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Functional Materials for 3D-Printed Soft Robotics: Conductors, Actuators, and Sensing Networks: A Review

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ABSTRACT

3D printing is transforming soft robotics by enabling complex geometries, rapid iteration, and cofabrication of structure, actuation, and sensing. Central to this progress are functional materials that provide stretchable conductivity, stimuli-responsive actuation, and reliable sensing when deposited by additive processes. This review surveys recent advances in conductive materials for printed soft systems (conductive polymer composites [CPCs], liquid metals, conductive hydrogels, and metalized inks), printed actuators (pneumatic networks, stimuli-responsive hydrogels, dielectric elastomers, magneto-active and shape-memory composites), and sensing networks (resistive, capacitive, optical, and multimodal printed arrays). The paper emphasizes how material choices interact with printing modalities (direct ink writing [DIW], multimaterial fused deposition [FDM], inkjet/aerosol jet, and DLP/SLA), and further identifies constraints such as mechanical mismatch, postprocessing, long-term stability, energy supply, and multimaterial interfacial reliability that currently limit translation. Finally, highlighting promising directions such as printable self-healing conductive hydrogels, multimodal printed skins, embedded energy and computation, magneto-responsive inks for untethered actuation, and community standards for materials characterization and durability benchmarking.

1 | Introduction

Soft robotics has become a revolutionary field within robotics as it has shifted the paradigm from inflexible, metallic mechanisms to flexible, malleable structures. Such structures resemble the safety, adaptability, and flexibility of natural organisms. Apart from conventional rigid robots, soft robots are comprised of intrinsic materials that are compliant to carry out activities such as grabbing delicate objects, moving in confined spaces, or performing biomedical procedures [1]. Moreover, they can also adapt to environments that are complex and engage in safe human–robot

interaction [2, 3]. They have potential in a wide range of domains, such as bioinspired machines, wearable technology, prosthetics, and rehabilitation aids [4]. To achieve the full potential of soft robotics mainly depends on the functional materials that are being used, which should offer structural compliance along with the sensing capability, conductivity, and actuation [5, 6].

The development of additive manufacturing (AM), which is also known as 3D printing, has revolutionized soft robotics. It has opened the possibility of the creation of intricate shapes, unique designs, and multimaterial integration in a single production

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process. Additive methods include inkjet and aerosol jet printing, fused deposition modeling [7–11] (FDM), direct ink writing (DIW), and so on [12, 13]. Unlike traditional molding and assembly, such methods make it possible for direct fabrication of soft matrices, integrated architecture, and functional fillers [14, 15]. Thus, it reduces the complexity of integrating different system components. Such capability is crucial for soft robots having coupled of material functions to enable flexibility, responsiveness, and autonomy. Furthermore, the functional materials are the core of soft robotics [16, 17]. These materials are designed for printability and performance under significant cyclic deformations, and they can be divided into conductor, actuator, and sensor materials [15, 18].

Conductors are materials that provide electrical pathways for signal transmission, power implanted devices, and facilitate resistive or capacitive sensing [19]. Among the stretchable conductors are conductive polymer composites (CPCs). Printed metallic traces, conductive hydrogels, and liquid metals all provide distinct trade-offs in terms of conductivity, compliance, stability, and printability. In addition, actuators are things and materials that transform energy into movement. Dielectric elastomer actuators (DEAs), stimuli-responsive hydrogels, magneto-active composites, shape memory polymers (SMPs), and pneumatic/hydraulic chambers are examples of printable actuation mechanisms [19]. Different actuator types have distinct advantages (such as high forces, untethered actuation, and environmental responsiveness) and disadvantages (such as power density, response speed, or reliance on external drivers) [20]. Proprioception and environment interaction are made possible by the dispersed nature of sensing networks. Piezoresistive composites, capacitive sensors, optical waveguides, and multimodal arrays that map strain, pressure, and temperature across deformable bodies are all examples of printed sensing methods [21, 22]. The integration of sensor networks is necessary for feedback control and secure interaction in unstructured environments.

The system-level performance and autonomy of 3D-printed soft robots are determined by the interaction of these three functional material domains: conductors, actuators, and sensors [23, 24]. Figure 1 shows the various types of soft actuators based on the actuation types. However, there are still difficulties in reproducibility, energy integration, environmental stability, fatigue resistance, and multimaterial adherence. These issues can be solved by advances in printing techniques (such as coaxial extrusion, embedded printing, and voxel-level multimaterial deposition) and by novel material compositions (such as self-healing conductors and environmentally stable hydrogels) [26, 27].

This review seeks to summarize current advancements in functional materials for 3D-printed soft robotics, with an emphasis on sensors, actuators, and conductors. We emphasize design trade-offs, printing restrictions, integration challenges, and reliability issues that affect system feasibility by structuring the conversation around these material classes. Additionally, we look at new trends like printable self-healing conductors, magneto-responsive actuation, and multimodal sensing skins, which are expected to influence the upcoming generation of completely printed, autonomous soft robots [28].

2 | Scope of Review

This review covers the progressive advancement of operational materials in 3D-printed soft robotics, with a concentration on actuators, conductors, and sensing networks. The bibliometric patterns used in

the investigation are those taken from the Scopus data collection utilizing the keywords “soft robotics”, “functional materials”, and “3D printing”, covers the publication duration from 2010 to 2025.

Research process in this field has expanded exponentially over the past 10 years, as presented in Figure 2, in feedback to the increasing requirement for soft robotic, flexible systems that are responsive and versatile. In the first limited years (2010–2014), there was small investigation, mostly focused on generating conductive inks and elastomeric composites that may be used in AM. But since 2015, there has been a significant rise in publications because of advancement in materials design, multimaterial 3D printing, and flexible electronics.

A clear variation between the three primary material classes arises by 2020–2025.

- The combination of carbon nanotubes (CNTs), liquid metal networks, and graphene has resulted in the consistent rise of conductors, interconnections and stretchable circuits, enabling for the formation of flexible.
- The fastest rise in investigation is seen in actuators, which indicates growing attention in pneumatic systems that work with shape-memory materials, electroactive polymers, and 3D printing.
- Although initially underrepresented, sensor networks have gained prominence in recent years (2022–2025), highlighting the trend toward closed-loop, autonomous soft robotic systems that can perceive themselves and respond to their environment.

By highlighting the link between printing compatibility, robotic performance, and material functionality, this review aims to give a crucial overview of recent developments in each of these three types: actuators, sensing networks, and conductors. Moreover, it discusses the challenges engaged in integrating these materials into integrated soft robotic designs, like problems with material fatigue, Multiphysics coupling, and interfacial bonding.

This review's goal is to give a thorough overview of how new functional materials are changing the way 3D-printed soft materials are designed, manufactured, and used in the real world. robots, paving the way for the next generation of smart and adaptive robotic systems.

The publication trend shown in Figure 2 is obtained using the Scopus database. The search query was constructed using combinations of the keywords ‘soft robotics’, ‘3D printing’, ‘AM’, within the title, abstract, and keywords fields. The additional keyword “electronics, “sensing applications”, and “actuators” was added along with above keywords. Only peer-reviewed journal articles and review papers published in English between 2013 and 2025 were considered.

To contextualize the evolution of the field, key technological milestones including the emergence of multimaterial DIW (2014), the rise of printable soft actuators and sensor applications, and the growing adoption of 3D printing concepts in soft robotics are annotated in Figure 2.

3 | Printing Technologies Used

The functional materials employed in 3D-printed soft robots (conductors, actuators, sensors), as well as the potential for using

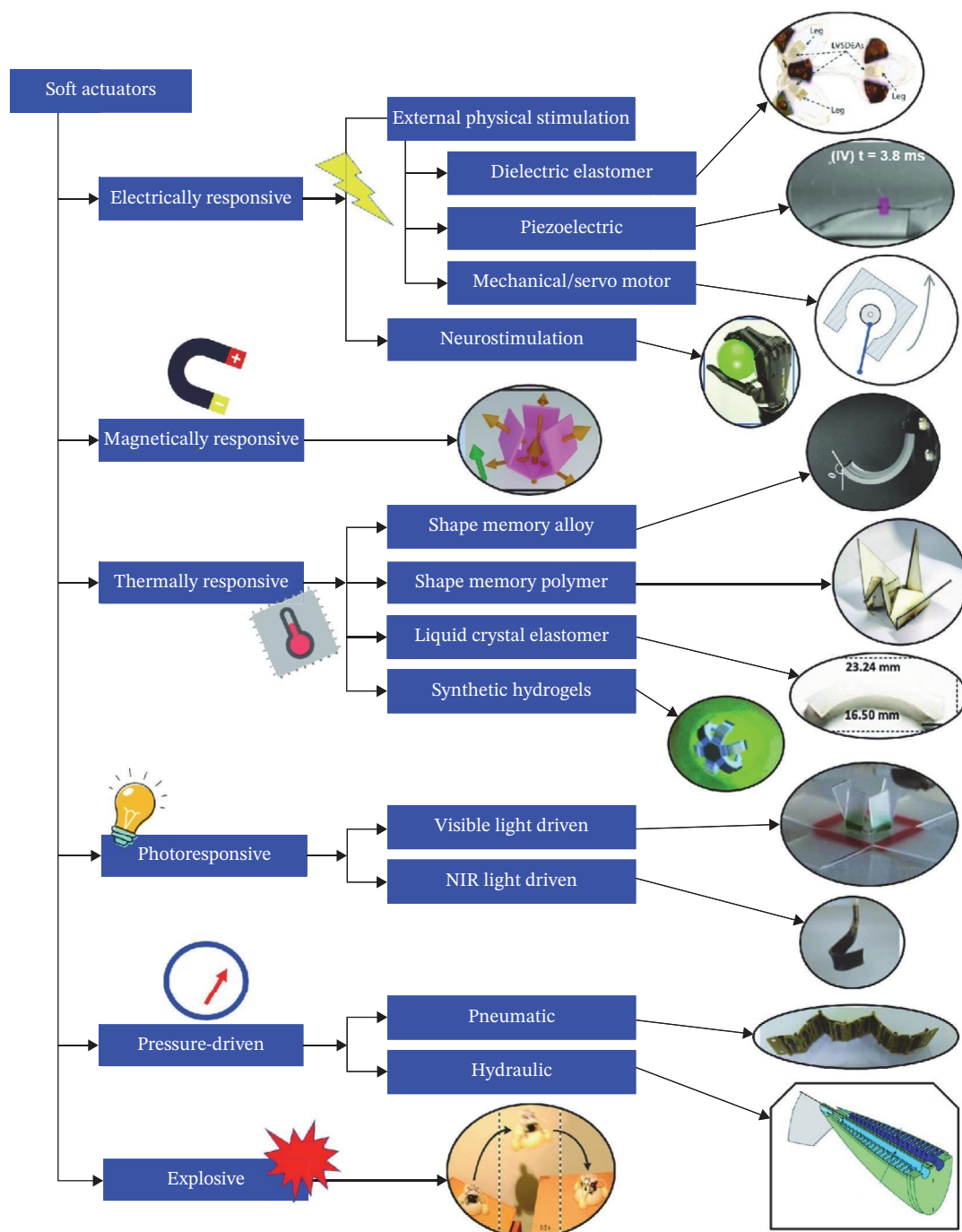


FIGURE 1 | Various types of actuators for soft robotics based on the type of actuation [25] (licensed under CC by 4.0, <https://creativecommons.org/licenses/by/4.0/>).

them, have a significant impact on their effectiveness. those materials, which are processed and integrated using AM methods. This section discusses the material properties that influence printability, the essential 3D printing methods used in soft robotics, as well as the trade-offs and restrictions that these methods involve. Figure 3 shows the schematic overview of 3D printing technologies used for soft robotics (DIW, FDM, SLA, Inkjet). Table 1 summarized the technology used in soft robotics with its limitations. Material performance in printed soft robots depends strongly on the deposition method. Common approaches with material used include:

Direct Ink Writing (DIW)/Extrusion: robust for viscous pastes, conductive composites, hydrogels and silicone inks; supports embedded channels and core-sheath filaments [19].

Multimaterial FDM/Coextrusion: uses thermoplastic elastomer filaments (TPUs) and coextruded conductive filaments; scalable but limited by filament formulation and resolution [19].

Inkjet/Aerosol Jet/Electrohydrodynamic Jetting: high resolution for low-viscosity conductive inks and thin patterned traces [19].

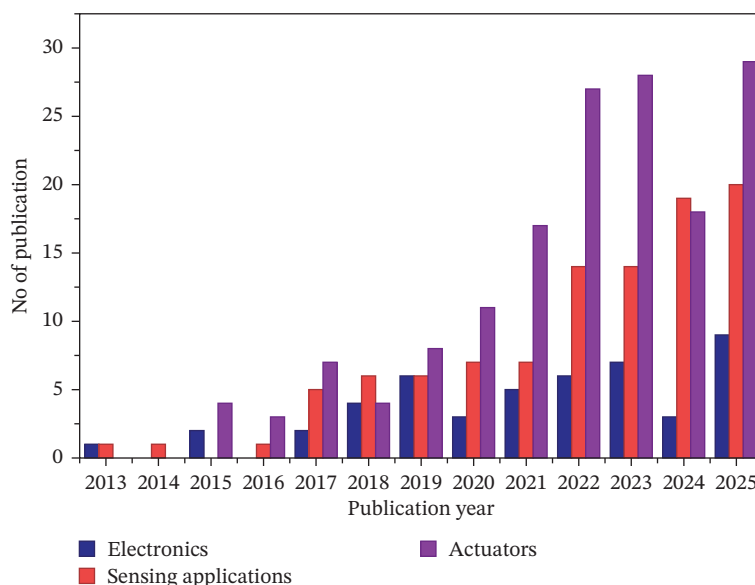


FIGURE 2 | Annual publication trends in 3D-printed soft robotics based on Scopus-indexed journal articles (2013–2025). (Figure is originally created by the authors).

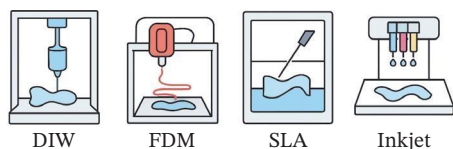


FIGURE 3 | Schematic overview of 3D printing technologies used for soft robotics (DIW, FDM, SLA, Inkjet). (Figure is originally created by the authors).

Vat Photopolymerization (DLP/SLA) with multi-resin switching: provides high resolution and smooth features for elastomeric photopolymers and magneto-active/dielectric composites, but conductive elements are more challenging [33].

Embedded/Sacrificial Printing: printing sacrificial materials to create internal channels (important for pneu-net actuators) or using support baths for soft inks [19, 34].

3.1 | 4D Printing for Time-Dependent Soft Robotic Functionality

Four-dimensional (4D) printing extends conventional AM by integrating time as an active design variable, enabling printed structures to undergo programmed shape and functional transformations in response to external stimuli such as heat, light, humidity, magnetic or electric fields. Unlike static 3D-printed parts, 4D-printed materials can autonomously evolve their shape or properties postfabrication, making them highly relevant for soft robotic systems that require self-deployment, adaptive motion, or environment-responsive behavior.

A prominent class of 4D-printable materials is liquid crystal elastomers (LCEs), which combine liquid crystalline order with flexible polymer networks to achieve large, reversible shape changes in response to thermal or optical stimuli. Recent reviews highlight that advanced printing techniques—such as DIW and vat photopolymerization—enable precise control of mesogen alignment and programmable actuation modes in 4D-printed LCEs, positioning them as promising actuators and adaptive elements in soft robotics and related technologies [36].

Shape-memory polymers (SMPs) represent another key 4D printing platform, capable of encoding temporary shapes during printing that later recover their original configuration when triggered by heat or other stimuli. SMP-based 4D-printed components have demonstrated multistep shape transformations, load-bearing deformation, and sequential actuation, offering strategies for deployable and morphing soft robotic parts. Studies on magnetically responsive SMP composites further expand the toolkit for remote, programmable actuation in soft robotic and wearable systems [37].

Hydrogel-based systems also play a central role in 4D printing, particularly for soft robots that harness stimuli-induced swelling and deswelling to perform shape morphing. Thermally or pH-responsive hydrogels have been used to fabricate grippers and manipulators that change configuration over time when subjected to environmental cues, underscoring the value of 4D printed soft robots for biomedical and adaptive applications [38].

Beyond individual material classes, 4D printing has been demonstrated in multifunctional soft robotic architectures, including liquid metal-integrated systems that combine compliant conductivity with programmed shape change, enabling light-driven locomotion and functional actuation in environments where traditional actuators would fail [39].

In summary, 4D printing provides a framework to embed temporal behavior directly into soft robotic structures through smart materials and tailored printing strategies. While significant progress has been made in programmable shape change and actuation, ongoing challenges such as resolution limits, response time optimization, and fatigue durability must be addressed to fully realize 4D-printed soft robots in practical applications.

3.2 | Printing Parameter Optimization for Functional Performance

The functional performance and durability of 3D-printed soft robotic systems are governed not only by material composition but also by the optimization of key printing parameters,

TABLE 1 | Summary of technology used in soft robotics with its limitations.

Technology	Principle/mechanism	Strengths for soft robotics	Typical applications (with examples)	Material limitations	Process limitations	Key references
FDM/FFF	Thermoplastic filament extrusion through heated nozzle	Low cost; compatible with TPU; multimaterial extrusion	Monolithic bending pneu-nets; TPU-based soft grippers; hybrid soft-rigid components (e.g., dual-TPU actuators)	Limited to thermoplastics; low elasticity vs. silicones; thermal degradation of fillers	Coarse resolution; anisotropic strength; weak interlayer adhesion; limited fine channels	[19, 29]
Direct ink writing (DIW)	Extrusion of viscous/yield-stress inks or pastes	Broad material compatibility; embedded channels; multimaterial printing	Silicone pneumatic actuators; conductive composite sensors; hydrogel actuators; embedded liquid metal traces	Ink rheology constraints; sedimentation of fillers; curing incompatibility	Nozzle clogging; limited resolution; shape collapse without yield stress	[19, 30, 31]
Inkjet/aerosol jet	Droplet-based deposition of low-viscosity inks	High-resolution conductive traces; thin films	Printed electrodes; strain gauges; capacitive sensor electrodes	Limited ink viscosity range; nanoparticle aggregation; solvent sensitivity	Low throughput; nozzle clogging; limited layer thickness	[19, 32]
Vat photopolymerization (SLA/DLP)	Photopolymer resin curing via UV/visible light	High resolution; smooth surfaces; fine microfeatures	Microfluidic soft actuators; optical waveguides; dielectric layers for DEAs	Limited elastomer chemistries; brittle photopolymers; photoinitiator aging	Resin switching complexity; oxygen inhibition; postcuring distortion	[19, 33]
Embedded/sacrificial printing	Printing within support bath or fugitive ink	Internal channels; complex 3D fluidic networks	Multichannel pneu-nets; vascularized soft actuators	Compatibility with support materials; residue contamination	Support removal; slow throughput; process complexity	[19, 34, 35]

including layer thickness, nozzle or extrusion temperature, printing speed, shear conditions, and curing protocols. Numerous studies have demonstrated that these parameters critically affect interlayer adhesion, microstructural uniformity, fatigue resistance, and electrical conductivity stability in elastomeric and composite soft materials [40]. Table 2 summarize the effect of printing parameters on soft robotics materials and same has been discussed below:

Layer thickness strongly influences interfacial bonding and stress transfer within printed structures. Reduced layer thickness improves polymer chain diffusion across layers, leading to enhanced interlayer adhesion and delayed crack initiation under cyclic loading. This effect has been shown to significantly improve fatigue life and electromechanical stability in 3D-printed elastomers and conductive composites used for soft robotics [40, 41]

Nozzle temperature and extrusion conditions control filament fusion, void formation, and conductive filler dispersion. In thermoplastic elastomers and conductive polymer systems, optimized extrusion temperatures promote homogeneous deposition and stable conductive pathways, while excessively high temperatures can induce thermal degradation or filler agglomeration, resulting in conductivity drift during cyclic deformation [42, 43].

Printing speed and extrusion pressure further affect filament continuity and dimensional fidelity. Lower printing speeds and controlled extrusion pressures generally yield uniform filament deposition and improved conductivity retention, whereas high-speed printing may introduce microvoids and electrical discontinuities that accelerate resistance increase under repetitive strain [44].

Shear rate during extrusion plays a particularly important role in conductive elastomer composites. High shear forces can induce alignment of anisotropic fillers such as CNTs or graphene, resulting in enhanced initial conductivity along the printing direction; however, this anisotropy can also lead to directional fatigue and long-term resistance instability under multidirectional deformation [41].

Curing time and curing kinetics, whether thermal or UV-based, are critical for elastomers, dielectric elastomers, and hydrogel systems. Insufficient curing leads to low cross-link density, creep, and mechanical degradation, whereas excessive curing increases stiffness and reduces stretchability. Optimized curing protocols have been shown to improve fatigue endurance, dielectric strength, and conductivity stability in multilayer soft actuators and stretchable electronics [45, 46].

Overall, these studies indicate that printing parameter optimization must be codesigned with material formulation to achieve reliable mechanical and electrical performance. Establishing robust process–structure–property relationships is therefore essential for translating laboratory-scale demonstrations into application-ready, 3D-printed soft robotic systems.

4 | Material Constraints

Material selection is constrained by rheology (printability), curing/postprocessing windows (temperature, UV), adhesion to

TABLE 2 | Influence of printing parameters on functional performance of 3D-printed soft robotic materials.

Printing parameter	Affected property	Impact on performance	Representative materials	Key references
Layer thickness	Interlayer adhesion, porosity	Improved fatigue life and conductivity stability under cyclic strain	Elastomers, conductive composites	[40, 41]
Nozzle/extrusion temperature	Filament fusion, filler dispersion	Enhanced mechanical integrity; stable conductive pathways; degradation at excessive temperatures	TPEs, PEDOT:PSS, CNT composites	[42, 43]
Printing speed/pressure	Filament continuity, dimensional accuracy	Reduced electrical discontinuities; improved electromechanical durability	Conductive elastomers, hydrogels	[44]
Shear rate during extrusion	Filler alignment, anisotropy	Increased initial conductivity; potential directional fatigue	CNT/graphene elastomers	[41]
Curing time and temperature	Cross-link density, residual stress	Improved fatigue resistance and conductivity retention	Silicone elastomers, DEAs	[45]
UV/postcuring conditions	Degree of polymerization	Enhanced mechanical and electrical stability	Photocurable elastomers, hydrogels	[46]

adjacent layers, stretchability, and stability under cyclic deformation [47]. Many of the performance trade-offs discussed below arise from these constraints. Reviews on 3D printing methods applied to soft robotics provide in-depth coverage [19]. Regardless of the printing technology, certain material properties critically define whether a material is printable and performs well once printed [48]. Keys among them are as follows:

4.1 | Rheology (Viscosity, Yield Stress, Shear-Thinning Behavior)

In extrusion methods or DIW, inks or pastes must flow under shear but support their own weight after deposition to retain shape. Shear-thinning behavior favors shape fidelity [30, 49]. Yield stress helps prevent sagging or collapse of printed features, but excessive yield stress creates high extrusion pressures and clogging. Example: printing silicones with yield-stress suspension (with fumed silica) to support patterning [31].

4.1.1 | Cure/Solidification/Gelation Kinetics

After deposition, materials often need to solidify (thermally, via UV/photoinitiation, crosslinking). The cure must not distort shape or degrade other printed parts. Fast and mild curing is desirable. For silicones, often a room-temperature or low-temperature cure is required so that rigid or temperature-sensitive fillers and previously printed layers are not damaged [31, 50].

4.1.2 | Mechanical Properties: Elasticity, Toughness, Fatigue Resistance

Soft robotics demands materials that can undergo large strains (often >100–200%), repeated cycles, and/or rapid deformation. Materials must maintain conductivity, actuation, and sensing function under repeated deformation. Interlayer adhesion, filler dispersion, and microstructure design influence fatigue life [15, 51].

4.1.3 | Material Compatibility and Multimaterial Interfaces

When printing with more than one material (for stiffness gradients, embed sensors, rigid connectors, etc.), the interface must bond well, and differential shrinkage, thermal expansion, or curing mismatch must be tolerated. Poor interface leads to delamination or crack initiation. For example, printing a PneuNet with a rigid air-connector component and a soft actuator component required choosing two TPU filaments for better interface strength, avoiding PLA/TPU mix, which showed weak bonding.

4.1.4 | Print Resolution/Geometric Fidelity

The smallest feature size (channel width, wall thickness, sensor trace) that can be produced depends on the nozzle/pixel size, minimum layer thickness, and ink or resin behavior (bleeding, spreading). For DIW and FDM, resolution tends to be in the 100 μm –1 mm range; vat photopolymerization offers finer resolution but often at the expense of print speed or material diversity [30].

4.1.5 | Environmental Stability and Postprocessing Constraints

Many soft robotic materials (hydrogels, conductive polymers, liquid metals) are sensitive to moisture, oxidation, UV, or thermal aging [52]. Postprocessing processes like crosslinking, solvent washing, sintering, and curing must not degrade in terms of functionality [53]. Additionally, the removal of supports and cleaning (for SLA/SLS) shouldn't harm fine features. Adding embedded or sacrificial supports complicates matters [15].

4.2 | Trade-Offs and Performance Limitations

Because of these restrictions on materials and technology, trade-offs must be made during the design process. The most noteworthy of them are listed below:

Throughput versus resolution: Increased resolution printing (smaller nozzles, thinner layers) tends to decrease build speed; faster printing may result in lower fidelity or the introduction of flaws [19].

Filler content versus elasticity and conductivity: A high filler loading increases conductivity but can also make the matrix less pliable and more rigid. Conductive composites need filler particles or networks [54].

Material diversity versus process simplicity: Printing with many materials in a single build increases capabilities (functional skin, sensors, actuators in one robot) but increases process complexity, risk of interface issues, misalignment, and print failures [43].

Mechanical robustness versus softness: More durable materials (higher modulus, tougher thermoplastics) may compromise compliance; very soft materials (e.g., low Shore hardness silicones or hydrogels) may lack mechanical strength, tear resistance, or long-term shape retention.

4.3 | Recent Advances to Mitigate Constraints

Recent research has addressed many of the above limitations. Some notable advances:

Material tuning: Creating inks with tailored rheology (yield stress, shear-thinning, viscoelastic recovery). Example: EMB3D silicone inks with fumed silica suspensions to balance flow and structural support [31].

Multimaterial printing with matched polymers: Using two TPU grades with different hardness but similar chemical affinity to ensure stronger bonding in dual-extruder FDM printing of pneumatic actuators [55].

Graded or composite structures: Methods to embed porosity or stiffness gradients (e.g., printing porous infill in fluidic actuators to tune deformation) [56].

Data-driven models for printability: Studies using large datasets of hydrogel inks to predict printability based on rheological metrics; improves the ability to screen inks before trial prints [56].

4.4 | Conductive Materials for Printed Soft Robotics

Soft robots need conductive pathways for sensing, heating, communication, and embedded control [7]. Desired attributes are high conductivity at large strains, mechanical compliance matching soft matrices, printability, and long-term stability. Below, we cover the main classes used in printed soft robotic systems.

4.4.1 | CPCs and Filled Elastomers

CPCs-elastomeric matrices (silicone, TPU, PDMS) loaded with conductive fillers (carbon black, CNTs, graphene, silver flakes/nanowires)-are widely used because they combine stretchability with acceptable conductivity and are compatible with DIW and FDM filament production [57]. By tuning filler loading and percolation, designers balance conductivity versus toughness and

elongation at break. Multiwall carbon nanotubes and graphene nanoplatelets enable relatively low percolation thresholds and maintain flexibility; silver flake composites provide higher conductivity but can embrittle the matrix at high loadings and suffer from fracture under cyclic strain [58]. Recent reviews summarize optimized CPC formulations for sensors and interconnects in soft robotics [59, 60].

Practical issues: anisotropic conductivity from printed filaments, strain-dependent resistance (which can be leveraged for sensing), and microcracking under repeated cycling that reduces conductivity. Strategies to alleviate these include percolating networks with deformable conductive fillers (e.g., buckled or serpentine metal traces) and microstructural design (e.g., helical/serpentine printed traces) [32].

4.4.2 | Conductive Hydrogels

Conductive hydrogels-ionic or electronically conducting polymer networks swollen with water or ionic liquids-offer very soft mechanical moduli close to biological tissues, transparency, and intrinsic ionic conductivity. They can be printed by DIW and photocuring and function as stretchable electrodes, strain sensors, and interconnects for soft actuators [61]. Their strengths are mechanical match and high deformability; weaknesses include dehydration over time, ionic migration, and limited electronic conductivity compared with metal-based conductors. Recent work has produced printable conductive hydrogels with improved stability, self-healing, and adhesion to elastomers, making them attractive for bio-integrated soft robots and wearable interfaces [52, 62].

4.4.3 | Liquid Metals (Gallium Alloys) and Core-Sheath Conductors

Liquid metal alloys (e.g., eutectic gallium-indium, EGaIn) provide metallic conductivity while remaining compliant. They can be printed as droplets, injected into microchannels, or extruded as inks (microencapsulated or within polymer carriers) [63, 64]. Liquid metals are excellent for stretchable interconnects and reconfigurable circuits and have been integrated into soft actuators and sensors [65]. Challenges include oxide skin formation (which changes rheology), encapsulation to prevent leakage, and biocompatibility concerns for certain applications, and limited resolution for extremely fine traces. Recent advances include microencapsulated liquid metal inks and patterned deposition via aerosol jetting or DIW [64].

4.4.4 | Metallization and Plated Traces

Where higher conductivity is needed, printed polymer traces are sometimes metalized postprint either by electroless plating, ink sintering of metallic nanoparticle inks, or chemical deposition to create thin metallic layers on elastomeric substrates. Plating can achieve bulk metal conductivities but typically requires careful surface preparation and may reduce compliance unless serpentine geometries or patterned thin films are used. Low-temperature sintering inks (photonic or chemical sintering) help avoid thermal damage to soft matrices [32].

4.5 | Trade-Offs and Design Rules for Conductive Printed Elements

- *Percolation versus stretchability*: higher filler loadings raise conductivity but reduce elasticity. Design choices include using hybrid fillers (carbon + metal flakes), hierarchical microstructures (buckled traces), or segregated conductive networks.
- *Geometry matters*: meandering, serpentine, or kirigami routing preserves conductivity under large stretch.
- *Integration*: coprinting conductors into actuator chambers or embedding them within hydrogel layers improves robustness but requires adhesion and curing compatibility. Readers wanting a comprehensive treatment of printable conductive hydrogels and CPCs should consult recent dedicated reviews [62].

4.6 | Printed Actuators: Materials and Mechanisms

Actuation in soft robots can be achieved with a variety of printable materials and transduction mechanisms. Here, we group actuators by their underlying stimulus and highlight printable material options. Figure 4 shows the CAD model and the corresponding 3D-printed linear actuator. The finalized actuator weighed 0.34 kg, featuring a bore diameter of 2.7 cm and a stroke length of 14.0 cm. The pneumatic cylinder comprised four primary components: (1) a 3D-printed cylinder body; (2) two 3D-printed sensor carriers positioned around the cylinder to hold the position sensors; (3) a metal piston rod equipped with a 3D-printed piston head; and (4) a 3D-printed end cap fitted with bushings. Table 3 summarizes 3D-printed actuators: materials and mechanisms.

To guide material selection for 3D-printed soft robots, Table 4 compares conductive materials based on key performance indicators relevant to stretchable interconnects and sensors. Table 5 compares major soft actuator classes according to actuation metrics that determine their applicability in soft robotic systems. These consolidated comparisons support the practical design and selection of materials by highlighting inherent trade-offs between electrical, mechanical, and manufacturing properties for conductors, as well as actuation performance trade-offs.

4.6.1 | Pneumatic/Hydraulic Soft Actuators (PneuNets, Bellows)

Fabrication approach: DIW, embedded printing, and multimaterial molding via 3D printed molds are common. Materials: silicone elastomers (PDMS, Ecoflex, Dragon Skin), thermoplastic elastomers (TPU) for FDM. Design: internal cavities and asymmetric wall thicknesses produce bending and contraction under inflation. 3D printing enables complex multichamber pneu-nets and graded wall thicknesses not possible with molding alone. Advantages include large forces and robustness; disadvantages include the need for external pumps and tubing, and potential leakage. Multimaterial embedded printing (printing sacrificial supports or fugitive inks) simplifies internal channel fabrication [35, 84]. Figure 5 illustrates the multimaterial embedded 3D printing process and performance of soft robotic actuators, highlighting fabrication steps, material properties, and actuator deformation under varying inflation pressures.

4.6.2 | DEAs and Electroactive Polymers

DEAs produce large strains under an applied electric field across a dielectric elastomer (e.g., VHB, silicone). To print DEAs, one requires printable high-permittivity elastomers and compliant printed electrodes (carbon, CNT films, liquid metals) [85].

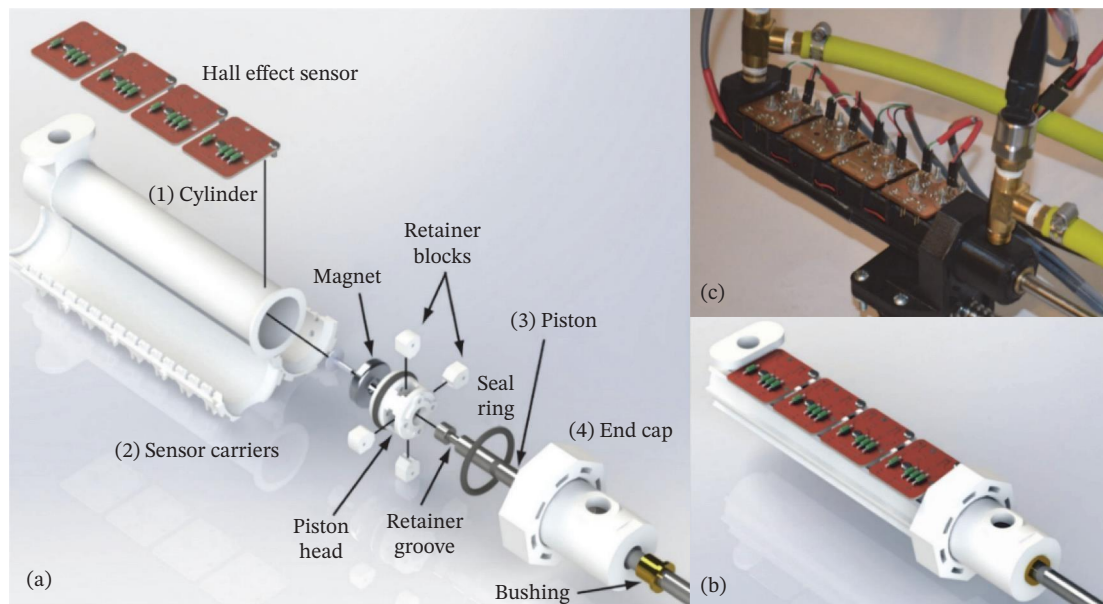


FIGURE 4 | Overview of actuator: (a) exploded view; (b) assembled view; and (c) final prototype [66] (licensed under CC by 4.0, <https://creativecommons.org/licenses/by/4.0/>).

TABLE 3 | 3D-printed actuators: materials and mechanisms.

Actuator type	Output force	Response time	Energy density	Typical applications (with examples)	Material limitations	Process limitations	Key references
Pneumatic elastomer actuators	Very high	Moderate (s)	Low	Soft grippers; continuum manipulators; wearable assist devices; soft exosuits	Silicone aging; air permeability; fatigue cracking	External pumps/tubing; leakage; bulky system integration	[19, 32, 67, 68]
Dielectric elastomer actuators (DEAs)	High	Fast (ms-s)	High	Artificial muscles; fast pick-and-place grippers; soft locomotion	High-voltage dielectric breakdown; limited printable high-k elastomers	Thin-layer uniformity; electrode alignment; electrical isolation	[20]
Ionic polymer-metal composites (IPMCs)	Low	Fast (ms)	Low	Micro-swimmers; biomimetic fins; bending micro-actuators	Solvent loss; limited force output; electrode delamination	Limited printable formulations; moisture sensitivity	[23, 69]
Shape memory polymer (SMP) actuators	Moderate	Slow (s-min)	Moderate	Self-folding robots; deployable structures; temperature-triggered morphing	Limited cyclic durability; thermal fatigue	Slow heating/cooling; poor spatial control	[30, 70]
Hydrogel actuators	Low-moderate	Slow (s-min)	Low	Drug delivery robots; biohybrid actuators; swelling-based motion	Dehydration; low mechanical strength; ionic drift	Long response times; environmental sensitivity	[62, 71]
Liquid crystal elastomers (LCEs)	Moderate-high	Fast (ms-s)	Moderate-High	Light-driven soft robots; programmable shape morphing	Limited printable chemistries; alignment sensitivity	Complex alignment; multistep processing	[72]
Magneto-active elastomers	Moderate	Fast (ms-s)	Moderate	Untethered microrobots; remotely controlled soft actuators	Particle agglomeration; stiffness increase	Magnetic field setup; particle alignment control	[73]

Printing challenges include depositing thin, uniform dielectric layers and compliant electrodes with low interfacial resistance. Vat photopolymerization can produce high-resolution dielectric layers, while DIW and inkjet can place electrodes. DEAs are attractive for electrically driven soft robots but require high voltages and careful electrical isolation [86]. Recent demonstrations combine printed high-permittivity composites with patterned compliant electrodes to make soft actuators [20, 85].

4.6.3 | Hydrogel and Swelling Actuators (Chemical/Thermal/pH Stimuli)

Hydrogels that swell in response to water, pH, or temperature can be printed into patterned bilayers or gradient structures that morph predictably. DLP and DIW have been used to produce hydrogel actuators with programmable shape change (4D printing). These systems are promising for soft micro-actuators and biomedical soft robots but are typically slow (diffusion-limited) and sensitive to environmental conditions. Hybrid designs combine hydrogels with elastomeric frames for faster, more controllable motion [26, 87].

4.6.4 | Magneto-Active and Magnetic Composite Actuators

Embedding magnetic particles (NdFeB micro-powders, iron oxide) in printable elastomer matrices yields materials that can be actuated remotely by external magnetic fields. Photocurable resins loaded with magnetic particles can be patterned by DLP/SLA to create complex magnetization profiles that produce programmable motion under fields. These actuators are attractive for untethered soft robots and small-scale locomotion [88]. Challenges include particle loading (affecting rheology and mechanical properties), alignment during printing (to set magnetization direction), and limited force density compared to electromagnetic actuators [73]. Recent works demonstrate DLP-printed magneto-active soft robots with untethered locomotion [73, 89].

4.6.5 | SMPs and Thermal Actuators

SMPs can be printed as filaments or photopolymers and programmed into temporary shapes that recover when heated above T_g . In soft robotics, SMPs enable deployable structures and variable-stiffness elements when combined with low-melting-point inclusions (e.g., eutectic alloys) [90]. Printing multimaterial SMP/soft elastomer composites allows local stiffening or actuation upon thermal stimulus. Limiting factors include heating mechanisms, slow response, and energy consumption for large devices [26].

4.6.6 | Embedded Actuation-Coprinted Fluidic and Electrical Systems

Moving beyond single actuation modes, AM enables the coprinting of actuators with embedded sensors and wiring. For example, pneumatic actuators with printed conductive traces for sensing, or magneto-active regions interleaved with flexible interconnects. Multimaterial printers and embedded sacrificial templates make these integrations more practical. However, assembly of pumps, valves, and power remains a system-level challenge [35].

TABLE 4 | Conductive materials – conductivity vs. stretchability vs. printability.

Conductive material	Electrical conductivity	Stretchability	Printability (AM compatibility)	Typical applications in soft robotics	Key references
Liquid metals (EGaIn, Galinstan)	Very High (10^6 – 10^7 S/m)	Excellent (> 300%)	Moderate	Stretchable interconnects, reconfigurable circuits, soft strain sensors	[44, 74]
Conductive elastomer composites (CNT/graphene/CB-elastomers)	Moderate (10^1 – 10^3 S/m)	Excellent (> 200%)	Excellent	Stretchable wiring, embedded sensors, wearable soft robots	[41, 42]
Hydrogels (ionic/conductive)	Low–moderate (ionic)	Excellent (> 500%)	Good	Bio-integrated sensors, artificial skin, biomedical soft robots	[44, 46]
Conductive polymers (PEDOT:PSS)	Moderate (10^2 – 10^4 S/m)	Moderate	Excellent	Flexible sensors, low-strain interconnects, bioelectronics	[43]
Metal nanoparticle inks (Ag, Cu)	High (10^4 – 10^6 S/m)	Poor (<50%)	Good	High-resolution electrodes, localized rigid regions	[75]
MXene-based composites	High (10^3 – 10^5 S/m)	Moderate	Moderate	Multifunctional sensors, EMI shielding in soft robots	[76]

TABLE 5 | Actuator materials – force vs. response time vs. energy density.

Actuator type	Output force	Response time	Energy density	3D Print compatibility	Typical applications in soft robotics	Key references
Dielectric elastomer actuators (DEAs)	High	Fast (ms-s)	High	Moderate	Artificial muscles, fast grippers, soft locomotion	[77, 78]
Pneumatic elastomer actuators	Very high	Moderate (s)	Low	Excellent	Soft grippers, manipulators, wearable assistive robots	[79]
Ionic polymer–metal composites (IPMCs)	Low	Fast (ms)	Low	Limited	Micro-actuators, biomimetic fins, sensors-actuators	[80]
Shape memory polymers (SMPs)	Moderate	Slow (s-min)	Moderate	Excellent	Deployable structures, self-folding soft robots	[81]
Hydrogel actuators	Low–moderate	Slow (s-min)	Low	Good	Drug delivery systems, biohybrid robots	[82]
Liquid crystal elastomers (LCEs)	Moderate–high	Fast (ms-s)	Moderate–high	Moderate	Programmable shape morphing, light-driven soft robots	[83]

4.7 | Printed Sensing Networks for Soft Robots

Sensing in soft robotics requires sensors that deform with the structure while providing reliable, repeatable signals. 3D printing enables distributed sensor placement, conformal skins, and multimodal arrays. Table 6 summarizes the types of printed sensing networks for soft robots and its applications.

4.7.1 | Resistive (Piezoresistive) Sensors

Piezoresistive sensors exploit changes in resistance under strain. Printable CPC traces, conductive hydrogels, and micro-structured printed conductive foams are common implementations.

Advantages: simple readout, easy fabrication. Limitations: non-linearity, hysteresis, and drift over cycles. Recent work uses hierarchical microstructures (microcracks, foam pores) and patterned geometries to linearize response and tune sensitivity. Integration with printed interconnects and multiplexed readout circuits enables large area sensor arrays. Reviews on printed electromechanical sensors summarize fabrication-to-application workflows [45, 65]. Figure 6 represents an example of a piezo-resistive sensor made using the DLP approach, explaining the structural and morphological characterization of rGO-P(AA-AM)-CMC hydrogels along with their 3D-printed architectures and bilayer configurations through EDS, SEM, and macroscopic imaging. Figure 7 shows schematic of the fabrication steps for the

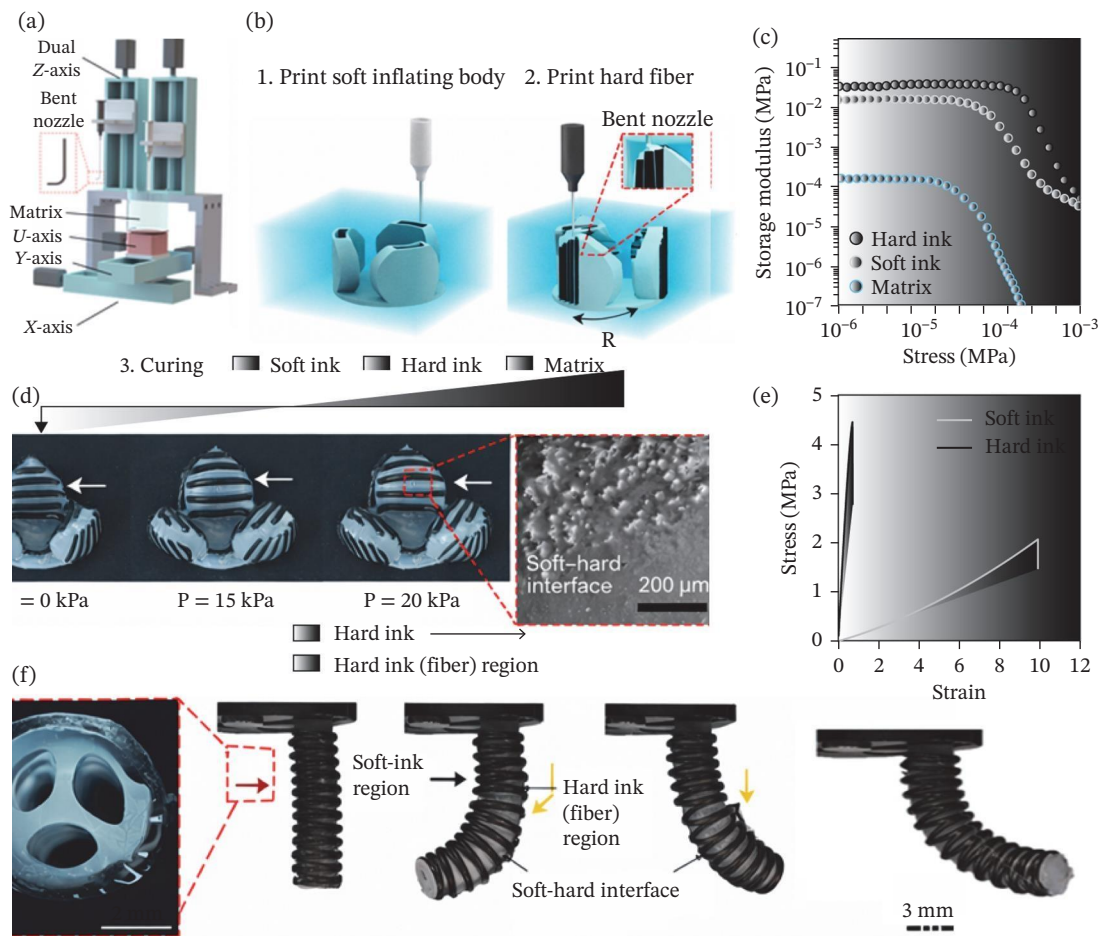


FIGURE 5 | Overall representation of embedded printing using multimaterials for robots and soft composite actuators. (a) A multiaxis embedded 3D printing setup for dual-material. (b) Fabrication procedures for a soft pneumatic flower. (c) For embedded printing, the moduli for hard and soft inks were about 2 orders of magnitude. (d) Figure showing the blooming of the printer flower at an inflation pressure of about 20 kPa, along with the SEM images displaying the interfaces among the composite. (e) The strain–stress curve for hard and soft inks. (f) Under several inflating conditions of 3-channel (right), an omnidirectional bending actuator with three embedded channels (left) can bend in various directions [35] (licensed under CC by 4.0, <https://creativecommons.org/licenses/by/4.0/>).

flexible piezoresistive WPU/SWCNT/CNF sponge using a DIW-based 3D-printing and lyophilization process, along with the overall device assembly and the pressure-sensing test setup.

4.7.2 | Capacitive Sensors and Soft Dielectric Layers

Capacitive sensing (two compliant electrodes separated by a deformable dielectric) offers low drift and good sensitivity for large deformations. Printing soft dielectric layers by DLP or DIW and printing compliant electrodes (liquid metal or conductive hydrogel) produces stretchable capacitors that can be arranged in matrices for spatial mapping. Careful electrode encapsulation is needed to avoid shorts in wet environments. Capacitive skins are well-suited for proprioception and touch sensing in soft robots [91].

4.7.3 | Optical and Photonic Sensors

Printing optical waveguides (clear elastomers or hydrogels) with integrated Bragg gratings or microfluidic dye channels enables strain and curvature sensing via light transmission changes. Vat photopolymerization yields high-quality optical features, and

DIW can create embedded channels for light guides. Optical sensors are immune to electromagnetic interference but require alignment and light-coupling components [32].

4.7.4 | Multimodal Sensor Fusion and Printed Sensor Networks

Rather than relying on a single modality, printed sensor skins increasingly combine resistive, capacitive, and temperature/chemical sensors into fused arrays [98]. These networks, when paired with onboard signal conditioning and machine learning, provide robust tactile sensing and terrain recognition for soft robots [99, 100]. Advances in printed sensor multiplexing, low-power signal routing, and stretchable electronics are accelerating the demonstration of large-area sensing skins [21, 101].

4.8 | Integration: Multimaterial Printing, Embedded Electronics, and System Architecture

Integration of conductors, actuators, and sensors into a working soft robotic system requires attention to interfacial adhesion,

TABLE 6 | Printed sensing networks for soft robots.

Type of sensor	Functional material	Printing technique	Sensing mechanism	Key features	Applications in soft robots	Representative references/links
Strain sensor	Carbon nanotubes (CNTs), Graphene, Conductive elastomer composites	Direct Ink Writing (DIW), Inkjet printing, Screen printing	Change in resistance (piezoresistive) or change in capacitance	High flexibility, stretchability, tunable gauge factor	Monitoring bending, elongation, and shape sensing	Hegde et al., sensing in soft robotics (2023) [91]; Moyer et al. (2025) on stretchable printed strain sensors [92]
Pressure/tactile sensor	Graphene foam, MXene, Ag nanowires, Carbon black, conductive composites	Inkjet printing, Aerosol-jet, Screen printing	Piezoresistive (resistance change under pressure) or capacitive	High sensitivity, conformal contact	Tactile feedback, grip force sensing	Goh et al., 3D printing of soft sensors for soft gripper applications (2022) [93]
Capacitive sensor/capacitive network	Silver nanoparticle ink, conductive elastomer + dielectric elastomer	DIW, screen printing	Capacitance variation due to deformation (distance change, dielectric thickness)	Good stretchability, low power, spatial sensing possible	Distributed tactile “skins,” soft fingertips	Dong et al., application of 3D printing in soft robots (2024) [15]; 3D-printable soft capacitive sensors review [23]
Temperature sensor	PEDOT: PSS, CNT composites, reduced graphene oxide (GO)	Inkjet, screen printing	Change in resistance (thermoresistive) or thermoelectric effect	Lightweight, conformal, local temperature measurement	Thermal mapping, thermal feedback control	Hegde et al., sensing in soft robotics (2023) [91]
Humidity/moisture sensor	GO, polyaniline, cellulose nanofibers, conductive polymers	Inkjet, aerosol jet	Change in dielectric properties or resistance with humidity	Fast response, simple fabrication	Environmental sensing, soft robot ambient monitoring	Kumar et al., printable flexible and stretchable tactile sensors (2019) (discussion of moisture/humidity sensing in flexible sensors) [94]
Optical/waveguide sensor	Elastomer matrix with embedded optical paths, dyed PDMS, and transparent polymers	Embedded printing, waveguide embedding, DIW	Light intensity modulation (absorption/scattering) under deformation	Immune to electromagnetic interference, long lifetime	Shape sensing, curvature sensing in soft limbs	3D-printing of stretchable waveguide networks in soft robots (biogel + optical); Capp et al. on optical fiber embedding in printed fingers (2025) [95]
Self-healing/reconfigurable sensor	Ionic gels, conductive polymers (e.g., PEDOT: PSS with self-healing elastomer)	DIW, hybrid additive manufacturing	Ionic conductivity variation or resistive change after damage	Self-repair, reusability, resilience	Durable robot skins, long-life soft robots	Discussion in soft robotics sensing reviews on resilient sensors
Multimodal/hybrid sensors	Composites combining CNT, metal nanoparticles, MXene, and ionic gels	Multimaterial 3D printing, hybrid DIW + inkjet	Combined responses (strain + temperature + pressure)	Compact, multifunctional, integrated	Robotic fingertips, soft robotic surfaces with multiple sensing channels	Hegde et al., survey of integration of multiple modalities in soft robotics sensing (2023) [91]; Blihan et al., fabrication of soft robotics by additive manufacturing (2025) [19]

thermal/chemical compatibility, and coprocessing sequences. Key strategies include:

- Sequential multimaterial printing with low-temperature cures to avoid damaging previously printed bio/soft layers [102].
- Embedded sacrificial templates for pneumatic channels and liquid metal injection postprint.
- Coaxial/core-sheath extrusion to print conductive cores within insulating elastomer sheaths for protected interconnects [103].
- Hybrid workflows where high-performance rigid components (microcontrollers, batteries) are pick-and-placed into printed housings or sockets-full electronic printing is still nascent for complex control systems [104].
- Packaging and encapsulation to protect conductive elements from oxidation, humidity, and mechanical wear; conductive hydrogels and liquid metals require encapsulation strategies for longevity [105].

Examples of integrated printed soft robots include 3D-printed pneumatic grippers with embedded sensors, DLP-printed magneto-active crawlers, and multimaterial printed tentacles with distributed sensing. Despite these successes, achieving reliable, long-lived systems suitable for field deployment requires further improvements in materials durability and standardized testing [35].

4.9 | Reliability, Durability, and Failure Modes

Printed soft systems are subjected to repeated large strains, environmental exposure, and fatigue. Common failure modes include:

- Electrical failure: Loss of conductive percolation due to microcracking, oxidation (liquid metal skin formation), or conductor delamination [106].
- Mechanical failure: Tear initiation at interfaces between stiff and soft materials, or at sharp geometry transitions [107].
- Environmental degradation: Hydrogel dehydration, UV-induced polymer aging, corrosion of metal particles [108].
- Interfacial delamination: Due to incomplete bonding or mismatched curing kinetics [109].

Mitigation strategies include mechanical stress-relief patterns (serpentine), adhesive interlayers, protective encapsulants, humidity-stable hydrogels, and redundancy in sensor networks. Accelerated fatigue testing and standardized reporting practices are currently lacking and are needed to compare materials and designs across labs [30].

AM of elastomers particularly in vat, extrusion, and direct ink writing (DIW)-based processes, the entrapment and unclogging of soft material within fine features or mold holes can indeed pose a practical challenge, but its significance depends on the specific printing modality and geometry being fabricated [110]. For mold-based or embedded printing methods, where elastomeric material is deposited around sacrificial templates or within confined cavities, residual material can remain in recessed features or holes after printing and curing [111]. This can lead to defects such as incomplete feature definition, surface irregularities, and localized mechanical heterogeneities if not properly removed. Strategies such as optimized ink rheology, shear thinning behavior, tailored cross-linking kinetics, and controlled evacuation/solvent flushing have been shown to mitigate these issues by facilitating material flow and minimizing entrapment [112].

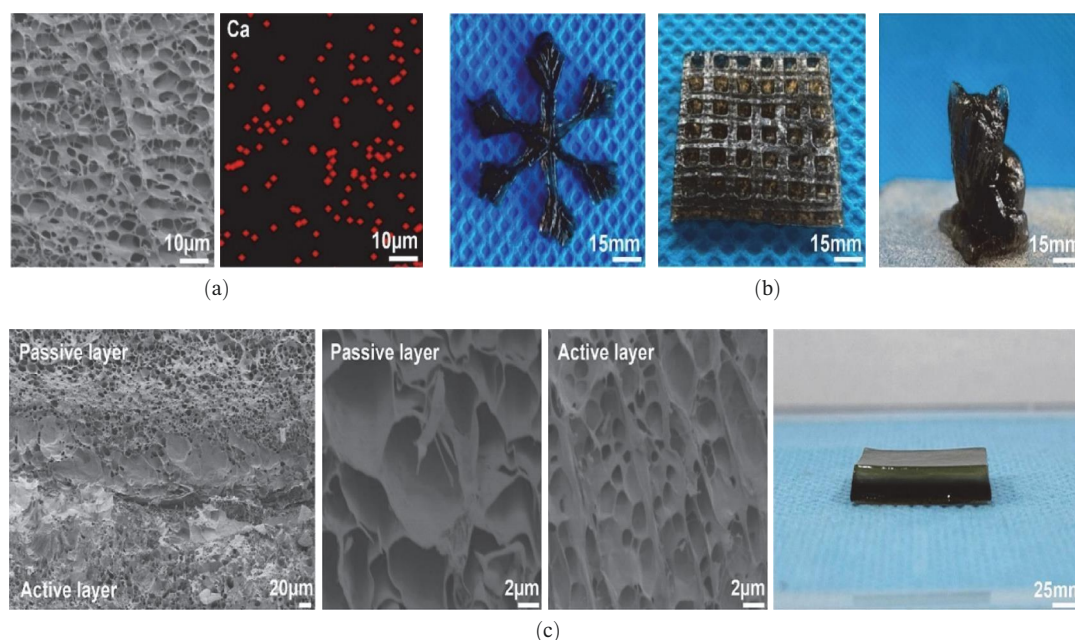


FIGURE 6 | (a) EDS and SEM images representing rGO-P(AA-AM)-CMC hydrogel. (b) rGO-P(AA-AM)-CMC hydrogel structures made using 3D printing approach. (c) Macroscopic images and cross-sectional SEM images of the Bilayer hydrogel [96] (licensed under CC by 4.0, <https://creativecommons.org/licenses/by/4.0/>).

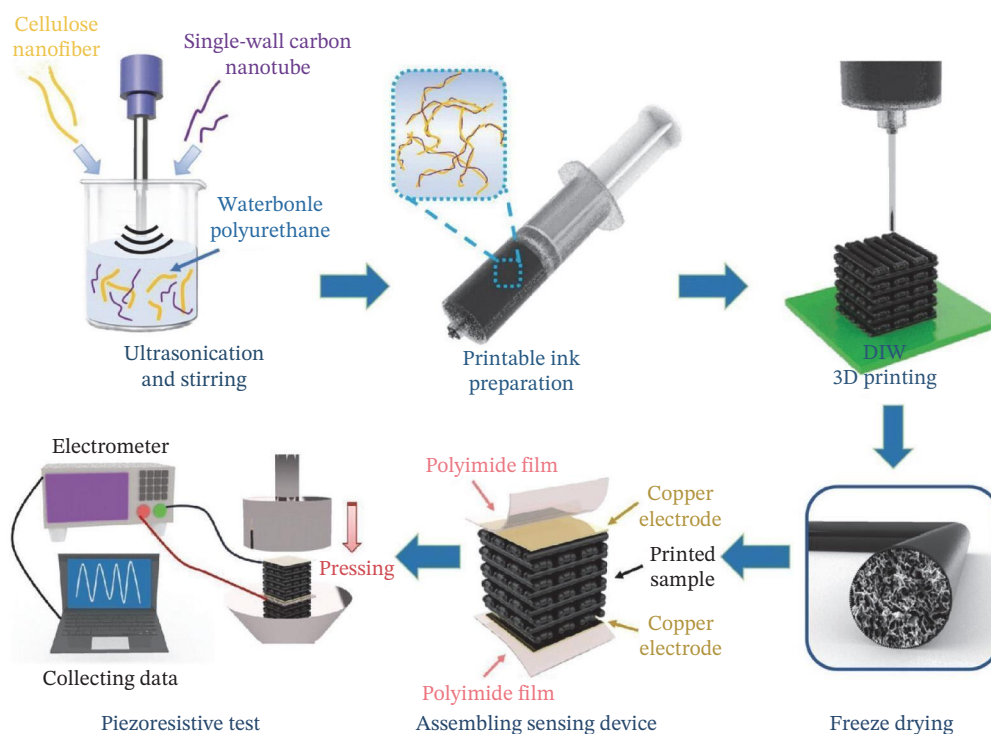


FIGURE 7 | Schematic of the fabrication steps for the flexible piezoresistive WPU/SWCNT/CNF sponge [97] (licensed under CC by 4.0, <https://creativecommons.org/licenses/by/4.0/>).

However, for open-path extrusion and DIW of elastomers, the issue of material clogging within mold holes is less prevalent compared to challenges like nozzle clogging, maintaining dimensional fidelity, and achieving sufficient interlayer adhesion [113]. In these approaches, the focus is more on ink formulation (e.g., particle loading, viscoelastic balance), curing mechanisms (e.g., UV, thermal), and printer hardware optimization to ensure continuous flow and resolution rather than mold clearance [7, 110].

4.10 | Energy, Control, and Computation: Gaps for Fully Printed Autonomy

While structure, actuation, and sensing are increasingly printable, energy storage and control electronics remain bottlenecks. Batteries and power electronics are typically rigid or require specialized packaging; fully printed stretchable batteries and printed power harvesters are active research areas, but not yet mature for complex, long-duration robots. Control electronics (microcontrollers, wireless radios) are often integrated as discrete components into printed housings. Advances in printed thin-film transistors and printable energy storage may enable higher degrees of autonomy, but hybrid assemblies will remain common in the near term [15].

4.11 | Standardization, Benchmarking, and Reproducibility

The field would benefit from community standards for material characterization (conductivity vs. strain, fatigue cycles, environmental aging), printability metrics (shear thinning, yield stress), and device-level benchmarks (force per unit volume, sensory SNR under cyclic load). Several recent reviews call for harmonized datasets and open material libraries to accelerate

engineering trade-offs and regulatory readiness. Reproducible data reporting (rheology, curing conditions, postprocessing steps) is essential for industrial translation [62].

To enhance comparability and reproducibility across studies, future research should adopt standardized mechanical and electrical testing protocols. For cyclic mechanical durability, relevant standards such as ASTM D7791 (fatigue crack growth), ASTM D3479 (tension–tension fatigue), and ISO 13,003 (fatigue behavior of fiber-reinforced plastics) can be adapted to characterize cyclic strain endurance and fatigue life of soft actuators and stretchable substrates. Cyclic tensile testing under controlled strain amplitudes (e.g., 10%–100% strain) and frequencies (0.1–5 Hz) should be consistently reported to enable meaningful benchmarking. For electrical reliability, conductivity, and resistance retention under repeated deformation should be evaluated using protocols adapted from ASTM D4496 and IEC 62631, with metrics such as percentage change in resistance after 10^3 – 10^5 strain cycles reported. Additionally, environmental stability tests (temperature–humidity cycling and aging) following ISO 188 and ASTM D3045 can provide insight into long-term performance retention. Furthermore, emerging benchmarking initiatives in soft robotics and wearable electronics emphasize standardized reporting of actuation strain, blocking force, energy efficiency, and electrical stability under cyclic loading. Adoption of community-driven benchmarking frameworks will be essential to enable objective comparison of actuator performance and accelerate translation of laboratory-scale demonstrations toward practical soft robotic and wearable systems.

5 | Emerging Directions and Future Outlook

Based on recent trends, promising directions include:

- CPCs and printable self-healing conductive hydrogels that restore electrical consistency after mechanical degradation. Progress in dynamic cross-linking and self-healing chemistries (e.g., ionic interactions, hydrogen bonding) indicates functional durability enhancements [62].
- Multimodal printed skins combining capacitive, resistive, and optical sensing with local preprocessing (analog circuits) to reduce wiring complexity [32].
- Magneto-active photopolymers patterned with spatially varying magnetization to enable complex untethered behaviors (crawling, grasping) without onboard power. DLP approaches are enabling high-resolution magnetization patterning [73].
- Hybrid printed systems with embedded discrete electronics, standardized socketing for plug-and-play control modules-facilitating modular autonomy while printable components handle soft mechanical and sensing layers [35].
- Environmental robustness: printable conductors and encapsulants that resist humidity, UV, and biological fouling for wearable and biomedical soft robots [62].

Finally, the convergence of AM, materials informatics (data-driven material selection), and automated design optimization (topology and multimaterial layout) will accelerate the creation of soft robotic systems optimized across mechanical, electrical, and functional metrics.

6 | Conclusions

3D printing of functional materials is transforming the design field for soft robotics. Conductive hydrogels, liquid metals, metalized printed traces, and conductive polymer composites each provide supplementary trade-offs for flexible transfer; dielectric, a diverse actuator palette-pneumatic, magneto-active, shape-memory, and hydrogel-can be produced with additive techniques; and printed sensing networks now give rich, separated feedback for closed-loop soft robotic control. Key difficulties remain fatigue and long-term durability, energy autonomy, standardized testing, and multimaterial interfacial reliability.

Addressing these will require coordinated materials development, improved printing hardware for true multimaterial deposition, open benchmarking datasets, and hybrid system architectures that combine printed soft functionality with compact, reliable power and control modules. We expect that in the next 5 years, advances in printable self-healing conductors, printed energy storage, magneto-active photopolymers, and multimodal sensor skins together with improved manufacturing standards will enable more capable, reliable, and autonomous 3D-printed soft robots suitable for practical applications in wearables, biomedical devices, environmental sensing, and exploration.

Author Contributions

Rashi Tyagi: conceptualization, literature survey, data curation, writing – original draft, visualization. **Suraj Ghising:** literature survey,

writing – review and editing. **Din Bandhu:** formal analysis, validation, writing – review and editing. **Ashutosh Tripathi:** resources, technical inputs, writing – review and editing. **Vinay Kumar:** supervision, validation, writing – review and editing. **S. M. Nabil Rahman:** visualization, writing – review and editing. **Himanshu Payal:** literature survey, writing – review and editing. **Daniel Amoako Darko:** conceptualization, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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