahzadi *et al.*[27] Copyright © 2022 American Chemical Society. (d) Schematic of fused deposition modeling (FDM) operation. Reprinted from Ahn *et al.*[28] (e) Schematic of direct ink writing (DIW) operation. Reprinted from Wang *et al.*[29] (f) Schematic of digital light synthesis (DLS) operation. Reprinted with permission from Wang *et al.*[30] Copyright © 2020 Wiley.

Abbreviations: DMLS: Direct metal laser sintering; EBAM: Electron beam additive manufacturing; EBM: Electron beam melting; LENS: Laser engineered net shaping; LOM: Laminated object manufacturing; SLS: Selective laser sintering.

Table 1. Comparison of different 3D printing manufacturing processes

Manufacturing process	Typical materials	Advantages	Disadvantages	Functional 3D-printable elastomer materials	Representative workflow diagram	Print resolution (μm)	American Society for Testing and Materials (ASTM) category
Selective laser sintering	Polymers; metal and ceramic powders	(i) Material diversity (ii) Complex structure manufacturing capability (iii) High material utilization (iv) Support-free printing (v) High degree of automation	(i) Loose structure and rough surface (ii) Complex post-processing (iii) Odor and contamination (iv) Long processing time (v) High equipment and material costs (vi) Difficult quality control	(i) Self-healing elastomer (ii) Thermoplastic elastomer (iii) Liquid crystal elastomer	–	>50[31]	Powder bed fusion
Fused deposition modeling	Engineering plastics; flexible materials; wood-based materials; metal materials; carbon fiber materials	(i) Material versatility (ii) High design flexibility (iii) Simple operation (iv) Rapid manufacturing (v) Significant cost efficiency (vi) Environmentally sustainable	(i) Poor print accuracy (ii) Rough surface finish (iii) Difficult to remove support structures (iv) Limited material properties	(i) Super-stretch elastomer (ii) Self-healing elastomer (iii) Ultra-soft elastomer (iv) Thermoplastic elastomer	**Figure 1d**	100–300[32]	Material extrusion
Direct ink writing	Polymer gels; ceramics and ceramic composites	(i) High precision (ii) Complex structure manufacturing capability (iii) High solid content printability (iv) Scaffold-free printing (v) High design freedom (vi) Significant cost efficiency	(i) Poor print accuracy (ii) Limited material selection (iii) Relatively slow printing speed (iv) Complex post-processing (v) High equipment and technical barriers	(i) Ultra-soft elastomer (ii) Dual-network particle elastomer (iii) Magnetorheological elastomer (iv) Liquid crystal elastomer	**Figure 1e**	10–100[33]	Material jetting

(*cont'd...*)

Table 1. (*Continued*)

Manufacturing process	Typical materials	Advantages	Disadvantages	Functional 3D-printable elastomer materials	Representative workflow diagram	Print resolution (μm)	American Society for Testing and Materials (ASTM) category
Stereolithography	Photosensitive resin; filled resin with metal, ceramic, and nanopowder composites	(i) High precision (ii) Fast forming speed (iii) High design flexibility (iv) High automation level (v) Remote control and online operation capability (vi) Wide range of material options (vii) Supports personalized customization (viii) Environmentally friendly and energy-efficient	(i) High equipment and material costs (ii) Complex post-processing (iii) Limited material properties (iv) Demanding work environment requirements (v) Complex slicing software operation	(i) Self-healing elastomer (ii) Biodegradable elastomer	Figure 1c	>25[34]	Vat photopolymerization
Digital light processing				(i) Adhesive elastomer (ii) Conductive hydrogel elastomer (iii) High-strength tough elastomer (iv) Light-curable elastomer (v) Liquid crystal elastomer (vi) Multi-network elastomer	–	>10[35]	
Linear-based scanning vat photopolymerization	High-viscosity photosensitive resin (exceeding 600,000 cps)	(i) High-viscosity material printing capability (ii) Excellent mechanical properties (iii) High precision (iv) High design flexibility	(i) High equipment costs (ii) High technical barriers (iii) Relatively slow printing speed (iv) Complex post-processing	(i) Self-healing elastomer (ii) High-elongation, high-elasticity elastomer	–	>5[36]	
Digital light synthesis	Polyurethane materials; rigid materials (epoxy resin); medical-grade materials; specialty functional materials (e.g., silicone, cyanate ester); dental materials	(i) High precision (ii) High efficiency and high quality (iii) Material diversity (iv) Environmentally sustainable	(i) High equipment and material costs (ii) High technical barriers (iii) Complex post-processing	Nanoparticle composite elastomer	Figure 1f	>5[37]	
Liquid-phase deposition modeling	Organic silicon materials; alloy materials (titanium alloys, nickel-based alloys, cobalt-chromium alloys, stainless steel)	(i) Material diversity (ii) High-performance component manufacturing (iii) Production flexibility (iv) Environmental sustainability	(i) High material costs (ii) Equipment complexity and maintenance (iii) Low printing speed and efficiency (iv) Complex post-processing	High-toughness elastomer	–	Depends on the thickness of the laminate[38]	Sheet Lamination

Table 2. Comparison of 3D-printed elastomer materials and conventionally manufactured elastomer materials

Comparison criterion	3D-printed elastomers	Traditional manufacturing of elastomers
Design freedom and complexity	Manufacturing elastomer components with complex geometries and internal structures enables the creation of elastomer products featuring intricate lattice structures, hollow configurations, or specialized textures through precise digital design and printing processes.	Due to the complexity of molds and manufacturing processes, design flexibility is relatively limited, making it difficult to produce elastomer components with intricate structures and shapes.
Production efficiency and speed	Significantly shortening the production cycle from design to prototype and even final product enables rapid iteration and prototyping, accelerating product development and market testing. Suitable for small-batch, multi-variety, and customized production.	Requires a longer production cycle for mold design, manufacturing, and debugging, but possesses ultra-high continuous production efficiency and output once molds are prepared, which is optimal for large-scale standardized mass production.
Customization level	By adjusting printing parameters and material selection, elastomer components with varying elasticity, hardness, and wear resistance can be customized to meet specific application requirements. This enables small-batch or single-unit production to fulfill personalized needs.	For highly customized products, it may be necessary to redesign molds and production lines, increasing both costs and time. However, it achieves high consistency in large-scale products.
Material properties and diversity	An increasing variety of elastomer materials suitable for printing is becoming available, each possessing distinct physical and chemical properties to meet diverse application requirements. Simultaneously, multi-material printing enables the combination of materials with different properties to create components exhibiting complex functionalities.	Using standardized elastomer materials may result in relatively limited performance characteristics, but ensures stable and uniform material performance in mass production.
Environmental sustainability	Reduce material waste and energy consumption, support recyclability, and contribute to environmental protection and sustainable development.	Due to the need for mold manufacturing and production line adjustments, significant amounts of scrap and offcuts may be generated in small-batch production, but achieves high material utilization efficiency in long-term mass production.
Industrial production dominance	Still in the stage of rapid development and application expansion; difficult to replace traditional manufacturing in large-scale standardized production.	Holds absolute dominance in large-scale industrial production, with mature processes, low cost, and high stability.

manufacturing of structures, functions, and devices by coupling multiple printing mechanisms or introducing in-situ reaction/sintering during the printing process, which greatly improves the integration and performance stability of elastomer devices. Recent advances have demonstrated the capability of integrated printing to construct high-performance elastomer-based flexible systems with seamless interface integrattion.[39,40]

2.4.2. Multi-material printing

Multi-material printing enables the on-demand deposition and heterogeneous integration of different elastomers, or elastomers with plastics/metals/conductive materials in a single printing process, which is critical for constructing flexible devices with gradient performance, regional functionalization, and rigid–flex combination. Representative progress has realized high-precision multi-material printing of elastomers with stable interface bonding.[41,42]

2.4.3. Four-dimensional printing and structural programming

Four-dimensional (4D) printing endows 3D-printed elastomer structures with time–space programmable

deformation, stimulus responsiveness, and adaptive functions based on smart material design and structural programming, which is a core technology for next-generation soft robots and smart devices. Typical achievements include programmable shape transformation, multi-stimulus response, and sequential actuation of elastomer structures.[43]

2.4.4. Support-free printing

Support-free printing eliminates the need for sacrificial support materials during the fabrication of overhangs, high-aspect-ratio, and suspended structures, significantly improving forming efficiency, surface quality, and material utilization. Advanced support-free strategies have been successfully applied to high-precision manufacturing of silicone and polyurethane (PU) elastomers with complex architectures.[44]

These emerging advanced technologies have greatly expanded the boundary of 3D printing for elastomers and will play an increasingly important role in the development of high-performance, multifunctional, and integrated elastomer devices.

3. Material selection for 3D-printed elastomers

Owing to the inherent constraints of 3D printing processes on material properties, the chemically cross-linked conventional elastomers cannot be directly printed, and their corresponding printable systems (precursors/thermoplastic elastomers/solutions) often require chemical or physical modification to optimize printability and post-printing performance. Numerous research groups have reported high-performance 3D-printable elastomers developed from diverse matrix systems. Improving the toughness of 3D-printed elastomers remains a central research focus, as mechanical performance directly influences their reliability and service lifetime. Accordingly, this section categorizes and discusses 3D-printed elastomers according to their underlying matrix materials, with a focus on core design principles, recent breakthroughs, and current technical bottlenecks for each system.

3.1. Polyurethane-based 3D-printed elastomers

Polyurethane (PU) is a versatile polymer synthesized through the reaction between polyisocyanates and polyols. The PU molecular structure comprises urethane linkages (amide bonds) and aliphatic or cyclic alcohol groups, imparting excellent physical properties and chemical stability,[45] thereby contributing significantly to its utility in 3D printing. However, conventional PU elastomers often fail to meet the performance requirements of demanding industrial and consumer applications, prompting extensive research and development in this field.

3.1.1. Light-curable polyurethane elastomers

Lightcurable PUbased elastomers are materials in which photosensitive moieties are incorporated into the PU molecular chains. Exposure to photopolymerization conditions initiates polymerization, rapidly converting liquid PU prepolymers into solid elastomers, and their curing characteristics are compatible with vatphotopolymerization 3D printing techniques. A landmark achievement in this field is the work of Huang *et al*.,[36] who synthesized a highviscosity, closedchain polyurethane functionalized with photosensitive groups. The design exploited dynamic hindered urea bonds (HUBs), which release –NCO groups upon heating; these subsequently react with amine chain extenders to form interpenetrating polymer networks (IPNs). Coupling this design with a lowshear vatphotopolymerization process—engineered to overcome viscosity constraints in AM—yielded highstrength, hightoughness 3Dprinted elastomers via a dual photothermal curing mechanism (Figure 2a). Building on this, Fang *et al*.[46] employed digital light processing (DLP) to fabricate a PUbased 3Dprinted elastomer exhibiting recordhigh tensile strength (94.6 MPa) and toughness (310.4 MJ m^{-3}), which is the highest mechanical performance for 3D-printed PU elastomers reported to date (Figure 2b). Additionally, Zhang *et al*.[47] developed a recyclable PU-based elastomer that can be repeatedly printed via DLP while retaining excellent mechanical properties, addressing the sustainability issue of light-curable PU systems. Researchers have further explored the manufacturing processes of PUbased 3Dprinted elastomers, particularly in the context of lightcuring AM. Li *et al*[48] applied a liquidcrystal displaybased process to optimize printed architectures, producing PU acrylate (PUA) elastomers with triply periodic minimal surface lattice structures. These lattices exhibited exceptional recovery under cyclic loading–unloading and superior energy absorption performance. Yang *et al*.[49] extended investigations from conventional soft elastomers to PUbased 3Dprinted elastomers. Integrating digital light synthesis manufacturing with dynamic thermomechanical analysis, they elucidated deformation nonlinearity, thermal sensitivity, and strainrate dependence in these materials. To enable automated production, Rapp *et al*.[50] integrated semicontinuous batch chemistry with vat photopolymerization, establishing a semicontinuous PU polymerization protocol (Figure 2c) capable of continuous synthesis and fabrication of PUA 3Dprinted elastomers.

3.1.2. Thermoplastic polyurethane elastomers

Thermoplastic polyurethane elastomers are PU-based materials capable of undergoing flow deformation when heated and retaining their shape upon cooling, and their rheological and thermal properties are well-suited to material-extrusion-type 3D printing.[51] Hu *et al.*[52] first reported 3D-printable, high-heat-resistant TPU elastomers based on 3dimethyl4,4'diphenyl diisocyanate (TODI), with thermal stability up to 280 °C (Figure 2d). In a separate study, Hu *et al.*[53] developed a 1,5naphthalene diisocyanate (NDI)-based TPU elastomer with superior heat resistance for 3D printing. Together, these studies demonstrated the potential of TODI- and NDIbased highheatresistant TPU elastomers for high-temperature 3D-printing applications. Natali *et al.*[54] compared the mechanical properties of four TPU elastomers of varying stiffness with those of PU foam and found that optimizing material stiffness and printed geometries enabled TPU elastomers to potentially replace conventional PU foam. Lin *et al.*[55] reported the mechanical anisotropy of material-extrusion-printed TPU, a unique structural defect distinct from rigid 3D-printed plastics, which has become a key research focus for TPU extrusion printing. León-Calero *et al.*[56] determined that a fill density of 50% and a honeycomb infill pattern yielded optimal specific energy absorption and specific damping capacity for fused deposition modeling (FDM)-printed TPU, providing clear guidance for process parameter optimization. Similarly, Ngeow *et al.*[57] compared TPU materials fabricated via FDM with those produced by traditional compression molding, identifying distinct advantages of the 3Dprinted variants. Research on TPUbased 3Dprinted elastomers remains relatively limited, with most current investigations focusing predominantly on the influence of FDM process parameters on their mechanical and physical properties.

3.1.3. Composite polyurethane elastomers

Composite PU-based elastomers are novel materials obtained by integrating PU elastomers with reinforcing agents such as glass fibers, carbon fibers, or nanoparticles via composite processing. Khakbaz *et al.*[58] incorporated boron nitride nanoparticles into TPU elastomers and produced highly flexible and thermally conductive composites. However, conventional nanoparticle incorporation into PU elastomers often suffers from poor dispersion caused by particle surface chemistry, which compromises both printability and performance. To address this, Li *et al.*[59] encapsulated MXene nanosheets within photopolymerizable PUA resin and fabricated MXene–PUA nanocomposite elastomers via DLP, achieving a 100.8% increase in tensile strength (23.3 MPa) and a 37.8% increase in elongation at break (404.3%) at a filler content of 0.1 wt% MXene. Similarly, Rollo *et al.*[60] modified TPU composites for selective laser sintering (SLS) by adding 1 wt% multiwalled carbon nanotubes (MWCNTs) or MWCNT–graphene blends, reporting enhanced thermal stability together with improved electrical conductivity and mechanical strength. Nanoparticle incorporation increases crosslinking density between polymer chains, thereby improving mechanical performance. Following this strategy, Fei *et al.*[61] and Peng *et al.*[62] prepared nano-SiO2-modified PUA elastomers and reported a tear strength of 23.4 N mm^{-1}, attributed to the preferential fracture of sacrificial bonds and chain entanglement (Figure 2e). Beyond nanoparticle reinforcement, Ansaripour and Heidari-Rarani[63] applied sequential alkylation and silanization to produce highly dispersed flax fibers with a high aspect ratio, subsequently blending them with TPU particles and polylactic acid (PLA) to fabricate highimpactresistance elastomers via FDM. Yu *et al.*[64] reinforced water-based PU with cellulose nanofibers (CNFs) and produced elastomers with a tensile strength of 22 MPa and an elongation at break of 951% (Figure 2f), a remarkable achievement for water-based PU systems.

3.1.4. Nonisocyanate polyurethane elastomers

Nonisocyanate polyurethane (NIPU) denotes PU analogs synthesized via reactions between polyacids or polyols and polyamines, without hazardous isocyanate precursors, which improves environmental compatibility and occupational safety.[65] NIPU formulations have found increasing application in PUbased 3Dprinted elastomers. Pierrard *et al.*[66] functionalized polypropylene glycolpolyhydroxyurea with cyclic carbonates bearing unsaturated side chains and fabricated NIPUbased 3Dprinted elastomers exhibiting exceptional mechanical performance and tunable stiffness via DLP, expanding the green printable PU systems.

3.1.5. Technical bottlenecks of polyurethane-based 3D-printed elastomers

Despite the remarkable progress in mechanical performance and functionalization of PU-based 3D-printed elastomers, several critical bottlenecks restrict their further development and application:

(i) Printability-mechanical property trade-off: Reducing the viscosity of photosensitive PU resins to improve printing fluidity often leads to decreased crosslinking density and lower toughness; high-performance resins (e.g., 94.6 MPa tensile strength) have poor printability and can only be processed via high-precision DLP with low throughput.
(ii) Mechanical anisotropy of extrusion-printed TPU: Interlayer bonding defects cause obvious mechanical

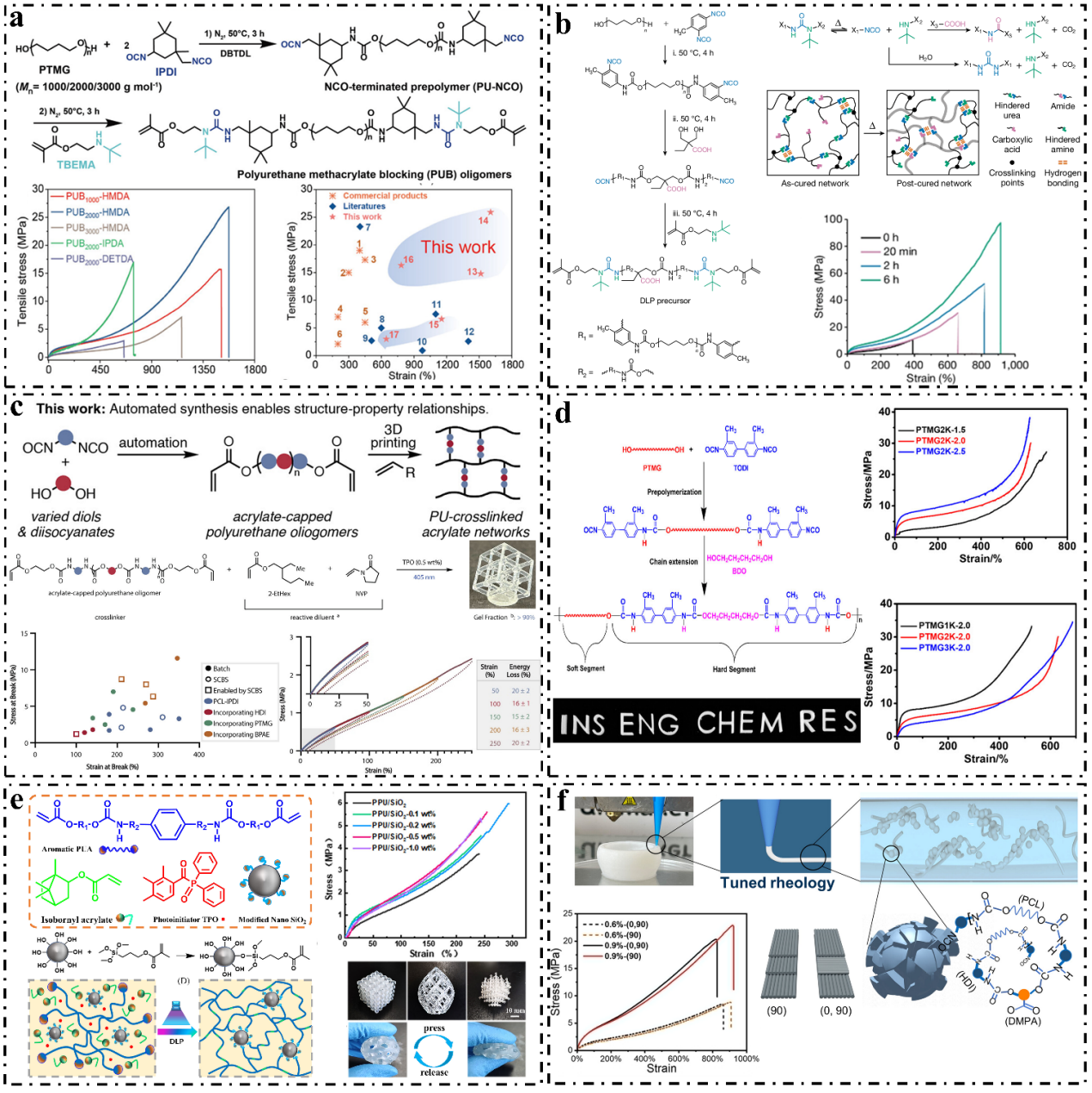

Figure 2. Synthesis strategies, curing mechanisms, and representative mechanical performance of 3D-printed polyurethane-based elastomers. (a) Schematic of the PUB oligomer synthesis pathway and photo-thermal dual-curing mechanism for high-strength elastomers. Reprinted with permission from Huang *et al.*[36] Copyright © 2023 Wiley. (b) Record-high mechanical performance of DLP-printed polyurethane elastomers and the deblocking mechanism of HUB. Reprinted with permission from Fang *et al.*[46] Copyright © 2024 Springer Nature. (c) Schematic of semi-continuous batch PU polymerization process for automated production. Reprinted from Rapp *et al.*[50] (d) Prepolymerization, chain extension, and 3D-printed samples of TODI-based TPU. Reprinted with permission from Hu *et al.*[52] Copyright © 2020 American Chemical Society. (e) DLP-printed modified SiO_2/PUA elastomers with excellent tear resistance (23.4 N·mm^{-1}). Reprinted with permission from Fei *et al.*[61] Copyright © 2024 Wiley. (f) DIW-printed CNFs/water-based polyurethane elastomers with high tensile strength (22 MPa) and elongation at break (951%). Reprinted with permission from Yu *et al.*[64] Copyright © 2024 American Chemical Society. Abbreviations: CNFs: Cellulose nanofibers; DBTDL: Dibutyltin dilaurate; DETDA: Diethyltoluenediamine; DIW: Direct ink writing; DLP: Digital light processing; DMPA: Dimethylolpropionic acid; HMDA: Hexamethylene diamine; HUB: Hindered urea bond; IPDA: Isophorone diamine; IPDI: Isophorone diisocyanate; NCO: Isocyanate group; OH: Hydroxyl group; PCL: Polycaprolactone; PTMG: Polytetramethylene glycol; PU: Polyurethane; PUA: Polyurethane acrylate; PUB: Polyurethane methacrylate-blocked oligomer; TBEMA: 2-(tert-butylamino)ethyl methacrylate; TODI: 3,3-dimethyl-4,4'-diphenyl diisocyanate; TPU: Thermoplastic polyurethane.

anisotropy of FDM/material-extrusion-printed TPU, which is difficult to eliminate even by optimizing process parameters such as fill density and temperature.

(iii) Recyclability limitation: The optimal recycling cycle of most printable recyclable PU elastomers is limited to 3–5 cycles, with the best-reported systems maintaining ≈70–85% tensile strength retention, 65–80% elongation at break retention, and 75–85% toughness retention after 5 reprocessing cycles. Beyond this range, a dramatic drop in mechanical performance (strength, elasticity, and modulus) is commonly observed, which still cannot fully meet the long-term service and large-scale sustainable manufacturing requirements.

(iv) Filler dispersion problem: The interface compatibility between PU and inorganic nanofillers (e.g., MXene, boron nitride) is poor, and even surface modification cannot completely avoid filler agglomeration, which limits the further improvement of functional performance (e.g., thermal/electrical conductivity).

3.2. Silicone-based 3D-printed elastomers

Organic silicone elastomers are produced by compounding linear polysiloxane precursors with crosslinking agents and other additives, followed by vulcanization.[67] Polysiloxanes comprise backbones of repeating Si–O–Si linkages bearing organic substituents directly bonded to silicon, and this hybrid architecture imparts organic-inorganic character to silicone elastomers.[68] It should be explicitly distinguished that different silicone formulations are applicable to disparate 3D printing processes due to distinct requirements on viscosity, curing mechanism, rheological behavior, and reaction kinetics. Polydimethylsiloxane (PDMS) and polymethyl vinylsiloxane are typical materials for extrusion-based 3D printing (especially DIW) owing to their favorable rheological characteristics and printability, while low-viscosity photocurable silicone resins and jettable silicone systems are more suitable for material jetting and vat photopolymerization processes. Their exceptional flexibility, thermal stability, and tunable processability render them well suited to the above 3D printing modes, enabling broad deployment of silicone-based elastomers in AM.

3.2.1. Pure silicone elastomers

Conventional silicone inks display limited selfsupporting capability in DIW printing, which reduces printing efficiency. To address this limitation, Guell Izard *et al.*[69] developed a twocomponent, rapidlycuring siliconebased ink and realized one-step, support-free DIW printing of tall, overhanging, high-aspect-ratio structures, a breakthrough for silicone extrusion printing. In DIW printing, curing shrinkage is a critical factor affecting print success rates. Siliconebased inks can undergo isotropic gelation and curing, thereby reducing volumetric shrinkage. Shang *et al.*[70] implemented an ultravioletassisted DIW process with insitu heating to fabricate highfidelity structures from commercially available, highviscosity PDMS (DOWSILSE1700). For vat photopolymerization printing, the high intrinsic viscosity and limited intermolecular interactions of silicone resins are the main challenges.[71,72] Building on this approach, Chen *et al.*[73] used a solgel process to prepare a silicone-based 3D-printed elastomer with ultra-low viscosity and separation force, enabling high-speed fabrication (Figure 3a). Du *et al.*[74] incorporated thiourea groups into the system and significantly improved the elasticity of the printed material by tuning thiourea segment content (Figure 3b), solving the low elasticity problem of photopolymerizable silicone elastomers.

3.2.2. Composite silicone elastomers

Single-component silicone-based 3D-printed elastomers frequently fail to meet performance requirements, and composite modification has become a key strategy to enhance their mechanical and functional performance.[75] Wong *et al.*[76] developed a hydrophilic silicone–hydrogel composite based on polar-functionalized silicone and acrylamide, exhibiting low pre-gel viscosity and rapid curing. Nanomaterial reinforcement is a primary strategy to enhance mechanical properties and functional performance in 3D-printed silicone elastomers. Yang *et al.*[77] achieved *in situ* growth of silver nanoparticles on the swollen silicone-sugar composite and yielded highly conductive silicone elastomers. Shar *et al.*[78] incorporated highly dispersed carbon nanotubes (CNTs) into a single-component room-temperature-vulcanizing silicone and produced integrated, highly conductive, and flexible composite elastomers via material jetting (Figure 3c). Additionally, the long polysiloxane soft segments inherent to silicone-based 3D-printed elastomers can lead to inadequate mechanical strength and toughness for certain applications. Accordingly, composite design efforts focus on enhancing the mechanical performance of silicone 3D-printed materials. Ding *et al.* [79] used a platinum-based Karstedt catalyst to promote hydrosilylation reactions and significantly improved the mechanical properties and isotropy of the printed parts via UV activation during material jetting, addressing the mechanical anisotropy problem of silicone-based 3D-printed elastomers.

3.2.3. Technical bottlenecks of silicone-based 3D-printed elastomers

Silicone-based 3D-printed elastomers have excellent flexibility and thermal stability, but several core bottlenecks

limit their further application:

(i) Low mechanical strength: Pure silicone elastomers have low tensile strength (generally < 5 MPa) and tear resistance. While their ultra-low modulus is highly advantageous for biomedical implants and wearable devices that require soft tissue compliance, these properties are insufficient for load-bearing structural applications.
(ii) Printability limitation of photopolymerizable silicone: The high intrinsic viscosity of silicone resins leads to poor printability for vat photopolymerization; reducing viscosity via reactive diluents often leads to decreased crosslinking density and lower performance.
(iii) Curing shrinkage and structural fidelity: Silicone inks are prone to curing shrinkage during DIW printing, which affects the structural fidelity of printed parts; high-fidelity printing often requires complex in-situ heating/UV curing systems.
(iv) Limited functional diversity: Silicone-based elastomers have relatively limited functional modification space compared with PU; functional composite modification often leads to reduced flexibility and printability.

3.3. Polyolefin-based 3D-printed elastomers

Polyolefin-based elastomers constitute a major class of thermoplastic elastomers, with polyolefin elastomers (POEs) being a representative example. These copolymers are produced from ethylene or propylene as principal monomer units, copolymerized with αolefins such as 1butene, 1hexene, or 1octene. Their rheological and thermal properties are wellsuited to materialextrusion 3D printing, enabling widespread application in this domain.[80] Polyolefinbased 3D-printed elastomers combine the high toughness, aging resistance, and processability of polyolefin materials with the design flexibility afforded by 3D printing. However, characteristics such as excessive softness, shrinkage, and warping limit the mechanical performance of POE, constraining its utility in 3D printing.[81]

3.3.1. Modified polyolefin elastomers

Advances have been achieved by optimizing both feedstock formulation and processing parameters. Given that POE is primarily suited to materialextrusion processes, FDM thermoplastics have been used as benchmarks for assessing POE printability. On this basis, Liu *et al.*[82] blended POE with linear lowdensity polyethylene (LLDPE) and employed a pneumaticfeeding fused granule fabrication process[83] tailored to the material, which significantly improved the mechanical performance of POE-based 3D-printed elastomers (Figure 3d). Similarly, Xia *et al.*[84] blended acrylonitrile–butadiene–styrene (ABS) with POE and fabricated ABS/POE elastomers exhibiting high mechanical strength via FDM. Subsequent studies identified optimal printing parameters such as fill direction (0° or 90°) and infill patterns for polyolefin blend elastomers,[85] providing clear guidance for process optimization.

3.3.2. Composite polyolefin elastomers

Nanoparticle reinforcement is an effective strategy to enhance the mechanical and functional performance of polyolefin-based 3D-printed elastomers. Lv *et al.*[86] developed polyolefinbased composite elastomers with customizable porous architectures by incorporating POE/graphene nanoplatelets via ultrasonic dispersion and FDM. The synergy between the graphene nanoplatelet network and the FDM-printed porous structure conferred outstanding flexibility and electromagnetic shielding functionality (Figure 3e), expanding the application of polyolefin-based elastomers in functional materials.

3.3.3. Technical bottlenecks of polyolefin-based 3D-printed elastomers

Polyolefin-based 3D-printed elastomers have excellent aging resistance and processability, but their development is limited by the following bottlenecks:

(i) Poor mechanical performance of pure POE: Pure POE has excessive softness, low tensile strength, and serious shrinkage/warping during extrusion printing, which limits its direct application.
(ii) Blending modification trade-off: Blending POE with rigid polymers (e.g., LLDPE, ABS) improves mechanical strength but significantly reduces the elasticity and flexibility of the elastomers.
(iii) Limited printability optimization space: Polyolefin-based elastomers are only suitable for material extrusion printing, with limited optimization space for printability and structural fidelity compared with PU/silicone systems.
(iv) Functional modification limitation: The non-polar molecular structure of polyolefins leads to poor compatibility with polar nanofillers/fibers, making functional composite modification difficult.

3.4. Polyamide-based 3D-printed elastomers

Thermoplastic polyamide elastomers (TPAE) are segmented block copolymers comprising polyamide hard segments and polyester or polyether soft segments in the molecular backbone. Their properties are governed by the hard-segment chemistry and the lengths of both soft and hard blocks, and their rheological and thermal characteristics are well-suited to powder bed fusion and material-extrusion 3D printing, with especially widespread application in SLS.[87] Polyamide-based elastomers for 3D

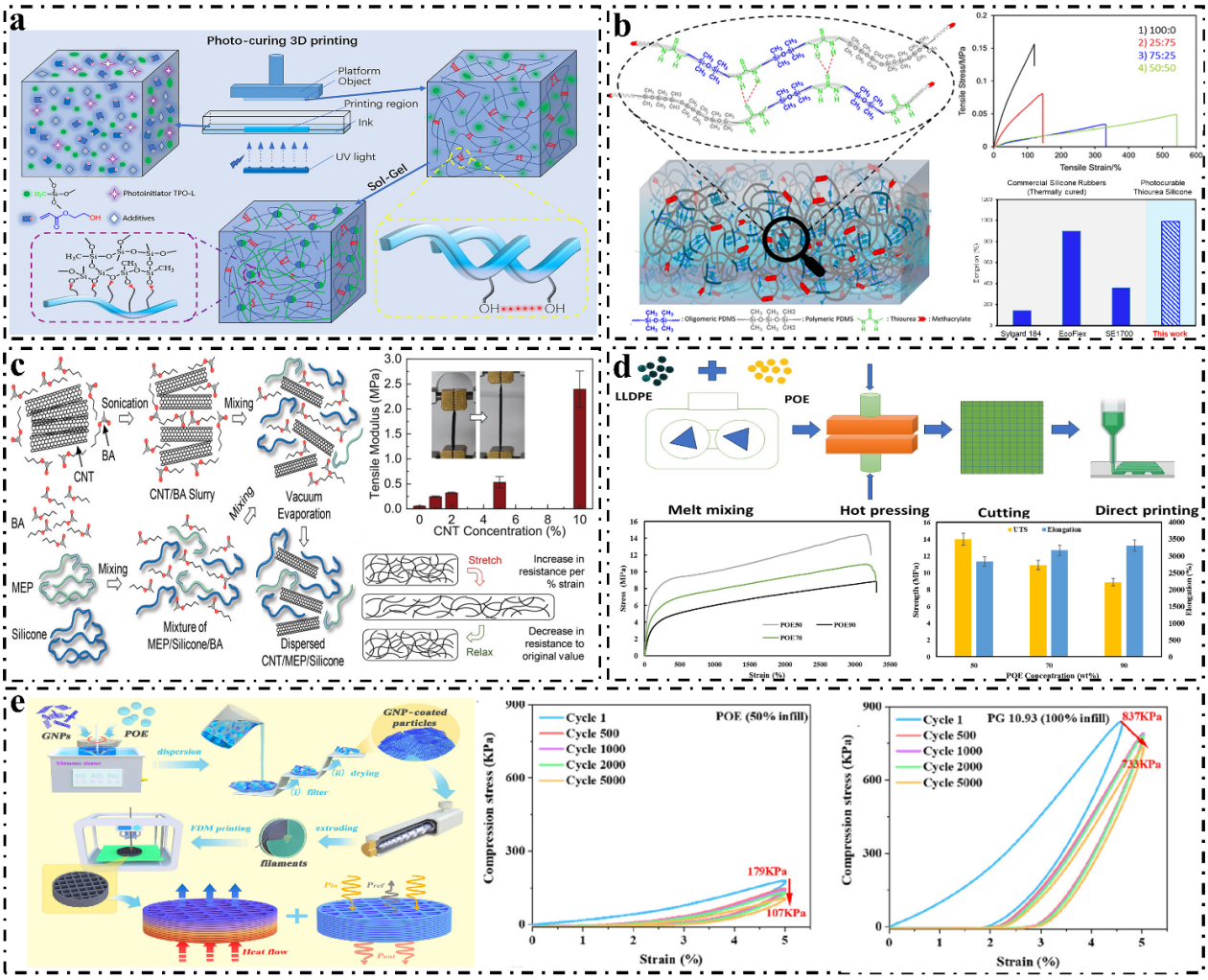

Figure 3. Fabrication strategies and functional performance of 3D-printed silicone-based and polyolefin-based elastomers. (a) Molecular design pathway for low-viscosity silicone elastomers for high-speed photopolymerization printing. Reprinted with permission from Chen *et al.*[73] Copyright © 2020 Wiley. (b) Thiourea-modified silicone elastomers with enhanced elastic properties via photopolymerization printing. Reprinted with permission from Du *et al.*[74] Copyright © 2021 American Chemical Society. (c) Material jetting 3D-printed CNT/silicone elastomers with high conductivity and flexibility. Reprinted with permission from Shar *et al.*[78] Copyright © 2022 Wiley. (d) FGF 3D-printed LLDPE/POE blend elastomers with enhanced mechanical properties. Reprinted with permission from Liu *et al.*[82] Copyright © 2020 Wiley. (e) FDM 3D-printed POE/GNPs elastomer with electromagnetic shielding functionality. Reprinted with permission from Lv *et al.*[86] Copyright © 2022 American Chemical Society.

Abbreviations: BA: Butyl acetate; CNT: Carbon nanotube; FDM: Fused deposition modeling; FGF: Fused granulate fabrication; GNPs: Graphene nanoplatelets; LLDPE: Linear low-density polyethylene; MEP: Methyl-terminated polydimethylsiloxane; PDMS: Polydimethylsiloxane; POE: Polyolefin elastomer; Si-Gel: Silicone gel; TPO-L: Ethyl (2,4,6-trimethylbenzoyl) phenylphosphinate.

printing exhibit elastic and flexible behavior suitable for functional parts.

3.4.1. Core research progress of polyamide-based elastomers

Owing to the stringent feedstock and processing requirements of 3D printing, research on polyamide-based 3D-printed elastomers is less extensive than on PU- and silicone-based systems. Establishing robust, reproducible printing parameter windows for polyamide-based elastomers remains a key research focus. Mei *et al.*[88] used cryogenic comminution to produce TPAE powder and identified optimal SLS conditions (156 °C sintering temperature, 21 W laser power, 0.10 mm layer thickness)

for TPAE printing, providing valuable guidance for further development of polyamide-based 3D-printed elastomers.

3.4.2. Technical bottlenecks of polyamide-based 3D-printed elastomers

Polyamide-based 3D-printed elastomers have good mechanical strength and thermal stability, but their research and application are limited by the following bottlenecks:

(i) Stringent printing process requirements: TPAE powder for SLS printing has stringent requirements for particle size and distribution; sintering temperature, laser power, and layer thickness have a significant impact on print success rate.
(ii) Low research attention: Compared with PU and silicone systems, polyamide-based 3D-printed elastomers have received less research attention, with limited breakthroughs in material modification and functionalization.
(iii) High production cost: The cryogenic comminution process for TPAE powder production is complex and costly, and the SLS printing equipment has high investment, limiting the large-scale application of this system.

3.5. Bio-based 3D-printable elastomers

Biobased elastomers are produced from biological resources via fermentation, chemical synthesis, and subsequent processing,[89] and can be classified as thermoplastic or thermosetting,[90] both of which are compatible with material jetting and vat photopolymerization 3D printing. When biobased feedstocks are used, precise control over deposition and curing enables fabrication of elastomers that are soft, deformable, wearresistant, and readily customizable, and these are predominantly composites with a biobased matrix.[91] Vat photopolymerization mitigates the high production costs and extended processing times associated with conventional biobased elastomer manufacturing, enabling rapid roomtemperature fabrication.

3.5.1. Core research progress of bio-based elastomers

Wu *et al.*[92] developed a noncovalent crosslinking system based on hydrogen bonding and metal–ligand coordination and fabricated vinyl palm oil-based elastomers with high tensile strength (4.2 MPa) and elongation at break (851%) via liquid crystal display printing. Because most biobased monomers lack photosensitive moieties, photopolymerization suitability is often achieved by chemically grafting photosensitive groups onto the biobased backbone. Rahman *et al.*[93] synthesized long-chain unsaturated dipropenoic acid monomers from rapeseed oil and produced elastomers with a tensile strength of 5.2 MPa even at 80 °C via inkjet printing (Figure 4a), a breakthrough for high-temperature application of bio-based elastomers. Additionally, Fei *et al.*[94] prepared photopolymerizable feedstocks from plant oil-derived dimer acids and fabricated elastomers with excellent mechanical properties via DLP (Figure 4b). For the structural collapse problem of bio-based elastomers during printing, Gu *et al.*[95] reinforced thermosetting poly(1,8octanediolcoF127 citrate) with chitosan nanoparticles, which acted as both a structural support and mechanical reinforcement. Furthermore, cellulose nanocrystals (CNCs), biobased fillers offering high stiffness, strength, and aspect ratio, show significant promise as reinforcements.[96,97] Palaganas *et al.*[98] fabricated tough, highly biobased elastomers via SLA by covalently attaching functionalized CNCs to thermosetting biobased matrices. Koo *et al.*[99] confirmed that CNC-mediated *in situ* polymerization produced homogeneous nanoparticle distribution within biobased elastomers. Building on this framework, Lu *et al.*[100] utilized carboxymethyl cellulose nanocrystals (C-CNCs) as templates for *in situ* polymerization of aniline and produced composites with high mechanical strength (4.4 MPa), toughness (13.33 $MJ \cdot m^{-3}$), and elasticity.

3.5.2. Technical bottlenecks of bio-based 3D-printed elastomers

Bio-based 3D-printed elastomers are a green and sustainable elastomer system, but their development is limited by the following core bottlenecks:

(i) Low mechanical performance: Most bio-based elastomers have low tensile strength (generally < 5 MPa) and poor thermal stability compared with petroleum-based elastomers, limiting their application in high-performance scenarios.
(ii) Lack of photosensitive moieties: Most bio-based monomers lack photosensitive moieties and require chemical grafting for photopolymerization printing, which increases the synthesis complexity and cost.
(iii) Structural collapse during printing: The low intrinsic stiffness of bio-based elastomers often results in structural collapse during printing, requiring the introduction of reinforcing agents, which often affects the printability and biocompatibility.
(iv) Limited biocompatibility: Residual small-molecule monomers and crosslinking agents in bio-based elastomers often exhibit certain cytotoxicity, restricting their application in biomedical fields.

3.6. Multi-matrix 3D-printed elastomers

Three-dimensional printing enables multimaterial architectures that integrate two or more of the elastomers

described above, or combine them with plastics or metals, to produce objects with complex geometries, enhanced mechanical properties, and diverse functionalities. Precise control of material deposition and curing enables highresolution fabrication and customized elastomer designs. This strategy preserves native material properties while imparting additional functionalities not present in the individual constituents. PU and siliconebased systems are preferred for multi-matrix 3Dprinted elastomers owing to their broad tunability, compositional diversity, and processability.

3.6.1. Core research progress of multi-matrix elastomers

Many siliconebased inks exhibit limited printing resolution, pronounced thixotropy, and a lack of intrinsic selfhealing, which can increase material waste and environmental burdens. Guided by the concept that hydrogenbonding interactions enhance shape retention and enable reversible crosslinking, Wei *et al.*[101] employed FDM and performed polycondensation with a PDMS elastomer using PU and polyetheramine as hydrogen-bond donors to yield a multi-matrix 3D-printed elastomer exhibiting high elasticity, improved shape fidelity, and excellent self-healing (Figure 4c). Similarly, PU–silicone multi-matrix elastomers are frequently fabricated via vat photopolymerization. Building on this approach, Pongwisuthiruchte *et al.*[72] grafted acrylate photosensitive groups to enable SLA of shapememory multi-matrix elastomers based on PU and silicone (Figure 4d), integrating the excellent mechanical performance of PU and the good flexibility of silicone.

3.6.2. Technical bottlenecks of multi-matrix 3D-printed elastomers

Multi-matrix 3D-printed elastomers can integrate the advantages of different elastomer systems, but their development is limited by the following bottlenecks:

(i) Poor interface compatibility: The interface compatibility between different elastomer matrices (e.g., PU and silicone) is poor, leading to insufficient interfacial adhesion and pronounced phase separation, which affects the mechanical and functional stability.
(ii) Complex printing process: Multi-matrix printing requires precise control of material deposition and curing parameters for different matrices, which increases the complexity of the printing process and the requirement for equipment.
(iii) Limited material combination: The number of compatible elastomer matrix combinations is limited; most multi-matrix systems are PU-silicone blends, with limited diversity in material combination.

The above section focuses on the fundamental matrix material systems for 3D-printed elastomers. Based on these material platforms, further function-oriented design endows 3D-printed elastomers with diversified stimulus-responsiveness, environmental adaptability, and intelligent properties, which are systematically summarized in the following section.

4. Function-oriented design and multifunctionalization of 3D-printed elastomers

Based on the fundamental matrix materials introduced in Section 3, function-oriented design and structural engineering further enable 3D-printed elastomers to achieve diversified intelligent properties. Owing to their high flexibility and elasticity, 3Dprinted elastomers can endure substantial tensile and compressive loads, and also demonstrate notable wear and corrosion resistance, combined with considerable design flexibility and customization potential. Consequently, these attributes confer distinct advantages in specialized applications, underscoring the importance of research into functional 3Dprinted elastomers. To facilitate intuitive cross-comparison and quantitative evaluation of different functional systems, a comprehensive comparison table is provided below to summarize matrix materials, printing strategies, functional components, key performance indicators, test conditions, typical applications, and bottlenecks. Ongoing research aims to optimize the performance of 3Dprinted elastomers by employing diverse strategies tailored to their matrix compositions, enabling these materials to acquire multifunctional capabilities, thereby meeting the requirements of varied application domains. This section focuses on the core design principles, recent breakthroughs, and application prospects of typical functional 3D-printed elastomers, with a brief analysis of their technical bottlenecks.

4.1. Magnetorheological 3D-printed elastomers

Magnetorheological (MR) 3Dprinted elastomers are fabricated by dispersing micronscale ferromagnetic particles within a polymermatrix printing ink. Curing under an applied magnetic field induces particle alignment into chainlike or columnar structures,[102] facilitating the fabrication of complex architectures via 3D printing. The alignment and interaction of ferromagnetic particles enable continuous, reversible modulation of mechanical properties in response to changes in field strength, conferring unique functionalities absent in conventional MR fluids—such as tunable magneticfield response, high structural stability, and shape controllability.[103] Compared with traditional casting methods, 3D printing—particularly

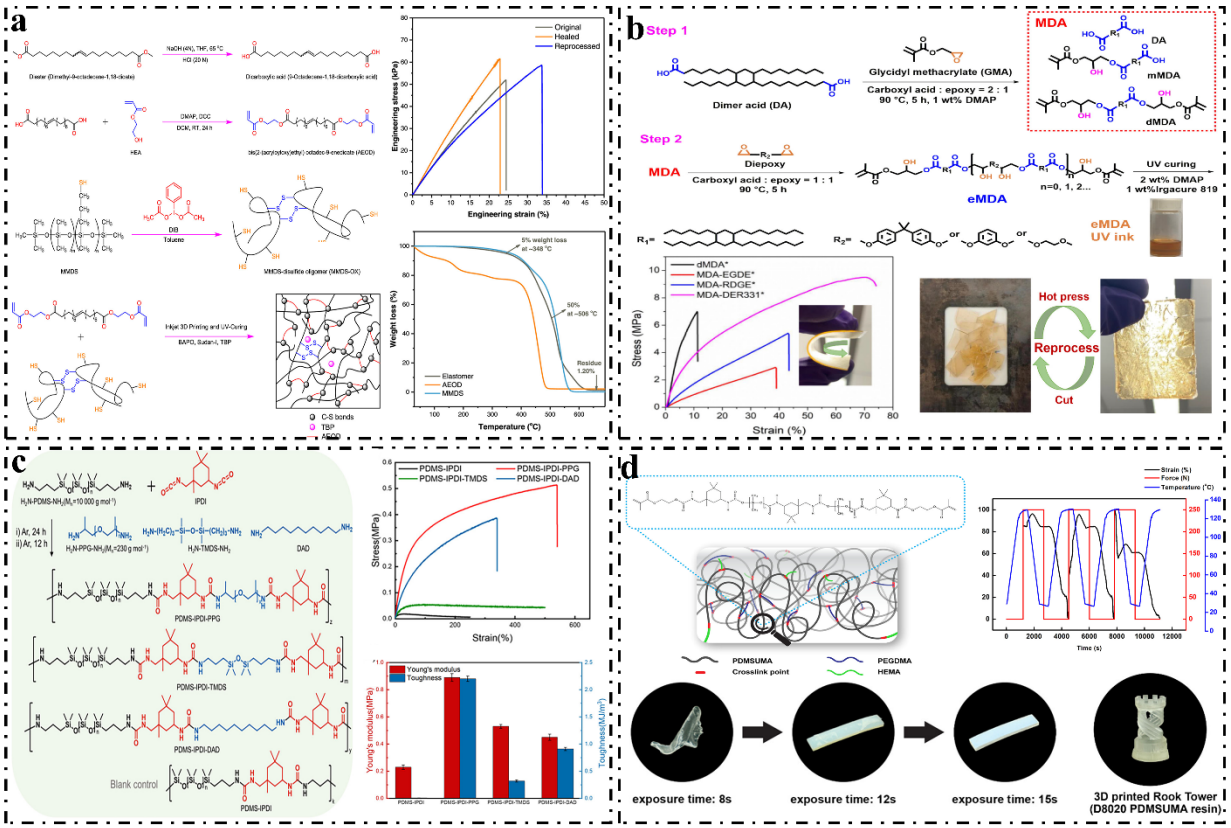

Figure 4. Synthesis routes, mechanical performance, and functional properties of 3D-printed bio-based and multi-matrix elastomers. (a) Rapeseed oil-based inkjet 3D-printed elastomers with high-temperature mechanical retention. Reprinted with permission from Rahman *et al.*[93] Copyright © 2020 American Chemical Society. (b) DLP 3D-printed elastomers from vegetable oil-based resins with excellent mechanical properties. Reprinted with permission from Fei *et al.*[94] Copyright © 2021 American Chemical Society. (c) FDM 3D printing of polyurethane-PDMS multi-matrix elastomers with self-healing properties. Reprinted with permission from Zi *et al.*[101] Copyright © 2023 Wiley. (d) SLA 3D-printed polyurethane-silicone multi-matrix elastomers with shape memory functionality. Reprinted from Pongwisuthiruchte *et al.*[72]

Abbreviations: BAPO: Bis(2,4,6-trimethylbenzoyl)phenylphosphine oxide; DA: Dimer acid; DAD: 1,10-diaminodecane; DCC: N,N'-dicyclohexylcarbodiimide; DCM: Dichloromethane; DLP: Digital light processing; DMAP: 4-dimethylaminopyridine; eMDA: Epoxy-modified methacrylated dimer acid; FDM: Fused deposition modeling; GMA: Glycidyl methacrylate; HEA: 2-hydroxyethyl acrylate; HEMA: 2-hydroxyethyl methacrylate; IPDI: Isophorone diisocyanate; MDA: Methacrylated dimer acid; PDMS: Polydimethylsiloxane; PDMSUMA: Polydimethylsiloxane urethane methacrylate; PEGDMA: Poly(ethylene glycol) dimethacrylate; PPG: Poly(propylene glycol); SLA: Stereolithography; TMDS: Tetramethyldisiloxane.

materialextrusion and inkjetting techniques—significantly improves particle dispersion in MR elastomers (MREs).[104] Current research primarily focuses on material selection, optimization of printing parameters, and postprocessing strategies.

Additively manufactured MREs typically comprise polymeric matrices (e.g., TPU), ferromagnetic particles (e.g., carbonyl iron powder), and optional additives. These composites exhibit MR and piezoresistive behavior. Singlephase MREs often display reduced MR response due to nonuniform particle dispersion. To address this, Guan *et al.*[105] developed a DIWprintable ink combining MR fluid with MRE and retained the high MR effect (11.1 MPa) of MR fluid while providing the mechanical stability of MREs. Similarly, a "fillandseal" technique was employed to encapsulate MR fluid within an Ecoflex substrate, producing tunablestiffness MREs suitable for flexible electronic sensors.[106] To enhance MR performance, Ding *et al.*[107] embedded carbonyl iron powder into silicone rubber and low-crosslinked PU to create hybrid MREs with strong shear-hardening behavior and high MR effect. Beyond matrix selection, researchers now emphasize optimization of printing processes.[108] Peng *et al.*[104] demonstrated that circular printing paths in FDM yielded greater MR response than linear paths (Figure 5a), providing a new strategy for optimizing the MR performance of MREs. Mondal *et al.*[109] found that honeycomb infill density modulated MRE MR response (Figure 5b), while Bastola *et al.*[110] used AM with an external magnetic field to control

stiffness and MR behavior, further improving properties with dotpattern architectures. Lou *et al.*[111] introduced dualmodulus 3D printing to simultaneously fabricate high modulus resilient elastomers and low modulus resilient elastomers, achieving magnetic-control performance 328.57% higher than single-modulus HMREs, a landmark achievement in MRE design.

However, technical bottlenecks still persist, such as the reduced MR response of single-phase MREs caused by non-uniform particle dispersion, the trade-off between MR effect and mechanical properties, limited large-scale manufacturing capabilities, and the high cost of ferromagnetic particles.

4.2. Bonded 3D-printed elastomers

Bonded 3Dprinted elastomers employ 3D printing to precisely control the layered deposition of adhesive elastomeric materials, enabling the fabrication of complex threedimensional structures with high elasticity, flexibility, and superior bonding properties.[112]

Bond strength is the primary criterion when selecting adhesive elastomers for 3D printing. For components subjected to high stress or impact, durable, highstrength adhesives are essential. Enhancing adhesion typically requires strong intermolecular interactions; acrylate monomers, for example, promote adhesion and feature unsaturated double bonds that function as photosensitive moieties widely utilized in vatphotopolymerization processes. Building on this principle, Wanasinghe *et al.*[113] developed a series of 3Dprintable elastomers with enhanced bonding properties and demonstrated that contour-matching print patterns significantly improved material bond strength via DLP (Figure 5c). Similarly, polyphenolic compounds can modulate molecular interactions by tailoring ionic polymer properties—from soft adhesives to tough materials—thereby enhancing interfacial forces and bonding strength[114] (Figure 5d). Lee and So[115] created tunable adhesive systems inspired by aphid morphology and improved bonding strength through biomimetic structural design (Figure 5e).

Operational convenience is a major advantage of bonded 3Dprinted elastomers over conventionally manufactured adhesive systems. Traditional fabrication can involve labourintensive, timeconsuming, and costly steps, whereas 3D printing allows rapid, efficient processing. Lee *et al.*[116] developed an adhesive polyvinyl butyral elastomer and enabled direct printing of maxillofacial prostheses with complex geometries via inkjet-type printing. Curing rate also strongly influences operational convenience. Many commercial adhesive elastomers require extended curing—often several days or weeks—posing application challenges. In contrast, certain DIWprintable thermosetting silicones gel and cure isotropically within minutes, enabling rapid curing without shrinkage and delivering high bonding efficiency and strength.[117]

Environmental adaptability is the third crucial factor in bonded 3Dprinted elastomer design. Many adhesive elastomers are formulated for underwater curing, necessitating emphasis on water resistance and weatherability.[118] Cui *et al.*[119] developed a hyperbranched polymer elastomer pressure-sensitive adhesive and achieved tough, durable underwater adhesion via 3D printing (Figure 5f), solving the underwater bonding problem of adhesive elastomers.

However, technical bottlenecks such as the trade-off between bond strength and elasticity, limited environmental adaptability (e.g., under high temperature and humidity), poor repeatability of bonding performance, and long curing times for certain viscoelastic materials still persist.

4.3. Dielectric 3D-printed elastomers

Dielectric 3Dprinted elastomers are fabricated by compounding flexible polymer matrices with functional fillers to produce highdielectric elastomers.[120] Using SLA/DLP or DIW, layered heterostructures comprising "electrode–dielectric layer–electrode" assemblies can be constructed. Conductivenetwork distribution is optimized via electricfield actuation or postprocessing, enabling integrated fabrication of complex electrodeformable structures within this intelligent material system.[121]

Siliconebased resins, including PDMS, PU, and polyacrylate, are among the most widely used dielectricelastomer matrices.[122] However, these materials often display low maximum strain and dielectric strength, constraining improvements in electromechanical performance. To address this, highdielectric composites are frequently prepared by incorporating ceramic fillers (e.g., $BaTiO_3$, TiO_2) or conductive reinforcements (e.g., graphene, CNTs, liquid metals), though each filler may adversely affect other material properties.[123] Consequently, simultaneously enhancing multiple properties remains a key challenge for highperformance dielectric elastomers. Dai *et al.*[124] incorporated an amino-complexed hybrid (Polyethyleneimine–silver) into PDMS and yielded a 3D-printable dielectric elastomer with low modulus (1.14 MPa) and excellent electroactuation performance (22.27% actuation strain at 35 V μm^{-1}) (Figure 6a).

High viscosity and low yield stress often hinder 3D printing of dielectric elastomers, particularly in DIW processes, where inks can produce highhardness elastomers with significant mechanical losses. To overcome these

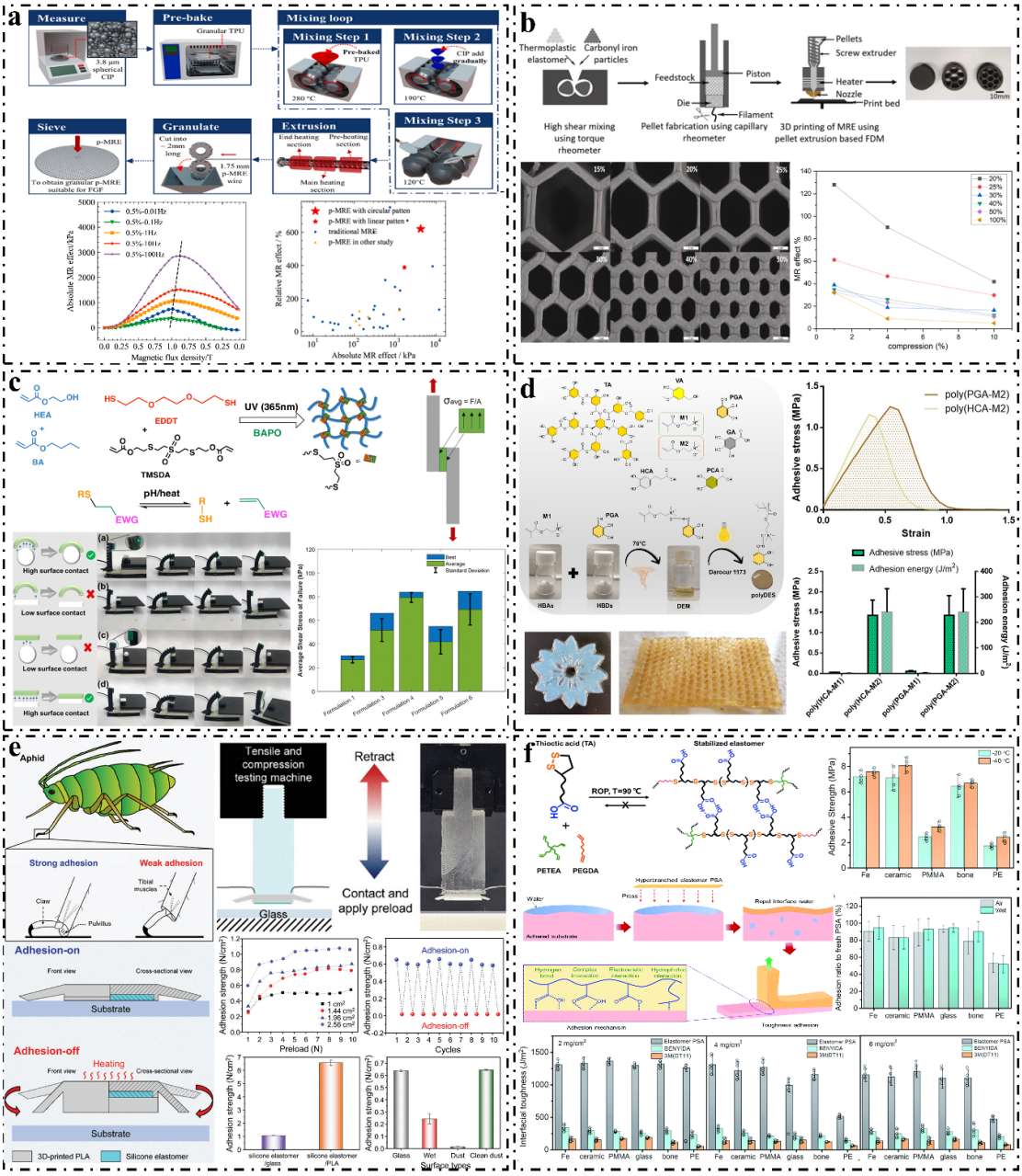

Figure 5. Fabrication and performance of 3D-printed magnetorheological and adhesive elastomers. (a) FDM 3D-printed TPU/CIP-based MRE with circular path performance optimization. Reprinted from Peng *et al.*[104] (b) 3D printing of honeycomb-filled MRE with MR effect performance versus packing density. Reprinted from Mondal *et al.*[109] (c) DLP 3D printing of acrylate-based adhesive elastomers with contour matching for enhanced bonding strength. Reprinted with permission from Wanasinghe *et al.*[113] Copyright © 2023 The Royal Society of Chemistry. (d) Polyphenol-regulated ion polymers for amplified adhesive force of 3D-printed elastomers. Reprinted from Lacalle *et al.*[114] (e) Aphid-inspired structural design for tunable bonding strength of 3D-printed elastomers. Reprinted with permission from Lee *et al.*[115] Copyright © 2023 Wiley. (f) Underwater-cured hyperbranched PSA elastomers for resilient, durable underwater adhesion. Reprinted with permission from Cui *et al.*[119] Copyright © 2022 The Royal Society of Chemistry.
Abbreviations: BA: Butyl acrylate; BAPO: Bis(2,4,6-trimethylbenzoyl)phenylphosphine oxide; CIP: Carbonyl iron powder; DEM: Deep eutectic monomer; DLP: Digital light processing; EDDT: 2,2'-(ethylenedioxy)diethanethiol; EWG: Electron-withdrawing group; FDM: Fused deposition modeling; Fe: Iron; GA: Gallic acid; HBA: Hydrogen bond acceptor; HBD: Hydrogen bond donor; HCA: Hydrocaffeic acid; HEA: 2-hydroxyethyl acrylate; MR: Magnetorheological; MRE: Magnetorheological elastomer; PCA: Protocatechuic acid; PE: Polyethylene; PEGDA: Poly(ethylene glycol) diacrylate; PETEA: Pentaerythritol tetraacrylate; PLA: Poly(lactic acid); PMMA: Poly(methyl methacrylate); polyDES: Polymeric deep eutectic solvent; p-MRE: Printed magnetorheological elastomer; PSA: Pressure-sensitive adhesive; ROP: Ring-opening polymerization; TA: Thioctic acid; TMSDA: Thiol–Michael-based sulfone diacrylate; TPU: Thermoplastic polyurethane; VA: Vanillic acid.

processing–performance tradeoffs, Danner *et al.*[125] applied capillary-suspension principles to design a DIW-printable dielectric-elastomer ink and produced an elastomer with a dielectric constant four times higher than commercial PDMS. Nevertheless, under high stress and operating voltages, 3Dprinted dielectric elastomers are prone to electrical or mechanical failure, leading to reduced service life and reliability. Nie *et al.*[126] developed a self-healing dielectric elastomer with high stretchability and large actuation force by using PVDF-HFP as the matrix and introducing a fluorinated surfactant (FS30), solving the service life problem of dielectric elastomers.

However, technical bottlenecks persist in pure polymer matrices, such as the trade-off between low dielectric constant and actuation strain, the balance between dielectric properties and mechanical flexibility, electrical/mechanical failures under high stress/high voltage, and limited service life.

4.4. Ultra-soft 3D-printed elastomers

Ultrasoft 3Dprinted elastomers are fabricated by combining ultralowmodulus polymer matrices (<100 kPa) with functional fillers (e.g., nanoclay) that impart tunable rheological properties. The composites are shaped under defined curing conditions and processed via highprecision 3D printing to yield flexible materials with complex biomimetic architectures and integrated functionality.[127] Bottlebrush polymers constitute the most intensively studied class of ultrasoft elastomers due to their ultra-low shear moduli (≈1–100 kPa).

Although bottlebrush polymers have not yet been widely adopted in 3D printing, several studies have integrated them with 3D printing to fabricate functional ultrasoft elastomers. Choi *et al.*[128] incorporated PEGLA into liquid photosensitive resins and fabricated ultrasoft materials containing dynamic disulfide-bond networks via DLP. Additionally, Asadi *et al.*[129] prepared a PDMS-based ultrasoft elastomer suitable for DIW with a low storage modulus (G' = 3.3 kPa) (Figure 6b). Similarly, Xu *et al.*[130] used PDMS as the base matrix and introduced single-walled CNTs as conductive fillers to obtain ultrasoft elastomers with Young's moduli of 2.98–10.65 kPa and conductivities of 2.06–17.84 S m^{-1}, and 3D-printed multilayer touch panels and ECG electrodes (Figure 6c), expanding the application of ultrasoft elastomers in soft electronic devices.

However, technical bottlenecks remain, including relatively low mechanical strength and structural stability under heavy loads. Notably, their ultra-low modulus is a critical advantage for biomimetic devices and conformal electronics, while challenges persist in complex structural fabrication, functional modification, and the high cost of bottlebrush polymers.

4.5. Liquid-crystal 3D-printed elastomer

Liquidcrystal 3Dprinted elastomers are advanced functional materials that combine the molecular order and deformability of liquidcrystal phases with the flexibility of elastomeric networks. Utilizing 3D printing, these materials enable geometrically complex structures with programmable deformation and stimulus responsiveness.[131,132] Conventional fabrication techniques have generally restricted liquid crystal elastomer (LCE) applications to thin-film devices (<150 μm) with limited actuation capabilities,[133] while 3D printing offers significant advantages in fabricating complex LCE geometries.

Liquidcrystal 3Dprinted elastomers can employ optical or thermal stimuli to control molecular orientation, imparting anisotropic mechanical and optical properties.[134] A key challenge is achieving precise alignment of liquidcrystal domains. Unlike conventional methods relying on surface chemistry or topographical cues, Peng *et al.*[135] designed a dual-network structure comprising an LCE network and a PUA elastomer network and achieved two opposing actuation modes in a single LCE (Figure 6d), overcoming the longstanding challenge of integrating conflicting actuation functions. Localized molecular orientation can also be achieved via lightinduced secondary crosslinking and phototriggered dynamic bond exchange; however, these approaches are incompatible with photoradical polymerization and thus unsuitable for DLP. To address this, Wan *et al.*[136] proposed "orthogonal photochemistry" and enabled UV-triggered dynamic bond exchange and reversible actuation for DLP-printed LCE actuators with spatially selective orientation.

Nanomaterials can be incorporated into LCE fabrication to replace chromophores such as azobenzene derivatives for photothermal actuation. Gold nanorods (Au NRs) are excellent photothermal agents, though aggregation can reduce efficiency. Skillin *et al.*[137] developed a two-step ligand-exchange strategy for Au NRs and achieved high photothermal conversion efficiency (>40%) and rapid actuation (>60%) at a low loading of 0.01 wt%, enabling the first millimeter-scale 3D-printed LCE structure (Figure 6e). Ford *et al.*[138] incorporated Au NRs into LCEs and realized complex motion control (bending, crawling, rolling) via DIW, a breakthrough for LCE-based soft robotics.

However, technical bottlenecks such as the difficulty in achieving precise alignment of liquid crystal domains, low drive strain and slow response speed, high cost of liquid crystal monomers, and limited large-scale manufacturing capabilities still persist.

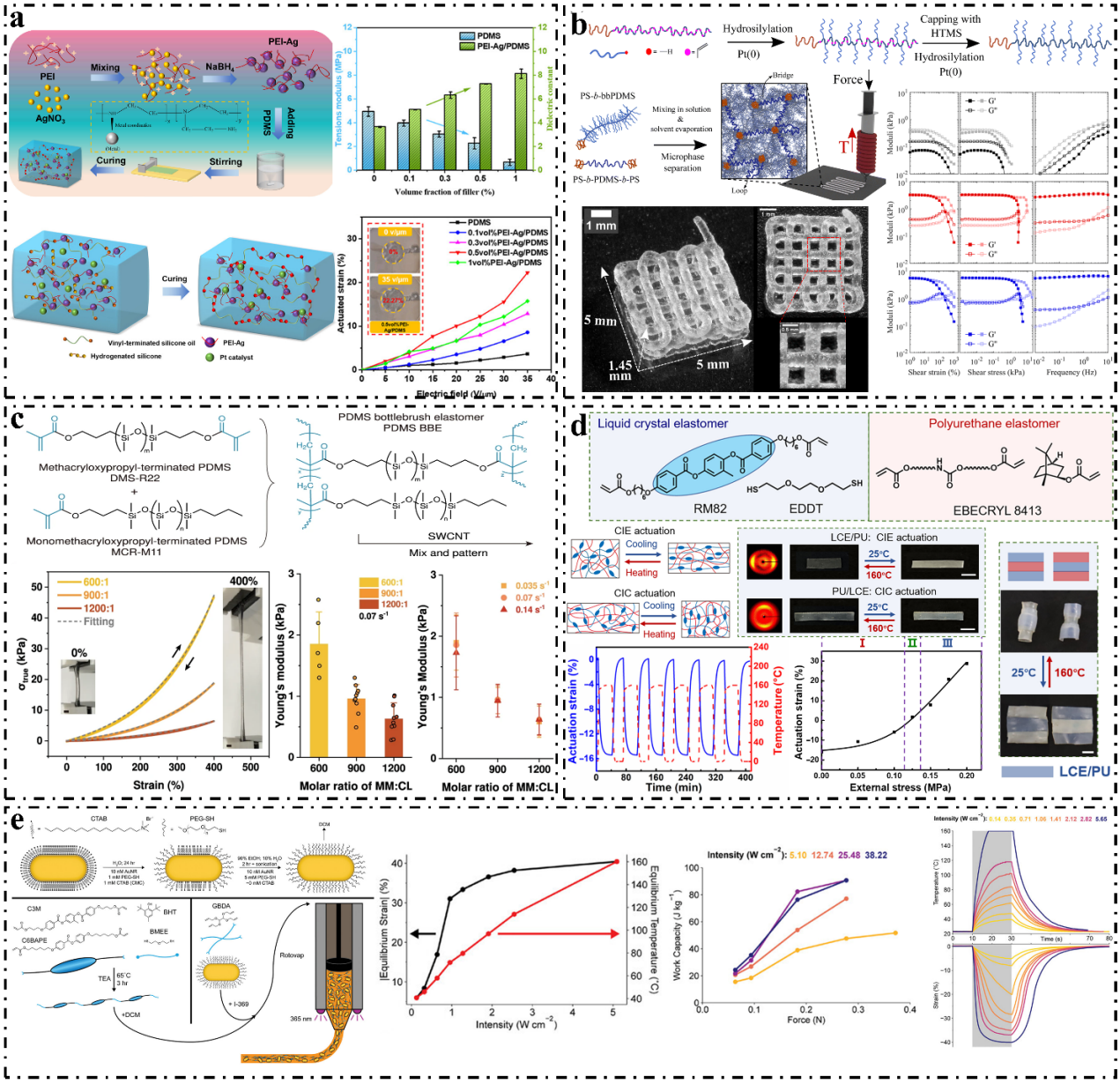

Figure 6. Design strategies and functional performance of 3D-printed dielectric, ultra-soft, and liquid crystal elastomers. (a) PEI-Ag/PDMS dielectric elastomers with low modulus (1.14 MPa) and high actuation strain (22.27%). Reprinted from Dai *et al.*[124] (b) DIW 3D-printed PDMS-based ultra-soft elastomers with low storage modulus (3.3 kPa). Reprinted from Asadi *et al.*[129] (c) PDMS/carbon nanotube ultra-soft elastomers for ultra-soft electronic devices (ECG electrodes). Reprinted from Xu *et al.*[130] (d) DLP 3D-printed LCE-polyurethane dual-network structures with bidirectional actuation. Reprinted from Peng *et al.*[135] (e) DIW 3D-printed Au NR/LCE composites with high photothermal conversion efficiency (>40%). Reprinted with permission from Skillin *et al.*[137] Copyright © 2024 Wiley.

Abbreviations: Ag: Silver; $AgNO_3$: Silver nitrate; Au NR: Gold nanorod; CTAB: Cetyltrimethylammonium bromide; DCM: Dichloromethane; DIW: Direct ink writing; DLP: Digital light processing; ECG: Electrocardiography; EDDT: 2,2'-(ethylenedioxy)diethanethiol; LCE: Liquid crystal elastomer; $NaBH_4$: Sodium borohydride; PDMS: Polydimethylsiloxane; PEG-SH: Thiol-terminated poly(ethylene glycol); PEI: Polyethyleneimine; PEI-Ag: Polyethyleneimine-silver; Pt: Platinum; PU: Polyurethane; RM82: 1,4-bis-[4-(3-acryloyloxypropyloxy)benzoyloxy]-2-methylbenzene; SWCNT: Single-walled carbon nanotube; TEA: Triethylamine.

4.6. Self-healing 3D-printed elastomers

Selfhealing 3Dprinted elastomers are fabricated by incorporating dynamically reversible chemical bonds or stimulusresponsive components into an elastomer matrix. Coupled with the precise structural control afforded by 3D printing, this design enables autonomous repair when triggered by external stimuli such as heat, light, or mechanical force.[139] This approach overcomes the "singleuse failure" limitation of traditional elastomers, extends service life, and achieves synergistic recovery of mechanical properties, functional stability, and complex structural customization.[140]

Dynamic bonds include both dynamic covalent bonds (e.g., sulfur, Diels–Alder, boronate, sterically hindered urea) and dynamic noncovalent bonds (e.g., hydrogen bonding, metal coordination, ionic interactions).[141] These interactions contribute to the material selfhealing and adaptive behavior. However, the tradeoff between rapid bond reversibility and network stability presents a challenge in achieving both efficient selfrepair and high mechanical strength. Moreover, precise control of bond density and spatial distribution during manufacturing is required, resulting in complex fabrication processes. To address these challenges, Qu *et al.*[142] developed a dynamic dual-network elastomer comprising polysiloxane and urea-functionalized PDMS and achieved near-complete mechanical recovery after thermal treatment. Zhang *et al.*[143] incorporated dynamic disulfide bonds and hydrogen bonds into a PU matrix and fabricated a self-healing elastomer with a healing efficiency of 95.86% (the elongation at break after self-repair is 1,366.75%) via FDM. Given that hightemperature healing has limited applicability, Lai *et al.*[144] developed a PDMS-based dynamic dual-network elastomer and achieved rapid room-temperature/underwater self-healing (>90% property recovery within 24 h) with reversible adhesion (Figure 7a), solving the high-temperature repair problem of self-healing elastomers. Beckett *et al.*[145] achieved hydrogen-bond-driven rapid self-healing (the tensile strain reached 344%, 90% mechanical recovery within 5 min) via hybrid photopolymerization and enabled rapid self-healing of 7 mm puncture damage in DLP-printed pneumatic actuators (Figure 7b), a breakthrough for the practical application of self-healing elastomers.

However, technical bottlenecks such as the trade-off between self-healing efficiency and mechanical strength, the requirement for high temperatures or energy in most self-healing systems, a limited number of healing cycles, and poor self-healing performance under extreme conditions still remain.

4.7. Biodegradable 3D-printed elastomers

Biodegradable 3Dprinted elastomers are advanced functional materials that integrate mechanical elasticity, multifunctionality, and environmental degradability. They are fabricated by combining biodegradable polymers (e.g., PLA, polycaprolactone) with dynamic bonding groups or environmentally responsive components, using additivemanufacturing techniques such as FDM or SLA.[146] The development of biodegradable 3Dprinted elastomers centers on achieving a dynamic equilibrium between functionality, processability, and controllable degradability.

Among biodegradable elastomers suitable for 3D printing, PU elastomers derived from biodegradable feedstocks are highly promising biomaterials due to their mechanical performance and biocompatibility.[147] However, conventionally prepared PU elastomers often have high melting points and slow degradation rates. Although biodegradable aqueous PUs have been proposed, their low 3Dprinting precision has limited broader applicability.[148] Feng *et al.*[149] developed a water-dispersible PU elastomer and achieved high-precision FDM printing with low inflammatory response for soft-tissue engineering scaffolds. To address limitations of conventional polymers—such as PCL's high Young's modulus (90 MPa) and hydrophobic surface (contact angle >80°)—Gokyer *et al.*[150] developed a microphase-separated PU urea and reduced the Young's modulus to 17.1 MPa (approaching natural muscle stiffness ~150 kPa) with elongation at break of 940% (Figure 7c). Recent research on biodegradable 3Dprinted elastomers has shifted toward multifunctional synergistic integration through dynamicnetwork design, overcoming longstanding tradeoffs between environmental sustainability and functional compatibility. For example, Luo *et al.*[151] developed a novel photosensitive ionic liquid and fabricated a hydrogen-bond-network elastomer with ionic conductivity (0.23 S m^{-1}) and complete dissolution within 2 h at 70 °C. Additionally, Hu *et al.*[152] incorporated gallium-based liquid metal into a multilayer dynamic-covalent-bond architecture and produced a self-healing, reconfigurable, and biodegradable multifunctional electronic device for skin monitoring, expanding the application of biodegradable elastomers in flexible electronics.

However, technical bottlenecks still exist, such as the difficulty in precisely controlling the degradation rate, the trade-off between degradability and mechanical properties, the low biocompatibility of some degradable elastomers, and limited functional diversity.

4.8. Shape-memory 3D-printed elastomers

Shape-memory 3D-printed elastomers represent an

advanced class of smart materials integrating dynamic polymer design with 3D printing technology, enabling programmable multi-shape transformations of complex structures (i.e., 4D printing).[153] Through molecular structural design incorporating reversible covalent networks, the material gains responsive properties, and heterogeneous components are integrated via interfacial welding to construct programmable sequential deformation multi-material structures.[154] Their ability to recover preset shapes after deformation under external stimuli like temperature or light makes them promising candidates for fabricating novel soft robots.[155]

The key to preparing shape-memory elastomers lies in imparting material response characteristics such as humidity responsiveness, temperature-dependent self-healing behavior, and pH responsiveness.[156] Among these stimuli, near-infrared (NIR) light offers distinct advantages. NIR responsiveness can be created by incorporating photothermal agents into thermally induced shape-memory polymers.[157] Compared to traditional photothermal agents like metallic nanoparticles, green biomass has been demonstrated to serve as fillers and integrate into resin matrices, conferring photothermal functionality to materials while enhancing sustainability.[158] For instance, Ren *et al.*[159] combined PLA, polyamide elastomer, and lignin and fabricated a 4D-printed material with high toughness and photothermal responsiveness via FDM. Sun *et al.*[160] constructed a fully bio-based photothermal elastomer and achieved excellent photothermal conversion and actuation capabilities under visible/NIR laser irradiation with full recyclability. Although biomaterials have been extensively applied in the synthesis of shape-memory 3D-printed elastomers, most elastomers can only recover their shape at extremely high temperatures or exhibit elasticity only above their transition temperature. Consequently, 4D printing of biodegradable shape-memory elastomers remains highly challenging. To address this, Song *et al.*[161] leveraged polyethylene glycol crystallization and photopolymerization crosslinking networks and achieved excellent elasticity across a broad temperature range (15–60 °C) with a shape recovery rate >97%. Similarly, Paunović *et al.*[153] developed biodegradable shape-memory elastomers with precisely controllable glass transition temperature (25–42 °C) and rapid recovery at physiological temperature (37 °C) with cell compatibility and controllable drug release capabilities (Figure 7d), a breakthrough for precision medicine applications.

However, technical bottlenecks such as low shape recovery rate and poor repeatability, high temperatures required for shape recovery, limited multi-shape memory capability, and poor mechanical properties of biodegradable shape memory elastomers still persist.

4.9. Other functional 3D-printed elastomers

Beyond the functional 3Dprinted elastomers discussed above, researchers are designing elastomeric materials tailored for extreme environments and specialized applications. These emerging systems expand the application space of 3Dprinted elastomers through biomimetic structural optimization, innovative chemistries, and advances in composite manufacturing.

To overcome limitations in mechanical performance and structural complexity in conventional porous materials, Bai *et al.*[162] drew inspiration from the dual-gradient architecture of sunflower pith and developed a PU porous elastomer with pronounced mechanical function amplification for impact protection and noise isolation. To overcome the limited loadbearing capacity of shearreinforced materials in extreme environments, Yang *et al.*[163] combined FDM and DIW to fabricate soft–hard phase elastomer composites with biomimetic lattice architectures and improved quasistatic load-bearing capacity and dynamic impact-energy dissipation (Figure 7e). To enhance chemical resistance and address processing challenges associated with fluorinated elastomers, Song *et al.*[164] developed a fluorinated PUA elastomer with high chemical resistance (250% elongation after 24 h immersion in tetrahydrofuran) and enabled seamless integration of rigid–flex composite structures in microfluidic chips (Figure 7f).

4.10. Summary of functional 3D-printed elastomers

In the past five years, functional 3D-printed elastomers have achieved significant breakthroughs in stimulus responsiveness, multifunctional integration, and practical application. As summarized in the comprehensive comparison Table 3, MREs have realized ultra-high MR effect and dual-modulus design; self-healing elastomers have solved the high-temperature repair problem and achieved rapid room-temperature/underwater self-healing; LCEs have realized complex programmable actuation and millimeter-scale 3D printing; biodegradable and shape-memory elastomers have been integrated with photothermal/conductive functionality for biomedical and 4D printing applications. However, the core bottlenecks for most functional 3D-printed elastomers are the trade-off between functional performance and mechanical properties, high cost of raw materials and manufacturing, and limited large-scale fabrication capability. The future research focus will be on the synergistic optimization of functionality and mechanical performance, the development of low-cost printable systems, and the improvement of large-scale manufacturing technology.

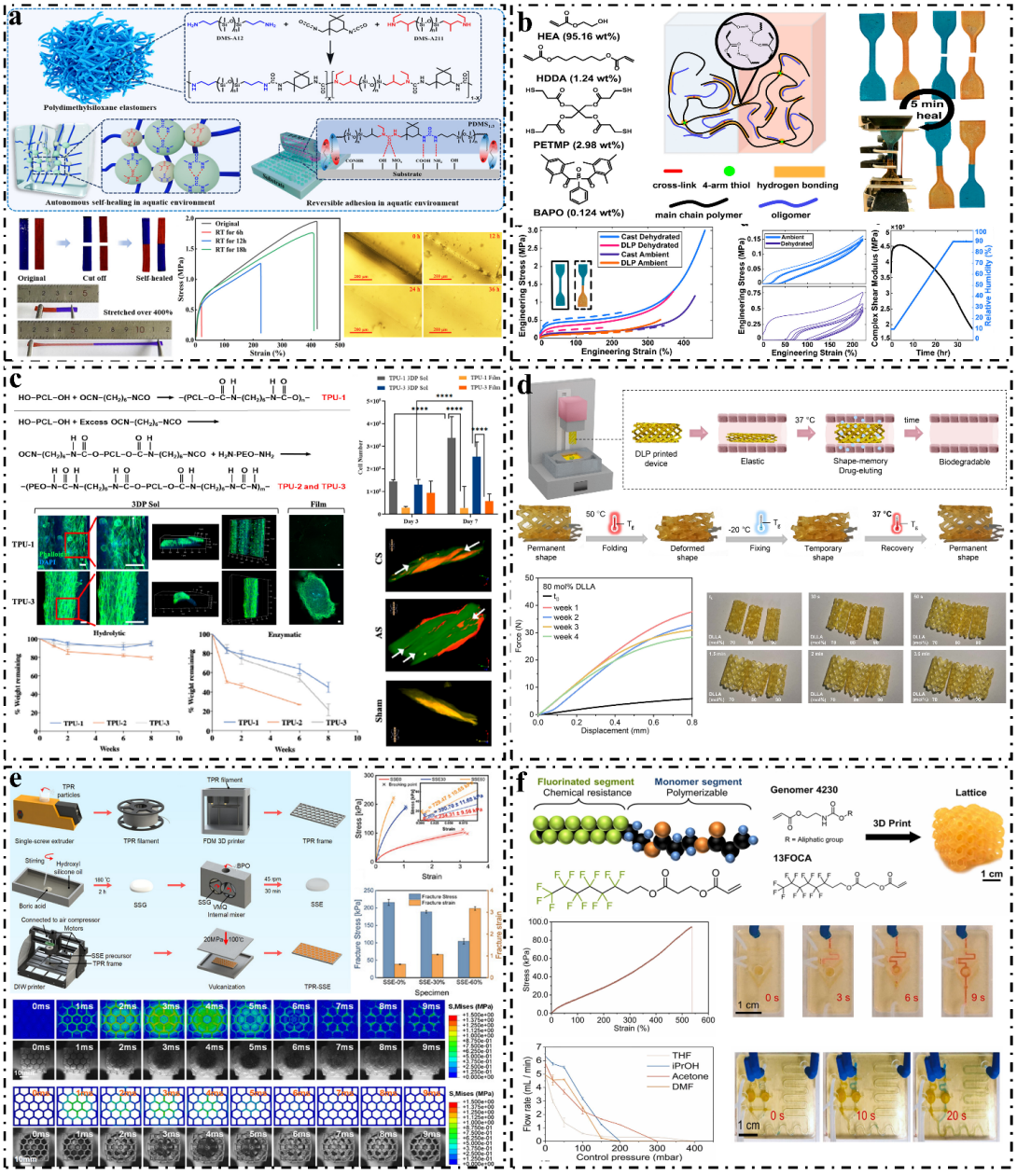

Figure 7. Fabrication and functional properties of 3D-printed self-healing, biodegradable, shape-memory, and chemically resistant elastomers. (a) PDMS-based dynamic dual-network elastomer with room-temperature/underwater self-healing and reversible adhesion. Reprinted with permission from Lai *et al.*[144] Copyright © 2024 American Chemical Society. (b) DLP-printed hybrid photopolymer elastomer with 5-minute rapid self-healing for soft actuator applications. Reprinted from Beckett *et al.*[145] (c) Low-temperature FDM-printed PCL-based polyurethane scaffold matching natural muscle stiffness. Reprinted with permission from Gokyer *et al.*[150] Copyright © 2021 American Chemical Society. (d) DLP printing of degradable elastomers with rapid deformation at physiological temperature (37 °C) for precision medicine. Reprinted from Paunović *et al.*[153] (e) FDM+DIW synergistic printing of TPR-SSE lattice with enhanced load-bearing and energy-dissipation properties. Reprinted with permission from Yang *et al.*[163] Copyright © 2025 Wiley. (f) Multi-material DLP-printed fluorinated elastomer with chemical corrosion resistance for microfluidic chips. Reprinted from Song *et al.*[164]

Abbreviations: 13FOCA: 3-oxo-3-((3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)oxy)propyl acrylate; BAPO: Bis(2,4,6-trimethylbenzoyl)phenylphosphine oxide; BPO: Benzoyl peroxide; DIW: Direct ink writing; DLLA: D,L-lactide; DLP: Digital light processing; DMF: N,N-dimethylformamide; DMS-A12: Aminopropyl-terminated polydimethylsiloxane; DMS-A211: N-ethylaminoisobutyl-terminated polydimethylsiloxane; FDM: Fused deposition modeling; HDDA: 1,6-hexanediol diacrylate; HEA: 2-hydroxyethyl acrylate; IPDI: Isophorone diisocyanate; iPrOH: Isopropanol; PCL: Polycaprolactone; PDMS: Polydimethylsiloxane; PEO: Poly(ethylene oxide); PETMP: Pentaerythritol tetrakis(3-mercaptopropionate); PLA: Poly(lactic acid); RT: Room temperature; SSE: Shear-stiffening elastomer; THF: Tetrahydrofuran; TPU: Thermoplastic polyurethane; TPR: Thermoplastic rubber.

Table 3. Comprehensive comparison of functional 3D-printed elastomers

Functional category	Matrix material	Printing method	Functional component	Key performance metrics	Testing conditions	Representative applications
Magnetorheological elastomers	TPU, silicone rubber	DIW, FDM	Carbonyl iron powder (CIP)	MR effect: 11.1 MPa; shear modulus	Magnetic field 0–800 kA/m; room temperature	Flexible sensors, soft actuators
Bonding elastomers	Acrylate, PVB, silicone	DLP, inkjet	Polyphenol, acrylate monomers	Bond strength: 100–300 kPa; underwater adhesion	Tensile test; dry/underwater environment	Tissue adhesion, maxillofacial prosthetics
Dielectric elastomers	PDMS, PU, PVDFHFP	DIW, SLA/DLP	$BaTiO_3$, CNTs, Ag hybrid	Dielectric constant: 4× PDMS; actuation strain 22.27%	35 V μm^{-1}; room temperature	Soft actuators, flexible electronics
Ultra-soft elastomers	Bottlebrush polymer, PDMS	DLP, DIW	Nanoclay, CNTs	Modulus: 2.98–100 kPa; stretchability >500%	Tensile test; dynamic mechanical analysis	Electronic skin, bio-interfaces
Liquid crystal elastomers	LCE, PU-acrylate	DLP, DIW	Au nanorods, azobenzene	Actuation strain >60%; photothermal efficiency >40%	NIR light; 25–80 °C	Bionic robots, programmable actuators
Self-healing elastomers	PU, PDMS	FDM, DLP	Disulfide bonds, H-bonds, urea bonds	Healing efficiency: 90–95.86%; room-temperature healing	Tensile recovery; 25 °C/60 °C	Soft actuators, durable devices
Biodegradable elastomers	PLA, PCL, waterborne PU	FDM, SLA/DLP	Ionic liquids, liquid metal	Degradation: dissolve in 2 h at 70 °C; modulus ~17.1 MPa	Soil/water medium; 37 °C	Tissue scaffolds, implantable devices
Shape-memory elastomers	PLA, PEG, bio-based PU	FDM, DLP	Lignin, photothermal agents	Shape recovery >97%; response at 33–37 °C	NIR / heat; 15–60 °C	4D printing, smart implants

Abbreviations: Ag: Silver; Au: Gold; $BaTiO_3$: Barium titanate; CIP: Carbonyl iron powder; CNTs: Carbon nanotubes; DIW: Direct ink writing; DLP: Digital light processing; FDM: Fused deposition modeling; H-bonds: Hydrogen bonds; LCE: Liquid crystal elastomer; MR: Magnetorheological; NIR: Near-infrared; PCL: Polycaprolactone; PDMS: Polydimethylsiloxane; PEG: Poly(ethylene glycol); PLA: Poly(lactic acid); PU: Polyurethane; PVB: Polyvinyl butyral; PVDF-HFP: Poly(vinylidene fluoride-co-hexafluoropropylene); SLA: Stereolithography; TPU: Thermoplastic polyurethane.

5. Application areas of 3D-printed elastomers

As performance and functional innovations in printable elastomers continue to advance, 3Dprinted elastomer technology is rapidly transitioning from laboratory research to industrial applications. Leveraging high resilience, tunable mechanical properties, and the ability to fabricate complex geometries, this technology shows substantial potential across applications such as medical implants, flexible electronics, and highend industrial components. This section examines five major application domains—biomedical field, wearable flexible sensors, soft robotics, industrial manufacturing, and consumer goods, focusing on how synergistic optimization of material modification, structural design, and functional implementation addresses core requirements across diverse use cases. It further elucidates the relationships between key material properties—such as biocompatibility, dynamicresponse behavior, and environmental tolerance—and practical performance in realworld applications.

5.1. Biomedical applications

Notably, the low modulus and high compliance of 3D-printed elastomers are highly favorable for matching the mechanical properties of soft tissues, making them ideal for personalized implants, surgical models, and tissue engineering scaffolds. 3Dprinted elastomer technology holds broad promise in biomedical applications due to its exceptional flexibility, tunable mechanical properties, and excellent biocompatibility. It enables the precise fabrication of customized instruments and models that accurately replicate complex human anatomical structures, offering innovative solutions for tissue engineering, minimally invasive surgery, and preoperative planning.

In smart implantable devices, shapememory polymers

have attracted considerable interest owing to their capacity to recover from temporary deformation to a predetermined permanent shape in response to external stimuli. However, clinical translation remains hindered by poor biocompatibility, a mismatch between phasetransition and body temperatures, and degradation of mechanical properties following shape transformation. To overcome these challenges, Li *et al.*[165] developed a 3D-printed shape-memory piezoelectric composite scaffold with phase-transition temperature tuned to 33 °C and achieved self-powered immune modulation and osteogenic differentiation for bone repair (Figure 8a). Addressing the limitations of petroleumbased PU elastomers in mechanical performance and biocompatibility, Zheng *et al.*[166] developed an ultra-tough biobased PU elastomer with high strength (82.29 MPa), exceptional toughness (993.08 MJ m^{-3}), and excellent fatigue resistance for artificial ligament repair (Figure 8b). Mahjoubnia *et al.*[167] developed a 4D-printable, biodegradable shape-memory elastomer and fabricated a customized left atrial appendage occluder for minimally invasive cardiovascular implants. In airway interventions, Paunović *et al.*[168] developed a customizable, bioabsorbable airway stent with tunable Young's modulus (≈3–6 MPa) and radial compressive strength that outperformed commercial silicone stents and eliminated the need for secondary removal surgery. Song *et al.*[169] addressed tracheal regeneration using a multitissueintegrated engineered trachea based on 3Dprinted bioelastic scaffolds. With a hierarchical microporous architecture (~258 μm macropores, ~27 μm micropores) and rapid hydrophilicity (contact angle to 0° within 10 s), the scaffold matched the compressive modulus (~268 kPa) and elastic recovery of native trachea. Twelve weeks postimplantation, cartilagematrix deposition and vascularization suggested strong clinical translation potential (Figure 8c).

For tunable mechanical properties and highfidelity reconstruction of complex anatomical features, Liu *et al.*[170] engineered an elastic hydrogel with Young's modulus adjustable from ~2 kPa to ~200 kPa by controlling matrix composition and Zr^{4+}–sulfonate coordination bond density. Using DLP, realistic multiorgan models incorporating perfusable vascular networks were fabricated with high water retention and lubricity, enabling realistic neurointerventional training (Figure 8d). Lu *et al.*[171] developed a self-healing, patient-specific liver model and enabled repeated cut–heal cycles for surgical training and preoperative planning (Figure 8e), improving the safety and predictability of liver resections. Preliminary clinical trials demonstrated that repeated resection training on the model facilitated optimal surgicalpath planning and improved negativemargin rates while preserving critical vasculature, thereby enhancing safety and predictability in liver resections.

5.2. Wearable flexible sensors

The low modulus and excellent conformal capability of 3D-printed elastomers enable tight, non-irritating contact with human skin, which is essential for high-performance wearable sensors and electronic skin. Wearable flexible sensors—such as electronic skin, pressure, and strain sensors—show great potential in healthcare, sports science, and human–computer interaction owing to their realtime, noninvasive health and motionmonitoring capabilities. Emerging 3Dprinting technologies offer an alternative by fabricating intricate sensors directly from computeraided design models, enabling custom, highperformance flexible devices. In recent years, additivemanufacturing techniques have been applied extensively to the fabrication of elastomerbased wearable sensors, leading to significant progress in both material systems and structural design.

In pressuresensing research, the trend is shifting from singlefunction toward multifunctionally integrated devices. Osman *et al.*[172] developed a sacrificial-template 3D-printed MXene-based porous piezoresistive sensor with a sensitivity of 9.859 kPa^{-1} (0–50 kPa) and 84.47 kPa^{-1} after optimization for pulse detection, laryngeal muscle motion monitoring, and pressure-distribution mapping. Wu *et al.*[173] developed a capacitive, selfhealing pressure sensor using an IPN elastomer fabricated via DLP. The dynamic hydrogen bonds and oximeurethane linkages endowed selfhealing and biodegradability. The resulting IPNPUAAD18.6% elastomer exhibited 17.8 MPa tensile strength, toughness of 64.5 MJ m^{-3}, and recovered 10.89 MPa strength after 12 h at 60 °C. Derived capacitive sensors showed a sensitivity of 0.125 kPa^{-1} (0–16 kPa range) and detection up to 700 kPa, with excellent cyclic stability (500 cycles) and fast response (530 ms). In strain sensing, Liu *et al.* [174] used particleextrusion 3D printing to create biobased thermoplasticelastomer nanocomposite sensors capable of >1,500% tensile strain. The resistive response was tunable via filler composition, achieving high sensitivity (gauge factor > 3,000) at 500% strain and enabling monitoring of human joint motion and respiratory behavior.

In flexible electronicskin applications, conventional conductive elastomers often show limited longterm stability due to solvent evaporation, leakage, and challenges in balancing conductivity with mechanical robustness. To address these limitations, Wu *et al.* [175] developed a liquid-free, conductive ionic elastomer and fabricated an electronic skin capable of detecting tactile stimuli as low as 123 Pa with strain sensors for real-time sign-language

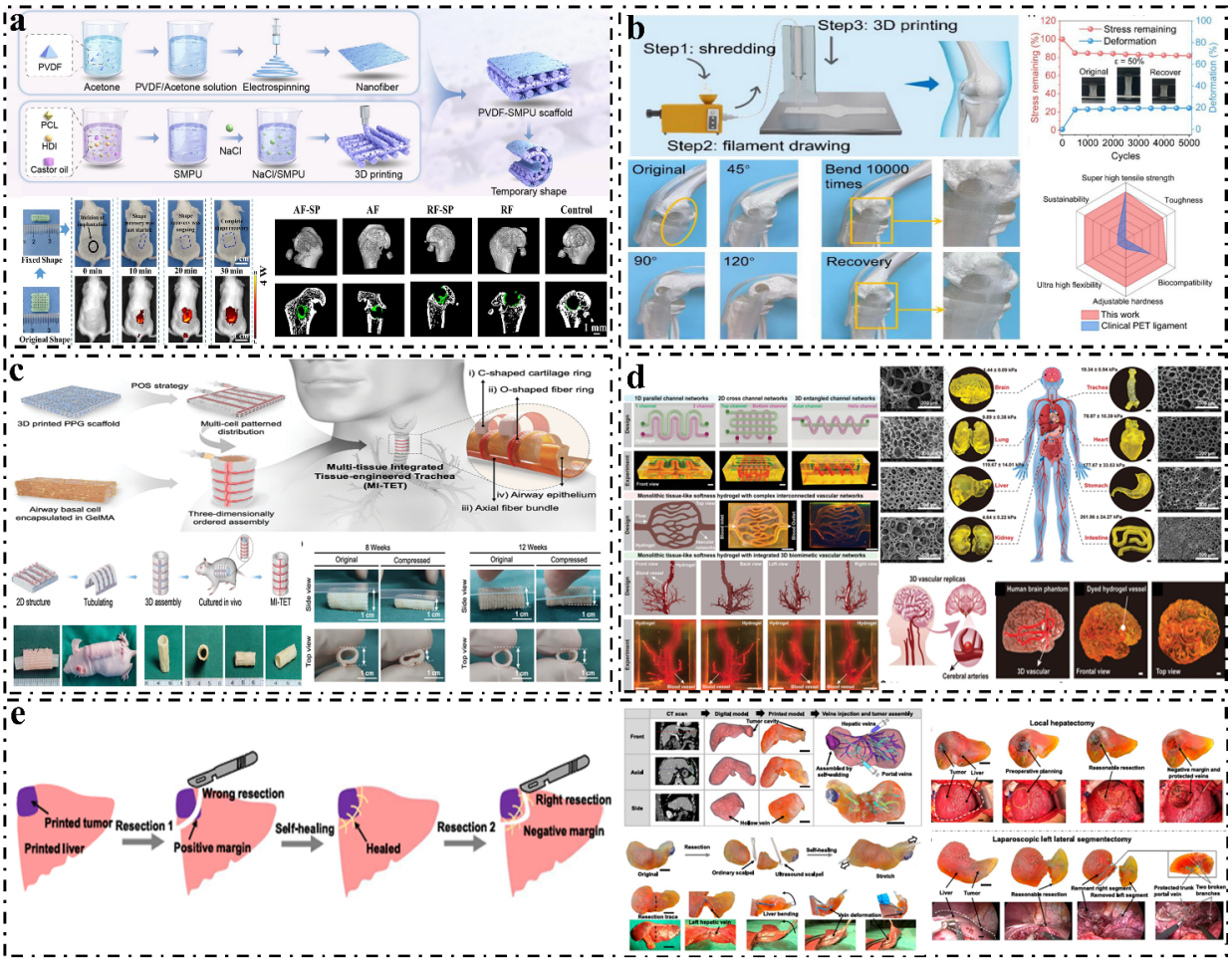

Figure 8. Biomedical applications of 3D-printed elastomers in tissue engineering, regenerative medicine, and surgical training. (a) 3D-printed shape-memory piezoelectric scaffold for self-powered bone repair. Reprinted from Li *et al.*[165] (b) 3D-printed ultra-tough bio-based polyurethane elastomer for artificial ligaments. Reprinted with permission from Zheng *et al.*[166] Copyright © 2025 Wiley. (c) 3D-printed bioinspired tracheal scaffold for cartilage regeneration. Reprinted from Song *et al.*[169] (d) DLP-printed elastic hydrogel for realistic organ models in interventional training. Reprinted with permission from Liu *et al.*[170] Copyright © 2023 Wiley. (e) 3D-printed self-healing liver model for surgical planning and training. Reprinted from Lu *et al.*[171]
Abbreviations: AF: Aligned-fiber scaffold; AF-SP: Aligned-fiber scaffold subjected to the shape-memory process; CT: Computed tomography; DLP: Digital light processing; FDM: Fused deposition modeling; GelMA: Gelatin methacryloyl; HDI: Hexamethylene diisocyanate; MI-TET: Multi-tissue-integrated tissue-engineered trachea; NaCl: Sodium chloride; PCL: Polycaprolactone; PET: Polyethylene terephthalate; PGS: Poly(glycerol sebacate); POS: Post-occupancy sacrifice; PPG: PGS/PCL-gelatin scaffold; PVDF: Poly(vinylidene fluoride); RF: Random-fiber scaffold; RF-SP: Random-fiber scaffold subjected to the shape-memory process; SMPU: Shape-memory polyurethane.

gesture identification (Figure 9a). Building upon advanced stimulusresponsive designs, He *et al.* [176] developed a sweat-gland-inspired smart-skin actuator using liquid-crystal elastomers and achieved autonomous evaporative cooling with local temperature reduction by ~10 °C.

Beyond singlematerial approaches, hybrid systems combining elastomers and ionic conductors have proven effective for enhancing sensor performance. Payandehjoo and Kwok [177] proposed a 3Dprinted TPU framework encapsulating polyacrylamide hydrogels, reducing waterloss rate from >80% to <2% within 60 h while improving durability. Custom frame designs (e.g., dogbone and fingersleeve formats) enabled multimodal sensing of strain, pressure, and bending. Additionally, Liu *et al.*[178] constructed a piezoresistive sponge sensor with tunable anisotropic sensitivity (peak sensitivity 7.31 kPa^{-1}) for direction recognition and gesture interaction (Figure 9b).

5.3. Soft robotics

In nature, many organisms exhibit exceptional

environmentalinteraction intelligence by seamlessly integrating sensing, actuation, and computation within soft tissues. Inspired by these exemplars, the core objective of soft robotics is to emulate such integrated functionality to create bionic systems capable of dynamic, intelligent interactions with complex environments. 3Dprinted elastomer technologies provide robust support for realizing this vision. Their key advantage is the integration of complex actuator architectures with functional materials in a single fabrication step, enabling soft actuators with "structural intelligence" in threedimensional space.[179]

Realizing highperformance soft robots fundamentally requires material systems that couple exceptional mechanical properties with amenability to complex geometric fabrication. Accordingly, Howell *et al.*[180] used an ultraviolet–thermal dual-curing PU-grafted acrylate ink to construct thermally shape-memory soft grippers and programmable bionic fingers with spatially variable stiffness (Figure 9c). Complementing this, Wu *et al.*[181] created a dynamically crosslinked interpenetrating network by incorporating multiple hydrogenbonding units. While maintaining good printability, the material achieved tensile strength of 43.5 MPa and toughness of 213.1 MJ m^{-3}. Pneumatically and electrically driven grippers fabricated from this elastomer exhibited rapid response and efficient grasping. Together, these studies show that sophisticated molecular design with multistep curing can unify structural design freedom, broadly tunable mechanics, and intrinsic actuation, establishing a robust foundation for nextgeneration, customised, highperformance soft robots.

For actuation and structural fabrication, DIWprinted elastomers provide a powerful route to manufacture complex, customized soft pneumatic actuators. For example, Li *et al.*[182] used DIW to print silicone elastomers and fabricate a dual-material artificial muscle with substantial axial contraction and a soft pneumatic gripper with trapezoidal air chambers for bidirectional bending. In parallel, Zhang *et al.*[183] integrated 3D-printed soft magnetic active materials with origami structures and realized wirelessly controllable actuators for gastric drug delivery and terrain-adaptive crawling (Figure 9d).

For intelligent, stimulusdriven applications, 4D printing based on LCEs provides a core route to programmable deformation. For example, Wang *et al.*[184] developed a photoresponsive gold-nanorod/LCE composite ink and fabricated a bionic crawling robot with directional locomotion on horizontal and 30° inclined surfaces (Figure 9e). To extend softrobot applications to extreme liquid environments, Wang *et al.*[185] employed a non-Euclidean 4D-printing strategy and fabricated a jellyfish-inspired robot with multi-mode motion (crawling, jumping, rolling) in organic solvents (Figure 9f).

5.4. Industrial manufacturing

In industrial vibrationdamping and impactprotection applications, conventional construction materials exhibit inherent limitations in damping efficiency, impact resistance, and selfhealing capability. In contrast, 3Dprinted elastomer composites enable innovative industrialmanufacturing applications owing to their exceptional flexibility, tailorable mechanical properties, and capability to form complex geometries without constraint. This technology overcomes the limitations of conventional processing, delivering customized, functionally integrated elastomeric solutions for critical scenarios such as structural vibration damping, smart tires, and highperformance thermal insulation.

The capacity to produce lightweight components with integrated functionality constitutes a primary advantage of 3Dprinting technology for industrial applications. Leschok *et al.*[186] developed a hollow-core 3D-printing technique and produced lightweight building-envelope units with excellent thermal-insulation performance and internal cavities for functional media. Beyond passive structures, direct integration of sensing and energyharvesting functions into elastomeric components represents a critical frontier in industrialequipment intelligence. Meena *et al.*[187] fabricated hybrid piezoelectric–triboelectric nanogenerator sensors for smart tires and achieved triboelectric energy harvesting (power density: 2.20 mW cm^{-2}) and real-time tread-wear monitoring with ≤1 mm accuracy.

Achieving active control of macroscopic mechanical properties via innovative structural design with integrated functionality is a central challenge in industrial vibrationdamping and intelligentstructure development. Larson *et al.*[188] proposed a rotating multi-material 3D-printing method and produced "springlike" filaments with Young's moduli tunable from ~10 MPa to over 100 MPa for adaptive damping systems. Actively modulating material properties via external physical stimuli represents another promising direction. Cai *et al.*[189] developed a grapheneorigami structure with giant thermoelastic response informed by surface functionalization and moleculardynamics simulation. It achieved adiabatic temperature modulation up to 180 K under low driving stress (~0.26 GPa), with a range of 100–600 K and hysteresisfree behavior, suitable for miniaturized thermalmanagement devices (Figure 10a). Inspired by diatom shells, Musenich *et al.*[190] used data-driven biomimetic design to optimize elastomeric honeycombs and achieved 250% higher specific energy absorption than

Figure 9. 3D-/4D-printed elastomers for flexible sensors, soft grippers, and bio-inspired robotic applications. (a) DLP-printed liquid-free ionic elastomer electronic skin for tactile perception and gesture recognition. Reprinted with permission from Wu *et al.*[175] Copyright © 2023 The Royal Society of Chemistry. (b) DIW-printed anisotropic piezoresistive sponge for directional sensing in human-machine interaction. Reprinted from Liu *et al.*[178] (c) Dual-curing polyurethane ink 3D printing for variable-stiffness soft grippers and bionic fingers. Reprinted with permission from Howell *et al.*[180] Copyright © 2022 Wiley. (d) Magnetically driven origami soft robot for gastric drug delivery and terrain-adaptive crawling. Reprinted from Zhang *et al.*[183] (e) Photo-responsive LCE composite ink 4D printing for directional motion in bionic crawling robots. Reprinted with permission from Wang *et al.*[184] Copyright © 2023 Wiley. (f) 4D-printed LCE jellyfish-inspired robot with multi-mode photothermal-driven motion in organic solvents. Reprinted with permission from Wang *et al.*[185] Copyright © 2024 Wiley.

Abbreviations: 3D: Three-dimensional; 4D: Four-dimensional; DIW: Direct ink writing; DLP: Digital light processing; FS: Fumed silica; LCE: Liquid crystal elastomer; NaCl: Sodium chloride; UGAP: Urethane grafted acrylate polymer.

conventional designs (Figure 10b). Addressing passive damping, Maity *et al.*[191] synthesized an acrylate-based elastomer with >97% impact-energy absorption and rapid self-healing (>95% property recovery within 10 min at room temperature) for impact-resistant coatings.

5.5. Consumer goods

The design flexibility and material adaptability afforded by 3Dprinting technology extend beyond highend applications to encompass a wide spectrum of consumer products. This technology not only enables highly personalized customization but also facilitates the seamless integration of complex mechanical architectures and electronic functionalities within a single product. Consequently, it supports the development of nextgeneration consumer goods—including footwear, apparel, and electronic textiles—that combine enhanced performance with intelligent human–machine interaction.

In footwear design, 3Dprinting technology enables active regulation of the macroscopic mechanical properties of midsoles by programming the material microstructure, thereby overcoming the inherent tradeoff between cushioning, stability, and energy return characteristic of conventional homogeneous foams. Sun *et al.*[192] optimized a chiral negative-Poisson-ratio structure and fabricated 3D-printed shoe midsoles with synergistically enhanced impact absorption and stability (Figure 10c). Inspired by ostrich toes, Zhang *et al.*[193] designed a biomimetic midsole inspired by ostrich toes and significantly enhanced cushioning performance within a limited forefoot thickness. 3Dprinting technology thus provides an ideal platform for manufacturing integrated functional components, advancing footwear design from passive protection to active intelligence. Kim *et al.*[194] fabricated customized triboelectric-nanogenerator insoles and achieved an output of 880 V and 3.75 mA during foot impact for self-powered wearable electronics. Similarly, Li *et al.*[195] fabricated flexible silvernanoparticle/graphene nanocomposite electrodes via photopolymerizationbased 3D printing. The electrodes exhibited low resistance ($\approx 1 \times 10^2\ \Omega\ sq^{-1}$), high fracture strain (300 %), and excellent wash resistance. Suitable for physiologicalsignal monitoring in smart footwear and apparel, these materials provide a robust foundation for healthmonitoring and motionanalysis wearables.

In smartfurniture design, the emergence of 4Dprinting technology offers new approaches to realizing dynamic, environmentresponsive structures. Cai *et al.*[196] employed DLP-based 4D printing to fabricate a liquid-free ionic elastomer and produced adaptive chair backs with thermal-responsive angle adjustment (shape-retention rate >95% after 80 cycles) (Figure 10d).

In electronictextile development, traditional functional fabrics depend on yarn or fabriccoating processes, which suffer from complex workflows, limited customization, and poor multilayer interconnectivity. 3Dprinting techniques—particularly directwriting and photopolymerization approaches—enable the realization of highly integrated, customizable, and multifunctional smart textiles. Yang *et al.*[197] produced a purecellulose 3Dprinting ink derived from cotton fibers, forming porous fabrics via freezedrying. The material combined cottonlike comfort with superior abrasion resistance and breathability, enabling DIW fabrication of wearable products such as garments and gloves, thereby overcoming the comfort limitations of synthetic fabrics. Furthermore, Pak *et al.*[198] developed a textile-electronics platform using multi-material DIW printing and achieved double-sided circuit integration and real-time monitoring of movement/respiration with 98.32% gesture recognition accuracy. Collectively, these studies illustrate that synergistic innovation in material design, structural engineering, and system integration through 3D printing underpins the advancement of nextgeneration wearable electronic textiles toward personalized, multifunctional, and highperformance applications.

5.6. Summary of application areas

Three-dimensionally printed elastomers have achieved widespread application across biomedical, wearable flexible sensors, soft robotics, industrial manufacturing, and consumer goods fields, driven by their tunable mechanical properties, complex structural fabrication capability, and functional integration potential. In the biomedical field, breakthroughs in biocompatibility and stimulus responsiveness have enabled the development of customized implants and surgical training models. In wearable sensors and soft robotics, high flexibility and stimulus response have facilitated the fabrication of high-performance electronic skin and intelligent actuators. In industrial manufacturing and consumer goods, the ability to balance mechanical performance and customizability has led to innovative solutions such as smart tires and adaptive consumer products. However, the large-scale application of 3D-printed elastomers in these fields is still limited by high production costs, insufficient quality consistency, and limited environmental stability of some materials. Future development will focus on reducing costs, improving mass production technology, and enhancing material performance to meet the diverse requirements of different application scenarios.

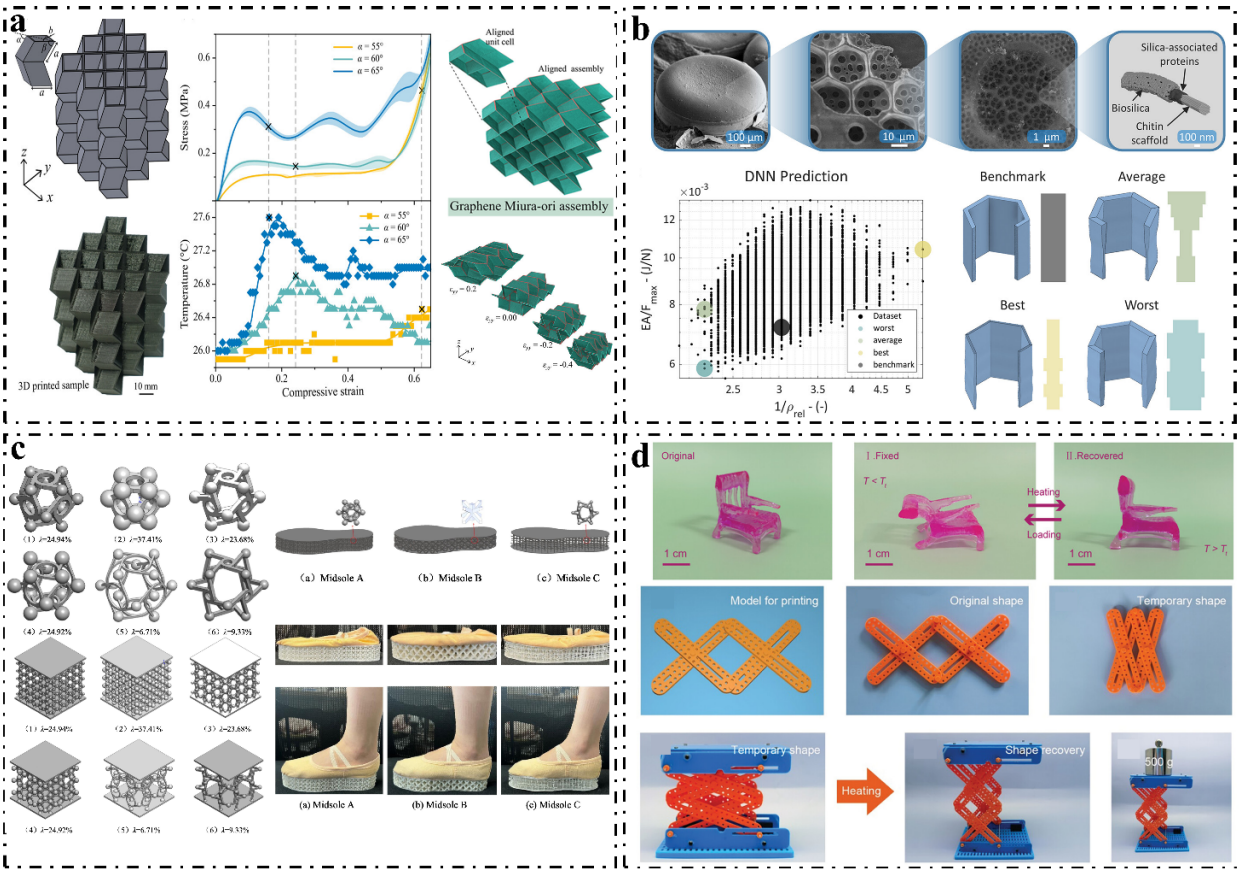

Figure 10. 3D-/4D-printed elastomeric metamaterials for mechanical optimization, energy absorption, and consumer applications. (a) Graphene origami structures 3D-printed for giant thermoelastic effects under low stress. Reprinted with permission from Cai *et al.*[189] Copyright © 2024 American Chemical Society. (b) Bionically optimized elastomer honeycombs 3D-printed with 250% greater energy absorption. Reprinted with permission from Musenich *et al.*[190] Copyright © 2024 American Chemical Society. (c) 3D-printed chiral negative Poisson's ratio shoe midsole for enhanced cushioning and stability. Reprinted from Sun *et al.*[192] (d) 4D-printed ion-elastic adaptive chair backrest with thermally responsive angle adjustment. Reprinted with permission from Cai *et al.*[196] Copyright © 2024 Wiley.
Abbreviations: 3D: Three-dimensional; 4D: Four-dimensional; DNN: Deep neural network; NPR: Negative Poisson's ratio; Tg: Glass transition temperature.

6. Challenges and prospects

6.1. Persistent challenges

Despite substantial advances in material innovation, functional diversification, and cross-domain applications of 3D-printed elastomers, large-scale industrial deployment and performance breakthroughs remain hindered by a series of critical scientific and technological challenges. These challenges are closely related to the technical bottlenecks of different material and functional systems discussed in previous chapters, and can be systematically summarized into three core aspects:

6.1.1. Material design challenges

The primary difficulty lies in balancing and simultaneously optimizing multiple key properties, and the existing material modification strategies have not yet fundamentally solved this trade-off problem. Most current 3D-printed elastomers fail to concurrently satisfy the requirements for high mechanical strength, excellent elastic recovery, efficient functional responsiveness, and favorable printability. For example:

- Ultra-soft elastomers based on bottlebrush polymers satisfy the compliance demand for bionic devices but typically exhibit relatively low tensile strength and insufficient structural stability.
- Inorganic nanofiller-reinforced composite elastomers can enhance mechanical strength, yet elasticity is often compromised to some extent along with processing fluidity.
- Dynamic functional elastomers (self-healing/shape-memory) face intrinsic conflicts between dynamic-

bond reversibility and network stability, such as high-temperature repair requirements, low self-healing efficiency, and reduced cycle stability.

Additionally, material compatibility and multi-matrix integration remain major bottlenecks. Insufficient interfacial adhesion and pronounced phase separation between matrices (e.g., PU and silicone) undermine the mechanical and functional stability of multi-matrix composite systems. For bio-based elastomers, the lack of photosensitive moieties and low mechanical performance compared with petroleum-based elastomers restrict their application scope.

6.1.2. Manufacturing process challenges

The trade-off between printing efficiency and resolution is particularly pronounced and has not been effectively resolved. High-precision photopolymerization techniques (DLP/SLA) can achieve micron-level resolution but are limited by low throughput, high equipment and material costs, and complex post-processing. High-throughput extrusion-based methods (FDM/DIW) suffer from low resolution, high surface roughness, and interlayer bonding defects (e.g., mechanical anisotropy of TPU).

Furthermore, systematic frameworks to optimize the compatibility between process parameters and material properties are lacking. The effects of thermal gradients, flow-field variations, and interlayer-bonding characteristics on final product performance remain insufficiently understood, leading to poor quality consistency and elevated scrap rates during mass production. For high-viscosity, high-solids-content, or functional-filler-loaded elastomer inks, optimization of rheological properties for process compatibility remains a major technical hurdle, often resulting in nozzle clogging or structural collapse.

6.1.3. Functional deployment and application challenges

Limited adaptability to extreme environments constrains the application scope of 3D-printed elastomers. Most elastomers undergo performance degradation under high-temperature, high-humidity, highly corrosive, or intense-radiation conditions. For example:

- Dielectric elastomers are susceptible to breakdown under high voltage.
- Bio-based elastomers have difficulty in precisely controlling degradation rates in physiological conditions.
- Silicone-based elastomers have low mechanical strength and poor tear resistance, limiting their application in load-bearing scenarios.

Functional singularity remains pervasive. Achieving synergistic integration of multiple functionalities (e.g., self-healing, electrical conductivity, magnetic responsiveness, biodegradability) into unified elastomer systems represents a significant research challenge. In high-end biomedical applications, stringent barriers persist to biocompatibility and clinical translation; parameters including cytotoxicity, immunogenicity, and long-term *in vivo* stability demand extensive preclinical validation. Moreover, quality control and cost management challenges persist during large-scale production, such as the high cost of liquid crystal monomers and ferromagnetic particles, and the complex production process of TPAE powder for SLS printing.

6.2. Future prospects

In response to the aforementioned challenges, and aligned with advances in material science, manufacturing engineering, and interdisciplinary technologies, future development of 3D-printed elastomers will focus on three core directions: material innovation, process optimization, and application expansion. This strategic framework offers significant potential to bridge the gap between laboratory-scale research and large-scale industrial application.

6.2.1. Material system innovation: Dynamic, sustainable, and multifunctional integration

Future material innovation should move beyond single-property enhancement toward integrated molecular and composite design strategies that simultaneously improve mechanical robustness, printability, sustainability, and functional responsiveness.

(a) Dynamic intelligent network design: This is a natural extension of the current dynamic bond modification strategy and a pivotal breakthrough for solving the property trade-off problem. On the basis of preliminary progress in balancing strength and self-healing performance via dynamic HUBs and disulfide bonds, future research will focus on spatially precise regulation of dynamic bonds—combining 3D printing's spatial shaping capability with dynamic bond distribution design, fabricating elastomers with regionally differentiated properties (e.g., high-strength non-healing regions and self-healing functional regions) to realize the synergistic optimization of "strength–elasticity–self-healing" triad. This strategy can fundamentally solve the trade-off problem of dynamic bond reversibility and network stability.

(b) Green and sustainable materials: Driven by the current bottlenecks of recyclability and biodegradability, future research will focus on two directions: (i) Precise synthesis of bio-based monomers with high

reactivity and mechanical properties (e.g., bio-based diisocyanates replacing petroleum-based diisocyanates) to prepare bio-based elastomers with performance comparable to petroleum-based ones; (ii) Design of fully recyclable thermosetting elastomers based on dynamic covalent networks, solving the problem of performance decline after recycling of current thermoplastic elastomers.

(c) Precision-engineered multifunctional composites: Future composite systems will evolve towards more precise structural design. Strategies including surface modification, oriented arrangement, and multi-scale structuring of nanofillers can synergistically enhance functionalities such as electrical and thermal conductivity, magnetic responsiveness, and optical activity. Example directions include dielectric elastomers that combine high dielectric constant, low modulus, and self-healing capability, and biomedical elastomers that integrate efficient photothermal conversion with shape-memory functionality and biocompatibility.

6.2.2. Manufacturing process optimization: Efficient, precise, and intelligent

In parallel with material innovation, advances in printing processes are required to improve fabrication accuracy, production efficiency, structural complexity, and quality consistency.

(a) Multi-field-coupled 3D printing technologies: Future research will advance magnetic, electric, ultrasonic, or infrared-assisted forming technologies, in which external physical fields precisely control elastomer curing, molecular orientation, and filler distribution to enable targeted performance regulation. For example, magnetic field-assisted DIW can optimize the alignment of ferromagnetic particles in MREs to enhance the MR effect; ultrasonic-assisted photopolymerization can improve the dispersion of nanofillers and reduce curing shrinkage.

(b) Advanced 4D printing technologies: Built on the current progress of shape-memory and LCEs, future 4D printing will focus on the integration of material design and structural programming, enabling elastomers with multi-stimulus responses (e.g., coordinated temperature–light–humidity actuation), multi-step sequential deformation, and adaptive intelligent behaviors in response to environmental changes. This will provide novel solutions for soft robotics, smart wearables, and related high-performance fields.

(c) Digital and intelligent manufacturing paradigms: Leveraging artificial intelligence and machine learning approaches, predictive models linking material properties, process parameters, and product functionality will be established. These models will enable real-time monitoring, automated control, and quality traceability during printing, significantly enhancing the stability and throughput of mass production. This is a necessary solution to the current problems of low production efficiency and poor quality consistency of 3D-printed elastomers.

6.2.3. Application expansion: Premiumization, diversification, and interdisciplinary convergence

With continued improvements in materials and manufacturing processes, 3D-printed elastomers are expected to expand from proof-of-concept demonstrations toward high-value, application-specific systems across biomedical, electronic, robotic, industrial, and consumer fields.

(a) Biomedical field: Personalized smart implantable devices will become research focal points, such as shape-memory scaffolds capable of real-time physiological signal monitoring and controlled drug delivery, and biodegradable elastomer devices that combine tissue regeneration induction with antimicrobial functionality. Future research will focus on solving the problems of long-term *in vivo* stability and precise control of degradation rate, promoting the clinical translation of 3D-printed elastomer implants.

(b) Flexible electronics and soft robotics: 3D-printed elastomers will drive devices towards lightweight, integrated, multifunctional architectures, such as ultrathin, highly stretchable, self-powered electronic skins and soft robots with complex motion patterns and environmental adaptability. The integration of 3D-printed elastomers with flexible electronics and the Internet of Things will create wearable, smart monitoring systems for health management and human–machine interaction.

(c) Industrial manufacturing and consumer goods: Mass production of customized functional components will become feasible, including vibration-damping components tailored for specific equipment, sensing units for smart tires, and lightweight elastic structural parts for aerospace applications. In consumer goods, 3D-printed elastomers will enable the development of highly customized products with integrated functionality, such as adaptive furniture and smart footwear with energy harvesting and health monitoring capabilities.

(d) Interdisciplinary convergence: 3D-printed elastomers will intersect extensively with biomedicine, electronic engineering, artificial intelligence, and bionics.

For example: (i) Integrating bioprinting and cell engineering approaches to develop bioactive, tissue-engineered elastomer scaffolds for bionic regeneration of complex tissues or organs; (ii) Drawing inspiration from natural organisms (e.g., spider silk, octopus tentacles) to develop biomimetic elastomer materials and devices with breakthrough performance enhancements; (iii) Combining 3D-printed elastomers with artificial intelligence to realize adaptive and self-learning smart systems.

6.3. Summary of challenges and future perspectives

The development of 3D-printed elastomers faces core challenges in material property balance, manufacturing process trade-offs, and functional application limitations. However, with the advancement of dynamic intelligent network design, green sustainable material development, multi-field-coupled printing technologies, and interdisciplinary convergence, these challenges are expected to be gradually addressed. Future 3D-printed elastomers will move towards high performance, low cost, large-scale production, and multifunctional integration, and achieve major breakthroughs in biomedicine, flexible electronics, soft robotics, and high-end manufacturing, thereby providing robust material support for the Fourth Industrial Revolution.

7. Conclusion

In summary, this review systematically summarizes recent progress in 3D-printed elastomers, focusing on mainstream printing techniques, diverse matrix systems (polyurethane, silicone, polyolefin, bio-based, multi-matrix), functional design strategies, and representative applications in biomedicine, flexible electronics, soft robotics, and consumer goods. Core challenges, including property trade-offs, manufacturing limitations, and environmental stability, are discussed, and future directions toward dynamic networks, green materials, multi-field coupling, and industrial translation are outlined, providing guidance for further development and practical deployment of 3D-printed elastomers.

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Conflict of interest

The authors declare no conflict of interest.

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