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Transformative 4D Printed SMPs into Soft Electronics and Adaptive Structures: Innovations and Practical Insights

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Shape memory polymers (SMP) have recently gained significant attention as multifunctional materials for flexible and wearable electronics applications. These polymers demonstrate smart functionalities, including self-healing and shape memory, with tunable, reversible responses that enhance advancements in soft electronics technology. The integration of smart materials with 3D printing (3DP) has also emerged as a transformative technology, enabling the creation of sophisticated architectures in the soft wearable electronics industry. This review highlights recent advancements in 3DP techniques that incorporate emerging multifunctional SMP materials for applications in e-electronics, soft actuators, biomedical devices, and many more. Strategies to commercialize this technology by addressing key challenges related to materials, 3DP technology, and multifunctionality on a large scale are discussed. Additionally, how 2D materials and sustainability can be integrated into 3DP to provide an innovative and robust platform for future researchers, with a focus on soft wearable electronics applications is explored. Finally, the current challenges in developing more advanced and practical applications are outlined and key future directions to foster further progress in this rapidly evolving field are discussed.

1. Introduction

The modern world is undergoing rapid transformation, driven by advancements in powerful intelligent systems such as artificial intelligence (AI), smart materials, and intelligent manufacturing.[1–3] The integration of smart materials with 3D printing (3DP) continues to push the boundaries of these technologies, fueled by innovations in material science and advanced 3DP techniques.[4] The scientific community is increasingly translating this paradigm into real-world applications, leveraging the tunable chemistry of novel smart materials to enable diverse smart functionalities. In recent years, smart industrial fields such as the Internet of Things (IoT), soft electronics, and adaptive or smart structures have gained unprecedented importance.[5] This has spurred a growing interest in using smart and soft materials to realize these smart applications.[6–8] Particularly, 3D-printed soft materials are regarded as ideal materials for creating highly realistic and sophisticated structures.[9–11]

The fundamental mechanism of the ever-growing soft wearable technology is rooted in the exploitation of intelligent soft materials, including liquid crystal elastomers (LCEs),[12,13] shape memory hydrogels,[14,15] and more importantly shape memory polymers (SMPs).[16] These innovative soft materials also referred to as stimuli-responsive polymers, display dynamic and multifunctional properties.[17] It is worth highlighting that the compliant programmable actuation and self-healing[18] owing to the dynamic shape programmability and reconfiguration abilities of SMP materials has triggered vigorous development.[19] For developing self-healing polymers, and vitrimers, the dynamic covalent network of bonds plays a crucial role.[20] Smart architectures from SMP have chain mobility, soft segment, and conductive additives which are responsible for their shape-changing phenomena such as one-way,[21] two-way,[22,23] three-way[24] or multi-way transformations.[25] This multiple shape-shifting behavior without the requirement of mechanical interference or re-programming stages is employed for practical applications.[26]

Advancements in SMP, which can change their shape, properties, or functions, represent a significant development compared to traditional materials such as metals, polymers, composites, and ceramics.[27–29] The innovative SMPs are enriched with many multifunctionalities when exposed to various stimuli including light exposure, temperature variations or electric, magnetic behavior, moisture, and pH changes.[30–32] Moreover,

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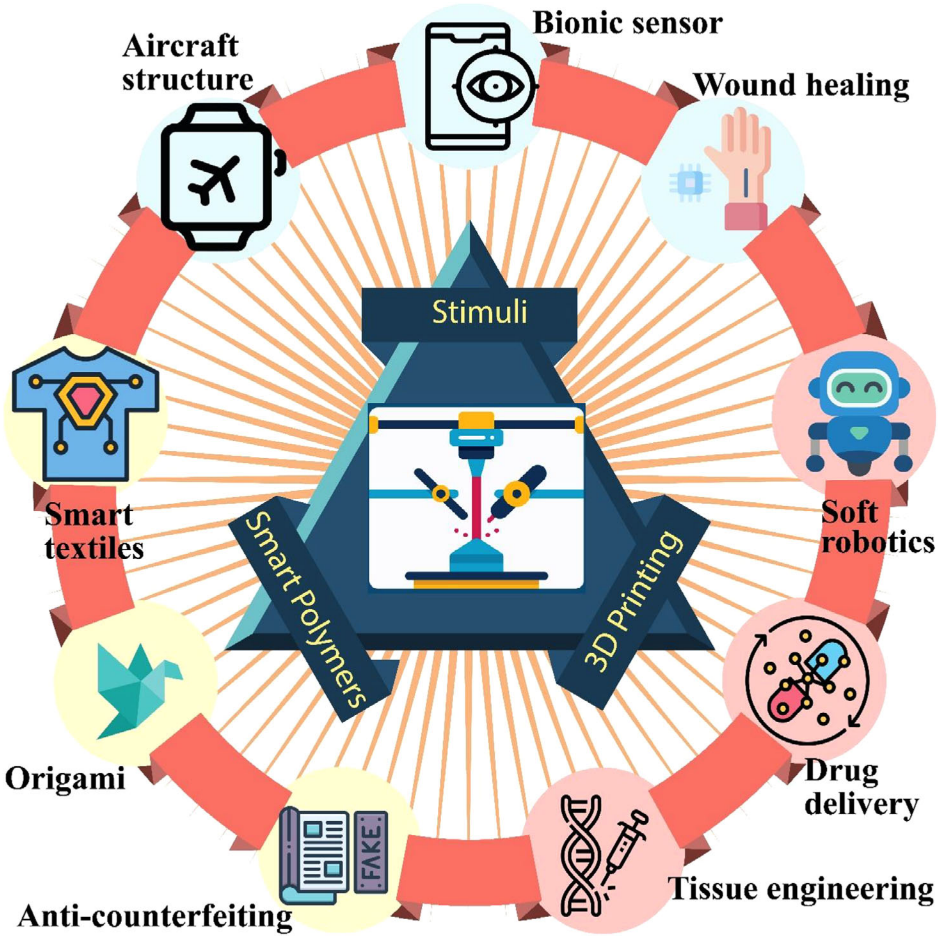


Figure 1. 3DP of SMP materials for the evolution of novel applications.

advancements in their controlled actuation have paved the way for more sophisticated and miniaturized technologies.[33,34] E-skin devices for monitoring human motions bring us a step closer to the ultimate personalized healthcare system. In this context, the latest research converged to more accurate control and predicting the response referring as shape-morphing.[35] Thus, the processing of SMP has increasingly focused on designing more complex shapes with tailored features to predict material behavior for various shapes, and functional properties.[36] These unique properties provide the potential for developing objects having abilities of self-healing,[37] self-assembling,[38] self-sensing,[39,40] self-adaptability,[41] or self-morphing[42] in response to stimulus offering new possibilities across numerous field sectors[43] as presented in **Figure 1**.

Recently, flexible and wearable electronics also referred to as e-skin or smart skins, have gained widespread recognition from academia and industry.[44–46] The ideal wearable electronics system often requires soft materials, now stimuli-responsive polymers, integrated with various conductive particles, which can be easily accomplished through 3DP processes.[47–49] Their vigorous development through 3DP, involving smart materials, has enabled the unique integration of electronic devices with biological tissues.[50] Interestingly, 3D-printed smart electronics demonstrate structures similar to human tissues and mimic almost the same performance.[51] The prosperity of wearable electronics has opened new avenues for matching various actuation performances, such as folding, bending, twisting, and stretching, under potential stimuli.[52–54] This allows researchers to monitor human health diagnostics such as disease monitoring, and bodily fluids (tears, urine, sweat, and blood).[55–57] Moreover, the data from these bodily fluids are shared wirelessly for continuous tracking of a patient's health status, which is useful in preventing life-threatening conditions. Wearable technology-driven "smart health" systems significantly influence today's health system through their unique characteristics.[58,59] Recent breakthroughs in 3DP technology for wearable electronics have advanced the field significantly.[60] For example, intelligent materials inspired by bionics aim to create an "active" material system with intelligent properties such as damage healing and shape memory behavior, playing a crucial role in the burgeoning wearable electronics technology.[61]

1.1. The Vision of the Current Review

In recent years, SMP have seen tremendous growth in technological innovation in the soft electronics field as outlined in **Figure 2**. This technology continues to advance and gain widespread

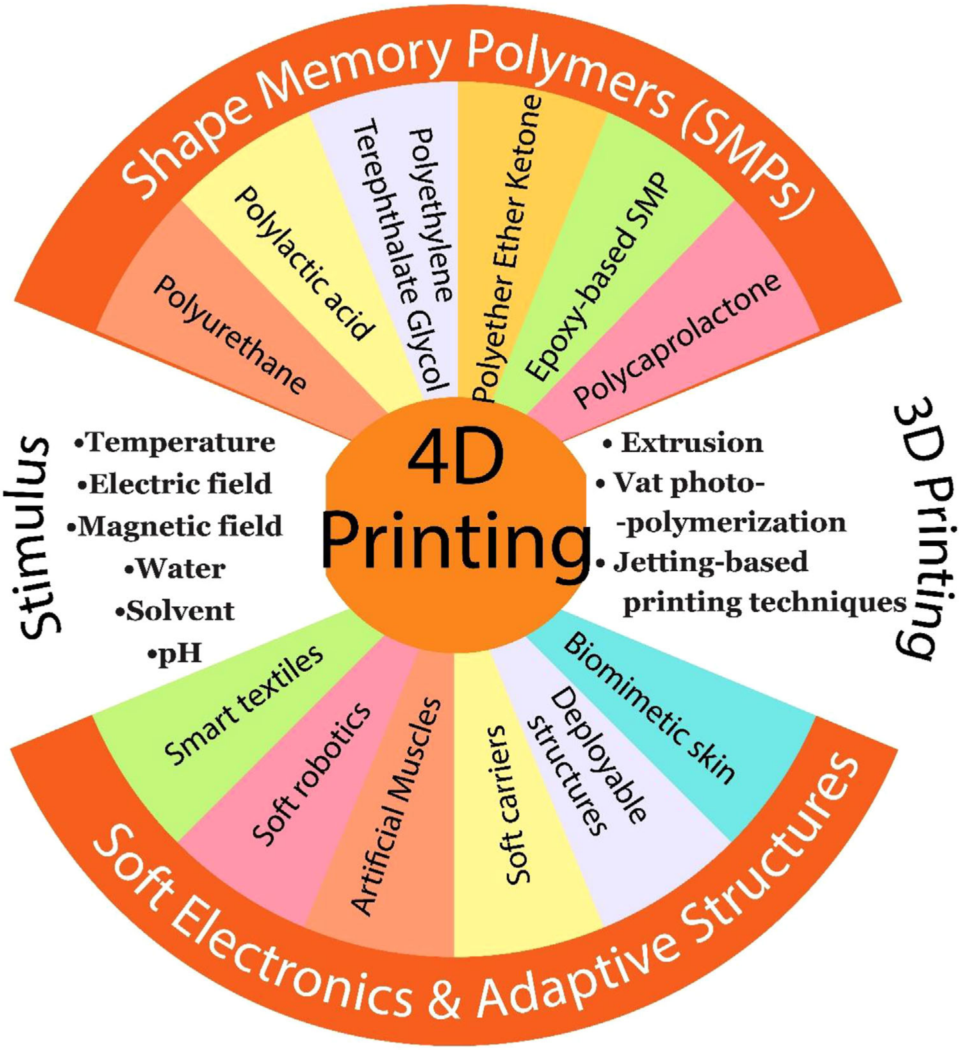


Figure 2. Overview of SMPs, actuation, and 3DP techniques for soft electronics devices and adaptive structures covered in this review.

adoption by responding to specific external stimuli, enabling functionality in the field of cutting-edge multifunctional electronics. Numerous researchers have recently conducted comprehensive reviews of stimuli-responsive systems and presented their up-to-date progress. However, these reviews usually focus on three main aspects: 1) the types of 3DP techniques suitable for smart materials, 2) the types of SMP-based soft materials adaptable to 3DP techniques, and 3) the emerging applications of these 3D-printed soft materials. In light of these dedicated review articles, as discussed in **Table 1**, we explore the 3DP of SMP with a complete focus on wearable and flexible electronics applications from the latest published studies. The primary objective of this review is to address the research question (RQ): Are 3DP-driven SMPs fully considered for practical soft wearable electronics applications? We believe that addressing this RQ through a comprehensive review will guide future developments in a wide range of applications in intelligent and smart wearable devices. To address this RQ, we first highlight the main types of 3DP techniques that are best suited for SMPs, as SMPs are prioritized over other materials in the field of soft electronics. Second, we discuss revolutionary smart functionalities in wearable electronics, such as self-healing and shape memory performance, in terms of their unique structures and application prospects. Moreover, we examine the dynamic reaction mechanisms responsible for these smart functionalities and how they evolve during 3DP to demonstrate satisfactory smart functionalities. The review methodology is also presented in **Figure 3** and its main headings are structured to evaluate the commercial viability of this field. Finally, we identify potential challenges that should be the focus of future research. Dedicated efforts are required to control the stimuli behavior responsible for the shape-shifting capabilities of smart structures. The valuable insights and recommendations provided in the last section will help future researchers fabricate novel structures from synergistic smart materials with improved resolution and accuracy at the commercial level.

2. Developing Advanced 3DP Processes

3DP or additive manufacturing (AM) has brought unlimited possibilities to various sectors, including engineering, medicine,

Table 1. State-of-the-art review papers in the field of 3DP of soft electronics (2023 onward).

Year	Title	Main highlights of reviews	Refs.
2025	Transformative 4D printed SMPs into soft electronics and adaptive structures: Innovations and practical insights	This review highlights multiple facets of large-scale 3DP in the realm of soft electronics and adaptive structures, exploring its potential applications, technological advancements, and the challenges faced in this innovative field.	Current review
2025	Current status and future outlook of 4DP of polymers and composites-A prospective	This review provides an in-depth overview of advancements in 4DP of soft polymers and their composites for broader engineering applications.	[62]
2024	Strategies toward large-scale 3DP without size constraints	This review focuses on large-scale 3DP in construction and also discusses various size constraints and strategies like multifunctional 3DP/4DP diverse materials, size-independent printers, and intelligent control.	[63]
2024	Manufacturing of 3D printed soft grippers: A review	This review covers the latest advancements related to 3D printed soft grippers with multifaceted challenges related to manufacturing costs and design processes for automation and robotics field.	[64]
2024	3DP of magneto-active smart materials for advanced actuators and soft robotics applications	This review provides firsthand information on magneto-active soft materials enriched with various multifunctionalities for only soft robotics applications.	[65]
2023	Propelling the widespread adoption of large-scale 3DP	This short perspective sheds light on the commercial adoption of large-scale 3DP technology.	[66]
2023	Electronic textiles: New age of wearable technology for healthcare and fitness solutions	This review focuses on advanced materials and synthesis strategies for soft sensors and devices integrated into textiles.	[67]
2023	3DP of polymer composites to fabricate wearable sensors: A comprehensive review	This review discusses multifunctional sensors with features such as multi-directionality, self-healing, multi-modality, self-powering, in situ printing, and ultrasonic imaging from the perspective of state-of-the-art advancements in 3D-printed wearable device	[68]
2023	The role of 3DP technologies in soft rippers	This review only focuses on the use of 3DP in soft grippers, made of nonfunctional and functional materials, materials for soft capacitive, piezoresistive, piezoelectric, and triboelectric sensors.	[69]
2023	Unleashing the potential of 3DP soft materials	This review explored 3DP of soft materials with a complete focus on soft functional structures for flexible electronics, soft robotics, and biomedical applications.	[70]

energy technology, food, and many more.[71–73] In AM processes, the product is fabricated from layer-by-layer prints to the final product from the computer-generated model.[74–76] Various prototypes with functional products and sophisticated geometry are easily fabricated directly by AM from digital data.[77–79] Thus, AM offers flexibility, accuracy, and customization for more complex and intriguing structures, which cannot achieved through traditional mass production processes.[80–82] Furthermore, integrating additive manufacturing technology with natural biodegradable materials, such as biopolymer inks, is a prominent research focus, especially in addressing pressing socio-economic and environmental challenges.[83,84] The literature shows that 3DP techniques can be utilized with the least amount of materials and energy following a circular economy approach for achieving various sustainable development goals.[85–87] Various AM technologies using biomaterials at both macro and micro levels provide many functional applications in the engineering, biomedical, and food industries.[88–90] There are various online tools and repositories that are extremely helpful for researchers in drawing, storing, and sharing 3DP designs. These resources (**Table 2**) simplify the operation and design of 3D printers, benefiting professionals such as clinicians, and engineers by reducing the need for specialized training and knowledge in 3DP.[91–93]

Since 3DP fabricates parts directly, layer by layer without the need for large formworks, molds (essential in casting), or subsequent subtractive or forming processes,[94–96] it has become a widely adopted technology worldwide. Its exceptional advantages include the ability to produce complex shapes with extreme accuracy and precision at a relatively low cost.[97] Moreover, interest in 3DP has been driven by 1) the high accuracy of 3DP systems can improve the automation level and reduce the reliance on manual labor, 2) the substantial degree of freedom that facilitates the creation of complex structures with desired features 3) unwanted minimization, 4) bulk customization, 5) ability to use naturally available material as a potential ink feedstock, and 6) minimal material utilization.[98–100]

3DP offers intricate designs that were previously impossible or economically unviable with traditional manufacturing processes.[101] 3DP is more sustainable than subtractive manufacturing, as it generates less waste by using materials only where needed, thus reducing excess scrap. Additionally, 3DP accelerates the innovation process due to the rapid turnaround time which facilitates faster product development and prototyping. Furthermore, 3DP has the ability to produce parts locally or on-site and optimizes the supply chain by lowering transportation and inventory costs, thereby enhancing the overall efficiency of the

Figure 3. Review methodology in the pursuit of 3DP for soft electronics devices and adaptive structures.

system.[102] The revolutionary 3DP technologies for SMP are truly fascinating and widen their applications.[103–105] Since the first report of the temperature phase transition property in stimuli-responsive, the temperature is so far the most widely used stimuli to date.[106–108] Magnetic and electro-stimuli-responsive polymers are the latest addition.[109] Now with time, many exciting stimuli such as redox potential, pH variations, enzyme activity, and ultrasound are being used for unleashing the true potential of stimuli-responsive polymers in real applications in controlled drug delivery.[110] Thus, with the fast growth of SMP, the demand for soft materials is anticipated to increase dramatically in the upcoming years.[111–113]

Material extrusion processes[114] comprise fused deposition modeling (FDM) (commercial trademarked term used by Stratasys, Inc.)[115] also referred to as fused filament fabrication (FFF) (open-source name)[116] and direct ink writing (DIW).[117] Notably, FDM or FFF offers controlled 3D structure composition and microstructure with versatility, making them the most affordable and widely used 3D printing methods. Materials are generally in filaments, which are melted and extruded through a hot nozzle.[118] In DIW, viscoelastic ink material is extruded through a deposition nozzle to fabricate a 3D structure; after some time, it solidifies and produces the desired structures. DIW is further classified into two main types: droplet and continuous ink extrusion. DIW, valued for its simplicity, low cost, and compatibility with various materials, including biomaterials, is widely utilized by universities and research organizations to create innovative structures with unique properties.[119]

Typically, the resolution of extrusion-based technologies is limited.[120] However, laser-assisted technologies provide sub-micrometer resolution using one photon in laser, referred to as vat photopolymerization (VPP) which includes stereolithography (SLA).[121] These laser-assisted techniques typically require photo-cured resin (polymerizable resin or photo-resist) for producing 3D structures under a laser source.[122] During light assisted digital light processing (DLP) method, a 3D object is fabricated layer-by-layer by exposing the solution to the light.[123] However, DLP requires specific light-sensitive materials and printing apparatus, ultimately increasing cost and material limitations.[124] Recently, two photon-based laser assisting technology referred to as two-photon polymerization (2PP) or direct laser writing (DLW) gained immense attention for the fabricating complex micro 3D structures in nanoscale with higher resolution, higher throughput rate, and promising patterning.[125] DLW involves two-photon excitation and later cross-linking of monomer/oligomer using typically epoxy-based and acrylic polymers under an intense pulsed laser beam without using any supporting structures.[126] One notable feature is the widespread use of 2PP for long-term fabrication when digital mirror devices

Table 2. Resources, databases, and useful tools for 3DP of soft materials (Reproduced with permission.[70] Copyright 2023 Elsevier Inc.).

Resources	Details	Important aspects	Applications
Sketchfab	3D models platform	Helpful for embedding interactive 3D content online with a sharing facility	Interactive 3D content, particularly suitable for VPP techniques
Thingiverse	3DP designs repository	Enables users to upload, share, and download 3D models	Offers a wide range of adaptable models, for ink jet printing (IJP)
MyMiniFactory	3D printable models platform	Renowned for excellent quality, curated, and tested models	Ideal for IJP designs that need low-viscosity applications
GrabCAD	An engineering and professional-focused database	Provides tools for managing 3DP projects with sharing design facility	Promising for all 3DP technologies, particularly beneficial for project management
Shapeways	3DP service	Give the facility to upload designs, select materials, and receive the finished product.	Best adapted for the VPP process with a variety of photocurable resins
NIH 3D Print Exchange	3D print files platform for the biomedical field	Designed as educational materials for researchers and medical 3DP, offering modeling tutorials	Suitable for DIW with high-viscosity models employed in academic and engineering-oriented designs
Autodesk Fusion 360 Gallery	Autodesk Fusion 360 users' gallery	Excellent for real engineering design models	Engineering-based designs, compatible with DIW for high-viscosity models
Tinkercad Gallery	Tinkercad users gallery	Useful in education for providing simple 3D models	Ideal for thermo-extrusion-based technologies having simple use
Cults3D	3D printable models marketplace	Useful for sharing or selling 3D printable models for designers	Suitable for simple, low-warping models for thermo-extrusion techniques
Yeggi	3D printable models (search engine)	Indexes different 3DP websites making the search process easier	Promising thermo-extrusion techniques
McMaster-Carr	An online catalog for mechanical, electrical, plumbing, and utility hardware	Provide many downloadable CAD models	CAD models are useful in all printing techniques

are used.[127] 2PP photoresists usually consume hybrid organic-inorganic materials, fused silica precursors, and biocompatible materials.[128] 2PP has attracted increasing attention in various applications such as microbots[129] and biosensing bioinspired structural colored metamaterials. There are various drawbacks associated with 2PP, such as lack of commercialization, low processing speed and volume, and low dynamic range because of the higher writing threshold.[130]

Table 3 provides a comprehensive overview of various printing techniques and their potential for nanomaterial integration. Advances in materials science have enabled the development of high-strength, 2D material-based long filaments, which are often combined with polymers or resins to produce durable, multifunctional 3D structures for diverse applications.[131–133] Additionally, there has been significant growth in 3D-printed electronics using stimuli-responsive polymers, enhancing the functionality of multifunctional devices.[134] **Figure 4** compares commonly used 3DP processes for soft materials. Notably, the unique behavior of soft materials particularly SMPs has driven extensive research into their application in wearable electronics, as illustrated in **Figure 5**. Furthermore, 3DP technology allows for the creation of highly porous, programmable structures tailored to specific user requirements.[135,136] Despite the progress in soft material printing,[137] a key limitation remains: most printed structures lack responsiveness to environmental stimuli, restricting their adaptability and utility.[138] To address this, dynamic manufacturing approaches such as 4D printing (4DP) discussed in the next section are expected to enable more efficient and customizable adaptive structures.

2.1. 4D Printing

4D printing (4DP) uses 3DP technology to create 3D structures capable of changing their shapes over the fourth dimension–"time" under various stimuli.[153]

$$4D = 3D + \text{stimt}(t) \quad (1)$$

where $\text{stimt}(t) = T(t), F(t), B(t), L_x(t), H(t), V(t)$..........,

T = temperature; B = magnetic field; F = Force; H = humidity; L_x = light; V = voltage.[154]

4DP is an advanced manufacturing technology also detailed in **Figure 6a–c** that employs smart materials that respond to specific stimuli, programmed design during printing, or a combination of both.[155–157] Three main types of multi-material structures such as gradient distribution, uniform distribution, and special patterns are typically used in 4DP under many external stimuli including water,[158] solvent,[159] heat,[160] magnetic field,[161] light,[162] electric stimulation,[163] pH,[164] etc., permitting programmable materials to change their either shape, function or property over time. 4DP is ingeniously integrated with more versatile printable inks to develop highly functional 3D-printed structures.[165] In 4DP, the shapes (or functions) of an object can be transformed in two ways, which is called two-way shape transformation: one-way 4DP and two-way 4DP, as detailed in Figure 6d. Based on the number of permanent and temporary shapes in a transformation of the 4DP process, they can be further divided into dual 4DP and multi 4DP. The 4D-printed structures, apart from complex shapes, have some unique and

Table 3. A comprehensive overview/comparison of various 3DP technologies.

Printing mechanism [Ref.]	3DP	Suitable materials		Multi-material ability	Built speed	Printing resolution		Manufacturing features	
		Molecules	Particles			xy [µm]	z [µm]	Strength	Weakness
Extrusion-based[139,140]	FDM/FFF	Thermoplastic polymers	Au, CB, CNF, CNT, Cu, Fe, Fe_2O_3, graphene, MWNT, MoS_2, SiC, SiO_2, SWNT	Fair	Fair	20-200	10-200	• Wide availability • Easy setup and simple operation • Efficient, low cost and environmentally friendly	• Low melting point plastic materials • Support always required • Inadequate surface finish
	DIW	Curable pseudoplastic polymer fluids	Ag, Au, Al_2O_3, CNF, CNC, CNT, GO, GnP, HA, MWNT, PANi, PEDOT:PSS, PPy, rGO, SiC, SiO_2, SNWT, Y_2O_3	Good	Fair	50-500	100-400	• The ability for multi material printing • Easily processing and low energy requirement	• Feature size is confined by material properties and nozzle diameter • Ink preparation is quite challenging • Low resolution
Jetting-based[141,142]	Direct inkjet	Low-viscosity polymer fluids	CB, CNT, graphene, SiN, SiO_2, TiO_2, ZnO_2, ZrO_2	Good	Good	10-150	10-50	Multi-material, multi-nozzle, compositional design	• High cost and short service life. • Printing depends on the viscosity of the ink
	EHD jet	Thermoplastic or soluble polymers	Ag, Au, CdSe, CdS, Co, CNT, Cu, G, HgTe, IZO, SWNT, TiO_2, ZnS	Fair	Good	0.03–50	1	High resolution	• Need controlled printing condition • High setup cost • Defects like coffee ring
	Binder jetting	Monomers and resins as binders	Polymer, ceramic and metallic powders	Poor	Outstanding	50	50-200	• Flexible printing • Powder forms can be employed	High defects and low-resolution
Vat-photopolymerization-based[143,144]	General SLA	Photopolymers with low viscosity	CB, CNT, graphene, graphene oxide, SWNT, MWNT	Good	Excellent	10-200	20-300	• Convenience in building large structures • Repeatable printing accuracy • High precision, good processing effect.	• Complex structure • Photopolymers are required • Slow printing process
	DLP	Photopolymers with low viscosity	Ceramics such as BN	Fair	Excellent	30-200	20-150	• High printing speed and patterning • Uncured photopolymer can be reused	• Brittle structure • Insecurity of the consumable material • Boxy surface finish due to its rectangular voxels. • Difficult to print large structure
	2PP[145]	-	-	Poor	Poor	>100		Support structure dependent on 3D geometry	Costly typically up to \$200000

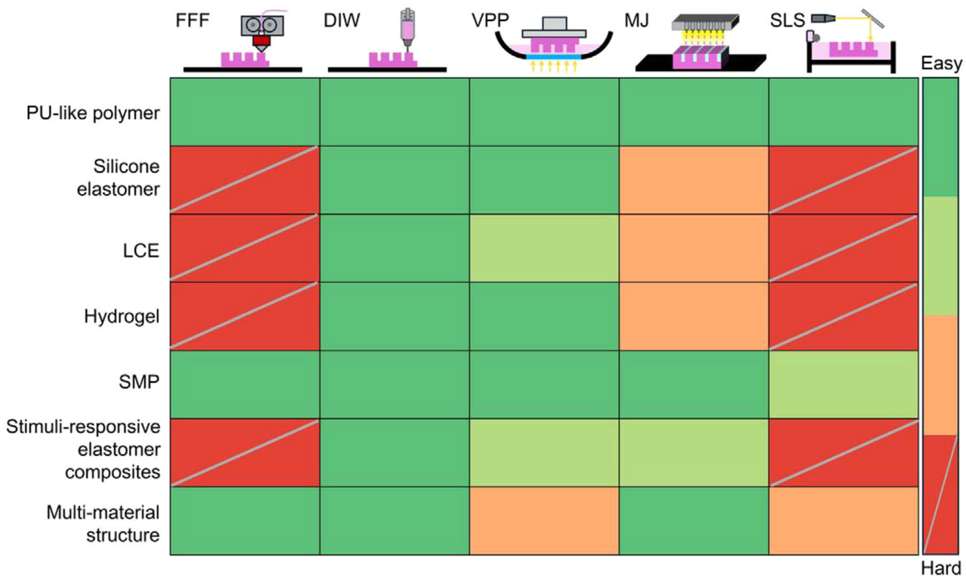


Figure 4. Capabilities of each 3DP process for various soft materials (Reproduced with permission.[146] Copyright 2024, The Author(s), Published by Wiley-VCH GmbH).

fascinating characteristics such as self-deformation, self-assembly, self-repair, and on-demand highly tailored structures.[166] Utilizing 4DP technology drives the boom in the manufacturing industries, such as aerospace,[167] robotics,[168] textile materials[169] electrically actuated structures,[170] medical devices,[171] tissue engineering,[172] and drug delivery carriers.[173]

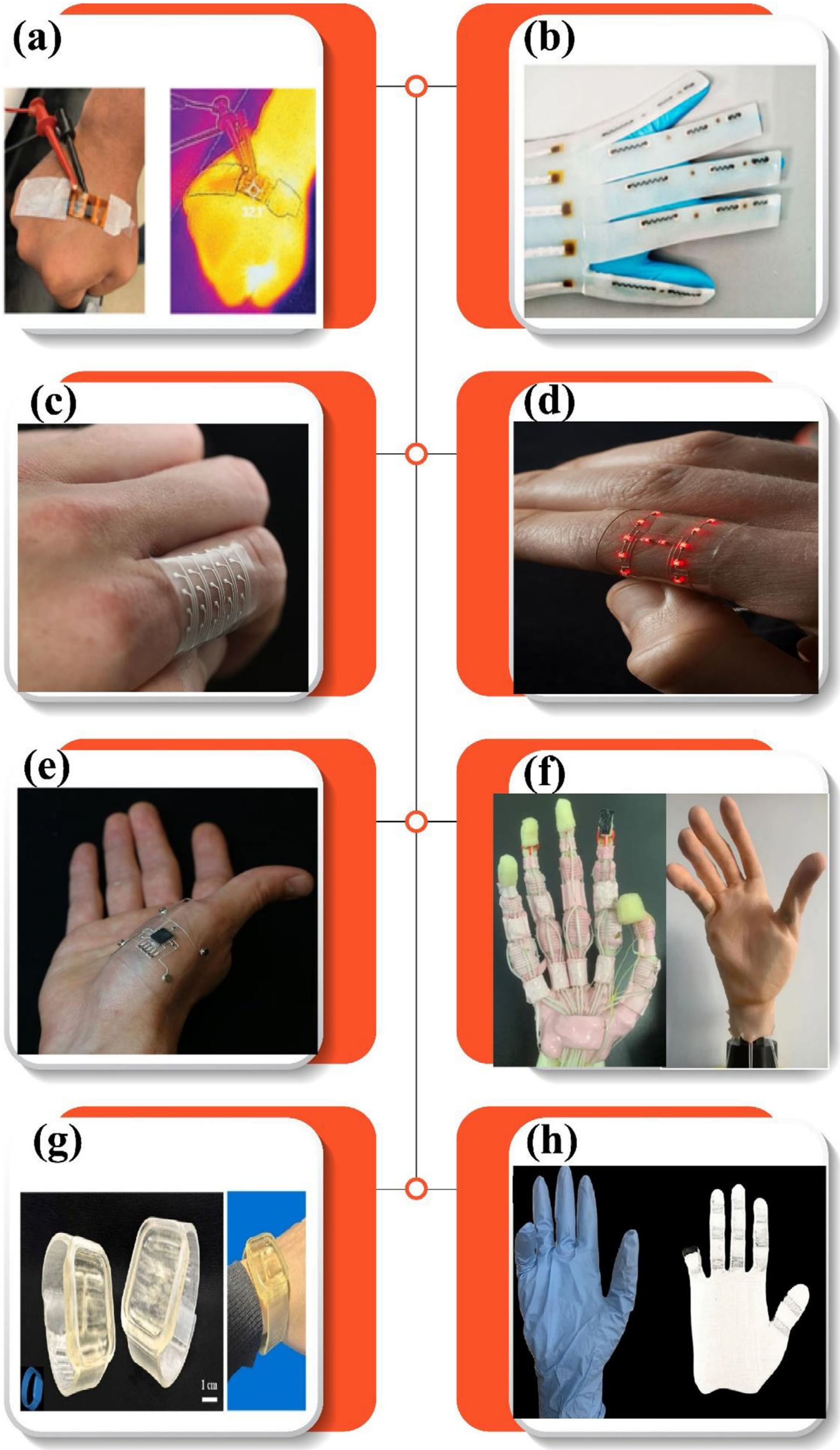
2.1.1. Types of SMPs in 4DP

4DP is trending and becoming one of the core technologies with the prospect of impact in various domains.[177] Printed parts through 4DP are no longer stationary; they have dynamic movements in their structures.[178–180] As a result of smart or intelligent materials,[181] shape-memory materials are typically polymers, ceramics,[182] metals,[183] alloys,[184] fiber reinforced composites[185] and more importantly, SMP[186] are highly promising materials for 4DP.[187,188] To date, various SMPs such as TPU,[189,190] poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS),[191] polyvinyl chloride (PVC),[192] acrylates,[193] polycaprolactone (PCL),[194] polynorbornene, polyethylene terephthalate,[195] cross-linked polyethylene,[196] polylactic acid (PLA),[197,198] and epoxy resin,[199,200] are used in low-temperature applications (<100 °C), such as wearable electronics and soft robotics. In contrast, SMPs for high-temperature applications (>100 °C) include polyamide (PA),[201] polyether ketone–ketone (PEKK),[202,203] and polyether ether ketone (PEEK).[204] These SMPs are typically used in structural applications, such as aerospace.[205] Apart from their satisfactory physiochemical properties, these SMP materials also have impressive shape memory and self-healing triggered under specific stimuli highlighting their indispensable role in both industry and academia.[206–208] Consequently, researchers have redirected their efforts toward developing novel chemistries and structural designs to modify tunable properties, enabling on-demand shape memory and self-healing capabilities for 3DP. This approach aims to enhance the reliability and durability of pre-printed complex structures.[209–211] Recently, Wang et al.[212] fabricated precisely controlled electrothermal origami using FDM-based 4DP for continuous carbon fiber-reinforced composites using Joule heating onto the hinges of the origami. This Joule heating was responsible for a highly controllable actuation process in electrothermal origami, which enabled them to achieve various reconfigured and locked features for different configuration demands by controlling various activation parameters. This highly versatile electrothermal origami with reconfigurable features is attractive for architected materials, and programmable wings. Bonetti et al.[22] introduced the reversible two-way shape-memory effect (SME) of methacrylated PCL-based smart structures from FDM-based 4DP. The 4D printed samples demonstrated significant shape-memory performance such as one-way and two-way under-stress behavior, with remarkable elongation-contraction response under heating/cooling cycles for crystallization and melting regions of PCL. This facile, and low-cost 4DP provides distinct features for shape-morphing structures for a wide range of applications in soft robotics, smart actuators, and medical devices.

The ability of SMP in 4DP to deform at higher temperatures beyond a certain threshold and upon cooling it "memorizes" a programmed shape which is retained until the material reverts to its original, pre-printed shape upon reheating.[213,214] This fascinating and controllable phenomenon triggers the development of complex structures for real-world application.

2.2. Multimaterials and Multisystem-Based 3DP

Multimaterials 3DP is a thriving research frontier for cost-effective, time-saving fabrication of flexible, miniaturized electronic devices.[215,216] This multilayer printing can be achieved


(a)
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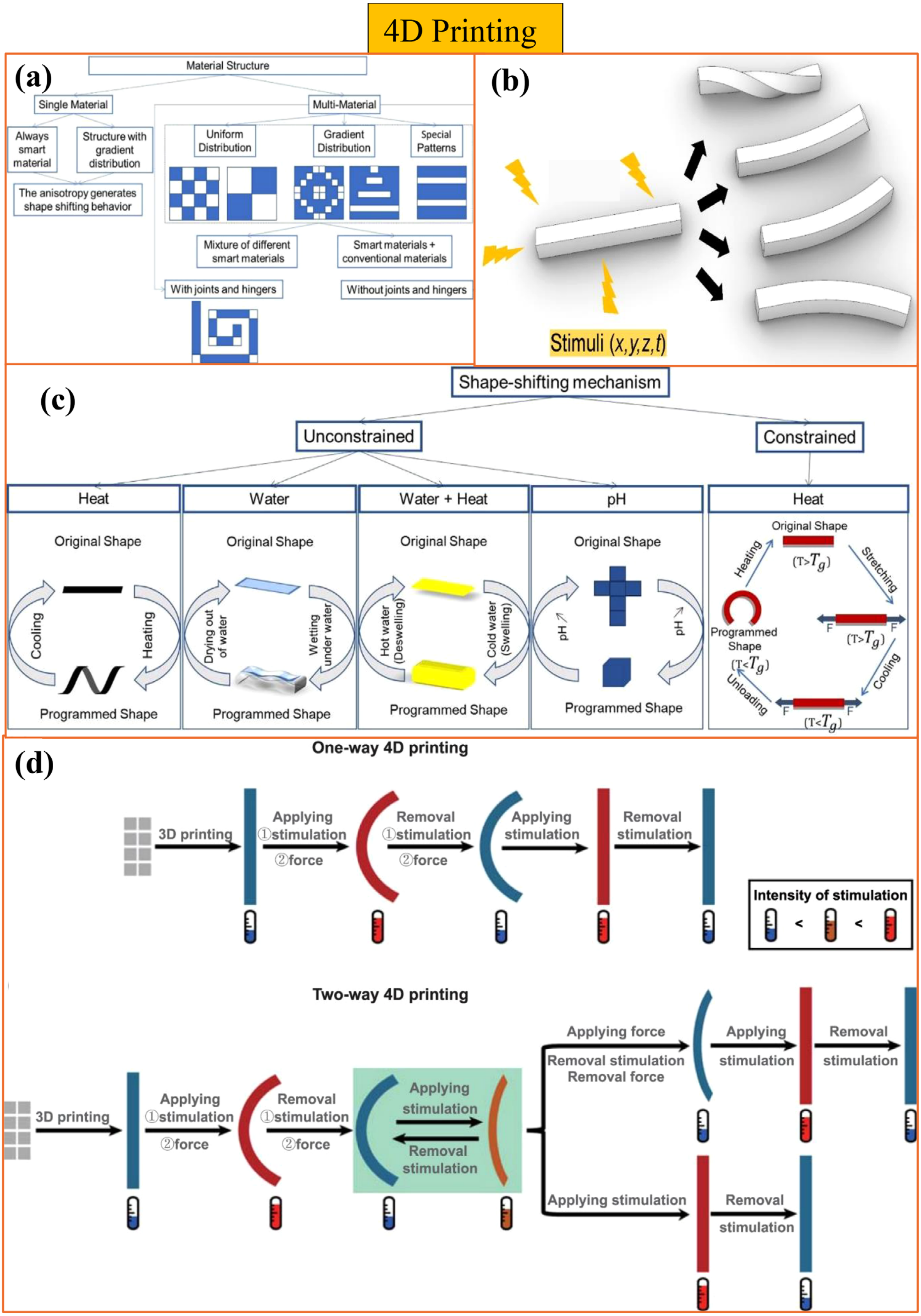
through the single 3DP technology to print multi-materials[217] or a combination of a variety of 3DP technologies (namely hybrid 3DP).[176,215] Particularly wearable technology can also benefit from multimaterial 3DP for pursuing their commercial applications.[218–220] Typically, wearable electronics or devices require at least two individual constituent materials, such as flexible materials, and conductive or functional materials.[221] In this regard, multi-material 3DP enables a sequential printing of hybrid materials, allowing the seamless integration of a multifunctional wearable device. The integration of the Microdrop dispenser head with the Autodrop Platform positioning system has recently enhanced precision in automated printing, improving affordability and efficiency for flexible devices utilizing diverse materials. Moreover, the Microdrop Inkjet printer surpasses conventional Inkjet machines with multiple dispenser heads, faster speed, larger nozzle diameter, and higher resolution. It can print a wide range of materials with larger particle sizes, reducing nozzle clogging issues. These advantages allow researchers to fabricate sophisticated structures with desired patterns efficiently.[222] Recently, Pasini et al.[223] explored the two-way SME of biocompatible thermoplastic polyurethane (TPU) with crystallizable soft segments by integrating electrospinning and melt electrowriting (MEW). Their approach utilized heating and cooling cycles to induce crystallization-driven elongation and melt-induced contraction. Electrospinning on a drum collector rotating the SMP at high speed integrates pre-stretching of the SMP directly in its manufacturing phase, on the other hand, 3DP of the elastomer component by MEW produced an easy modulation of its structure. This novel combined approach was highly effective for smart 4D objects demonstrating a remarkable two-way SME with reversible and repeatable actuation performance as presented in **Figure 7a**. Likewise, Song et al.[224] developed a unique strategy using Pd^{2+}-doped SMP for electroless plating, enabling selective metal-polymer interfaces via multi-material 3DP for 4D actuators as shown in Figure 7b. The proposed multi-layered smart structure features a nano-micro composite structure at interface with a pure polymer base, a metal-embedded intermediate layer, and a top metal layer, combining shape memory and metallic properties for electroactivity and electro-thermal control. This approach enhances 4D actuator programmability, enabling applications in smart robotics and electronics through electro-controlled deformation and densification.

Tandon et al.[225] studied multifunctional properties (shape memory and self-healing) for two different scales of fibers derived from the same PCL/TPU from FDM and MEW-based 4DP at two different scales. This shape memory polymer blend is comprised of PCL (30% by wt.)/TPU (70% by wt.). The FDM and MEW printed PCL/TPU fibers demonstrated remarkable shape memory properties as presented in Figure 7c such as shape recovery ratio (85%) and shape fixity ratio (95%), self-healing performance (The damaged samples heated at a temperature of 90 °C for 20 and 10 min for FDM and MEW respectively which induced healing of the fibers). Moreover, the small size of MEW fibers exhibited a quick recovery rate of 0.047 MPa min^{-1} (almost 1.5 times greater than FDM fibers). In summary, the developed intriguing bulk 4D printed structures can be employed as stents for coronary or vascular applications, due to their multiscale hierarchical nature using fibers at different scales.

Significant advances in 3DP continuously explore the integration of multiple printing systems to produce multifunctional SMP and their composites. Chen et al.[226] combined multi-jet fusion (MJF) and DIW-based 3DP techniques for creating multifunctional LCE-SMP composites. The proposed hybrid 3DP techniques, such as DIW, enable the printing of LCE with programmable mesogen alignment onto rapidly MJF-printed SMPs with tuneable electric conductivity distribution. Insights from this study show that LCE-SMP composites demonstrate stable temporary configurations under continuous reversible light stimulus. For instance, when near-infrared (NIR) was used to irradiate the sheet, it changed from its programmed temporary shape (State I) to an actuated shape (State II) dependent on mesogen alignment and then returned to its original flat shape (State III). NIR irradiation and removal repeatedly cause reversible shape changes between States II and II. Moreover, developed LCE-SMP composites facilitated bio-inspired dynamic structure evolution with high output power and enabled remote, on-demand object manipulation in soft intelligent device applications. Likewise, Liang et al.[227] designed 3D printed composite material containing LM dispersed droplets and a TPU matrix. Blended ink is prepared by adding LM to 10×50 wt% TPU and ultrasonically blending at 190 × 200 °C. In a Wellzoom desktop extruder at 190 °C and 400 mm/min, the composite fiber of LM-TPU was prepared by solid cooling. The final LM-TPU fiber was 3D printed at 240 °C for fabricating 2D and 3D flexible electronic devices with heating and conductive capabilities. Huang et al.[228] proposed a unique photocuring 4DP technique of gradient structures using multi-walled carbon nanotubes (MWCNTs) incorporated into the intermediate layer (fast layer (FL)) of multilayer SMPs for lowering the curing degree and absorbing overexposure. Insights of this study showed that shape memory performance of multilayer SMPs tuned by adjusting the layer ratio of FL with low curing degree for demonstrating sequential recovery and multiple

Figure 5. Selected examples of multifunctional 3D-printed wearable electronics including a) 3D-printed electronic skin act as a flexible temperature sensor, enabling real-time monitoring of body temperature as a flexible thermometer (Reproduced with permission.[147] under a Creative Commons Attribution license 4.0); b) Direct wire writing of silver wire on polyimide substrate for wearable strain sensors (Reproduced with permission[148] under a Creative Commons Attribution license 4.0); c-e) Various novel designs from a complete hybrid 3D-printed device flexes and conforms to the body shape made from the stretchable conductive ink is made of thermoplastic polyurethane (TPU), a flexible plastic that is mixed with silver flakes. Both pure TPU and silver-TPU inks are printed to create the devices' underlying soft substrate and conductive electrodes, respectively ((c-d) Reproduced with permission[149] Copyright 2017, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim), ((e) Picure Credit:Harvard Wyss Institute); f) The distal index finger bone with the 3D printed flexible, conformal and multi-directional sensor is assembled back to the robotic hand having integrated biomimetic and auxetic structure and next image shows this robotic hand covered in the artificial skin (Reproduced with permission[150] under a Creative Commons Attribution license 4.0); g) Image of 3D wearable polyurethane acrylate (PUA) band applied to a practical smartwatch (Reproduced with permission[151] Copyright 2024, Elsevier B.V.); (h) Representation of 3D-printed PLA/Polyvinylidene fluoride (PVDF)-based origami robotic hand with PLA/MWCNTs joints using 0.14 Carbon A electric current (Reproduced with permission.[152] Copyright 2025, The Authors, Published by Elsevier B.V).


4D Printing
(a)
Material Structure
Single Material
Multi-Material
Always smart material
Structure with gradient distribution
The anisotropy generates shape shifting behavior
Uniform Distribution
Gradient Distribution
Special Patterns
Mixture of different smart materials
Smart materials + conventional materials
With joints and hingers
Without joints and hingers
(b)
Stimuli (x,y,z,t)
(c)
Shape-shifting mechanism
Unconstrained
Constrained
Heat
Water
Water + Heat
pH
Heat
Original Shape
Cooling
Heating
Programmed Shape
Drying out of water
Wetting under water
Hot water (Deswelling)
Cold water (Swelling)
pH ↗
Original Shape
(T>Tg)
Heating
Stretching
Programmed Shape
(T<Tg)
Unloading
Cooling
(d)
One-way 4D printing
3D printing
Applying ①stimulation ②force
Removal ①stimulation ②force
Applying stimulation
Removal stimulation
Intensity of stimulation
Two-way 4D printing
Applying stimulation
Removal stimulation
Applying force
Removal stimulation Removal force
Applying stimulation

deformation behavior under electric actuation for potential application in time-delay devices, soft robotics, and flexible electronics.

3. Enhancing Precision and Effectiveness in 3DP at Large Scale

High printing resolution with reduced printing time is considered as main driving force for realizing practical applications of 3D-printed larger parts.[230,231] Recently, 100 cm^2-scale build area prints have been achieved which still needs to be pushed further to full m^2-scale build areas. A highly precise print significantly enhances the dimensional accuracy of 3D printed structures, reducing the need for post-processing.[232,233] Moreover, a highly precise 3D structure remarkably improves microstructure, minimizes stress concentrations, and optimizes reinforcement orientation, thereby strengthening various mechanical properties such as tensile, shear, and compressive strength.[234] The precision in 3DP also ensures the desired amount of material without generating any waste substantially making 3DP more energy efficient, for the creation of complex geometries even at large parts of commercial satellites.[235]

High-precision multilayer printing technologies are a pioneering approach for building interfacial layers. Stabilized functional interfacial layers with 3D architectures are crucial for efficient ion and electron transport pathways, which are critical for wearable electronics.[236] This can be achieved by combining medical imaging with various high-speed, high-resolution lithography-based printing techniques, such as DLP and volumetric additive manufacturing. These advancements will profoundly shape the future of the personalized biomedical field, as summarized in Figure 7d. Specifically, for spatially controlled cell patterning and materials, 3D-printed SMPs such as hydrogels can perform various functions, including minimal swelling and strengths similar to native organs. This enables on-demand, in situ, or in vivo, bioprinting of cells based on real-time medical images for personalized tissue regeneration applications.[229] Recently, Alam et al.[237] reported the DLP-based 3DP of SMP-based smart structures using a combination of liquid crystal in photocurable resin with 3D-print thermoresponsive structures. The structures were printed with different geometries, and the shape-memory response was measured. Various complex and highly precise objects such as lattice patches, foldable toys, smart packaging, and mechanical wrenches were successfully created and can be programmed to change their shape over time and then recovered to their original shape under heat stimulus as presented in **Figure** 8(a_1,a_2). Cheng et al.[238] combined biobased cellulosic materials and bioinspired 4DP for adaptive shading in building facades to lower carbon emissions and energy consumption. Furthermore, a 4D-printed hygromorphic bilayer has been investigated for its motion response to temperature and humidity. Self-shaping shading elements derived from this material will undergo year-long testing to evaluate their responsiveness, and the 4DP process will be scaled up for potential facade applications in building systems. As a resource-efficient and energy-autonomous solution for climate regulation and mitigation, hygromorphic bilayers can be used for weather-responsive facades at large scale.

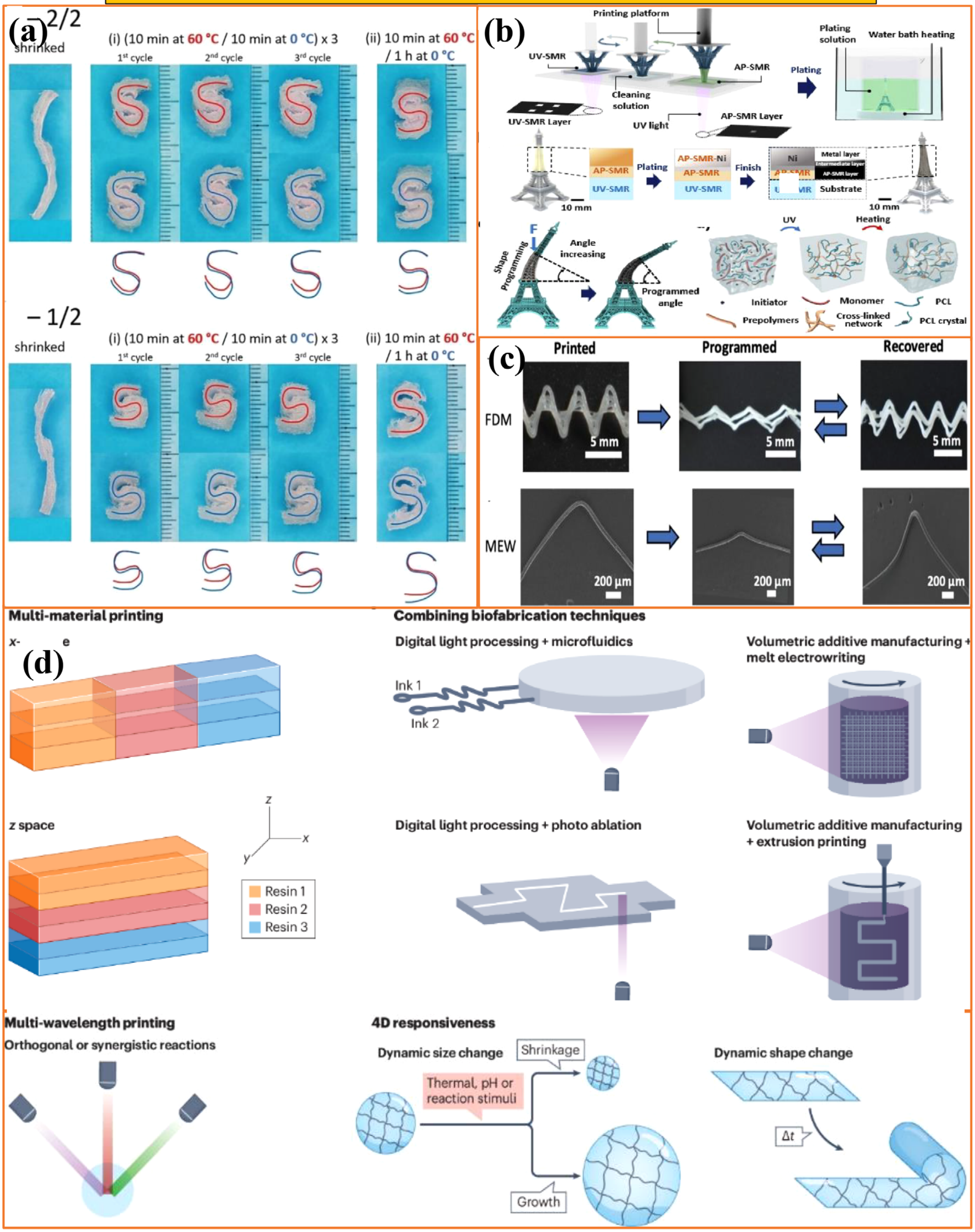
Another novel work by Li et al.[239] demonstrated a simple method to achieve excellent printability for DLP-enabled high-resolution 3DP, creating highly complex yet mechanically robust structures from covalent adaptable networks-SMPs. These structures exhibited remarkable weldability, allowing separate parts to merge into one piece after heat treatment. Applications include reconfigurable shape memory hinges with integrated microchannels for Joule heating and shape memory lattice structures utilized to create robotic grippers. Additional examples include a shape-programmable high-heel shoe constructed from assembled components and shape memory origami structures that can transform into various 3D configurations, as shown in Figure 8(b_1, b_2). Besides, these structures have a high glass transition temperature (T_g) (75 °C), a high room temperature modulus of 1.06 GPa, and excellent deformability at both programming and reconfiguration temperatures, exceeding 1400%.

3.1. Grayscale DLP Technology

Grayscale photopolymerization 3DP outperforms traditional VPP techniques for creating complex structures with gradient properties. The grayscale VPP method allows fine control of curing depth during the layer-curing process, allowing the fabrication of smooth surface structures.[240] Particularly grayscale DLP is a promising strategy in 3DP for pursuing high precision for complex geometry of structures and is based on a simple mechanism. It controls the local degree of monomer conversion through light intensity, manipulated at the pixel level by a grayscale image. This modulation affects the gel conversion rate and the material's physical and chemical properties by varying the crosslinking density.[241] Grayscale mask-assisted 3DP is fast and scalable, and offers high-resolution gradient structures.[242,243] Recently, Lu et al.[244] employed a grayscale printing method by using orthogonal photochemistry. In proposed 3D/4D photoprinting, the free radical initiator is activated by long wavelength light (405 nm). A shorter wavelength of light (365 nm) triggers the photoacid generator to activate acid-sensitive dye as shown in **Figure** 9a. Moreover, complex color patterns can be achieved on 3D prints using a basic DLP printer, with the potential for 4DP to add colors on dynamic surfaces. This simplified approach produces highly intricate, customizable colored objects. Likewise, Shan et al.[245] investigated the effects of the direction, grayscale, and structure pattern on the recovery and fixed ratios of SMPs. The SMP was prepared by combining polyurethane acrylate, PA-12, isopropyl benzoyloxyacetate (IBOA), and photoinitiator-819 in a specific ratio as shown in Figure $9b_1$. The insights of this study showed that the grayscale had almost no effect on the recovery ratio, indicating that the material's shape memory properties remain independent of the variations in color intensity. Furthermore, various printed structures

Figure 6. a) 4DP for smart material structures, (Reproduced with permission[174] Copyright 2023, Elsevier B.V.), b) Illustration of various shape-changing phenomena driven by 4DP under potential stimuli (Reproduced with permission.[175] Copyright 2024, The Authors, Published by MDPI); c) Representation of the shape-shifting mechanisms in 4DP (Reproduced with permission.[174] Copyright 2023, Elsevier B.V.); d) Demonstration of the most common 4DP such as one-way 4DP and two-way 4DP (Reproduced with permission.[176] Copyright 2024, The Author(s). Published by IOP Publishing Ltd).

Multi material and multisystem-based soft structures



exhibited shape memory performance as shown in **Figure** $9b_2$ where the ring structure demonstrated the highest recovery efficiency among all the structures.

4. Imparting Functionalities in 3D-Printed Structures

In this section, some noteworthy characteristics of 3D-printed smart materials are summarized.

4.1. Self-Healing Behavior

The self-healing properties of stimuli-responsive polymers are highly beneficial, enabling them to repair mechanical damage and restore functionality, thereby extending the durability and service life of these materials. Self-healing become a hotspot for many intriguing applications such as tissue engineering, wearable electronics, and soft robotics. Self-healing performance can be initiated under various environmental conditions such as light, temperature pH, catalysts and solvents, and magnetic field.[246] Self-healing behavior, widely studied globally, is primarily achieved through intrinsic mechanisms such as dynamic chemical bonds or physical molecular rearrangements, enabling autonomous repair based on the extent of the damage. The second is utilizing various releasing healing agents such as thermoplastic additives and reactive monomers. These dynamic bonds either covalent or non-covalent (referring to **Figure 10**a,b) are special chemical bonds with the ability to be broken and reformed under a potential stimulant environment.[247] The incorporation of dynamic bonds into polymer architectures enables self-repairing behavior by facilitating bond breakage and reformation. This allows the polymeric materials to reorganize their networks through reversible bond exchange processes under external stimuli, thereby modifying their macroscopic shapes and mechanical properties.[248] It is worth noting that adding dynamic covalent bonds into further 4DP paves the smart ways for the fabrication of next-generation materials with functionalities in terms of, self-healing ability, reshaping ability, recyclability, and mitigating multiple materials issues.[249]

Smart materials having impressive physiochemical characteristics for demonstrating excellent flexibility and self-repairability in the case of damage (self-healing behavior) have garnered significant attention. In this regard, SMP-based self-healing materials are very much up for stretchable devices due to their tremendous extensibility, compliance, and self-restorability.[251] Recently, Li et.al.[252] synthesized self-healing polyurethane (PU) which was made from two segments; a hard segment made from 4,4′-methylenebis (phenyl isocyanate) and PCL diol as the soft segment. These two segments are linked through 2,4-pentanedione dioxime as a chain extender. The self-healing PU -3 parts were printed using FFF and then were assembled into complex structures using the self-healing properties of the material as explained in **Figure 11**a. In addition, the self-healing PU-3 showed excellent mechanical properties with a tensile stress of 8.5 MPa and a fracture toughness of 20.1 MJ/m^3. The self-healing PU-3 material exhibited a self-heal efficiency of 92.9% at room temperature (25 °C) with a duration of 8 h.

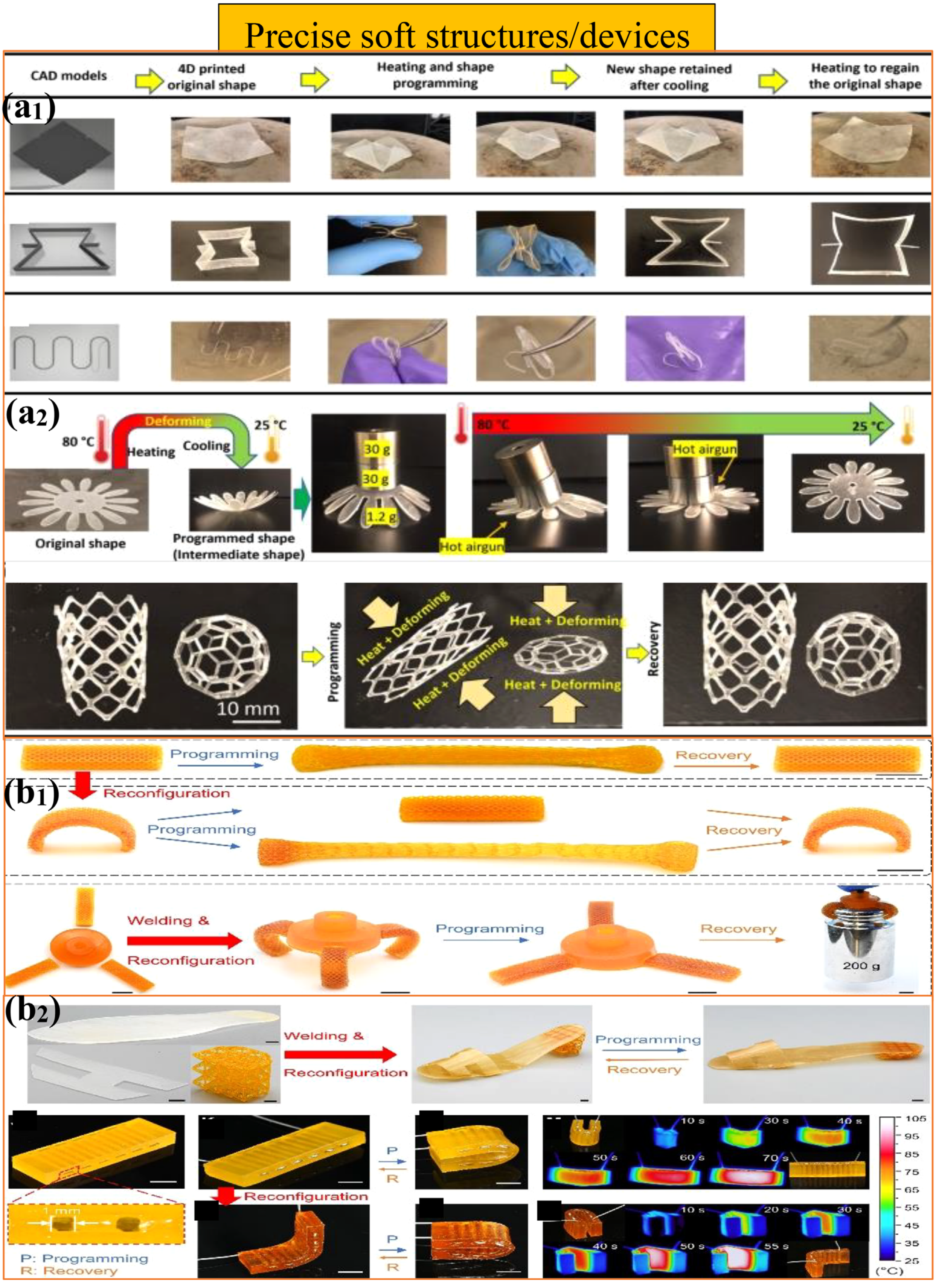
Currently, SMPs are grooming their role to perform a well-defined and complex shape morphing with the tunable self-healing ability for many soft electronics exciting applications.[253–255] Recently, Wu et al.[256] designed a flexible self-healing pressure sensor using interpenetrating polymer network polyurethane acrylate (IPNPUA), the pressure sensor relied on a dielectric layer of the INPUA with a checkerboard pattern and was prepared through DLP-based 3DP. The INPUA elastomer showed maximum tensile strength of 17.8 MPa and fracture toughness of 64.5 MJ/m^3. The INPUA elastomer was able to recover up to 60% of the original tensile stress after a healing process of 12 h at 60 °C. The self-healing property of the INPUA elastomer was due to the synergistic effect of multiple hydrogen bonds and dynamic oxime-carbamate bonds as demonstrated in Figure 11b. The 3D-printed pressure sensor was able to attain a pressure range of up to 700 kPa and a remarkable sensitivity of 0.125 kPa^{-1}.

Ma et al.[257] proposed a novel multi-stimuli responsive material based on a modularization scheme using shape memory epoxy resin/Fe_3O_4@graphene oxide (GO), and self-healing microcapsules from DIW-based 3DP technique. The developed smart materials exhibited self-healing efficiency (91.2%), tensile strength (17.2 MPa), and fast magnetic-stimuli responsive (15 s) as presented in Figure $11c_1$. Moreover, the recovery rate of fractured samples after three times fracture repairs reached 82.0%, indicating strong self-healing performance at room temperature. This study highlights that proposed smart materials can be exploited for a wide range of applications such as temperature sensors, space-deformable structures, and soft grippers (referring to Figure $11c_2$).

4.2. Shape Memory Behavior

As early as 1980, the notion of smart materials was put forward and since then it has penetrated their applications in a plethora of

Figure 7. a) Two-way SME of S-shaped specimens: images of a) 2/2 and b) 1/2 specimens after shrinking at Troom and during various thermal cycles (Reproduced with permission.[223] under a Creative Commons Attribution license 4.0); b) Schematic demonstartion of the 3D selective construction of the TSMP/M heterointerface and 4D electronics using multi-material 3DP, figure illustarting The multimaterial-DLP3 DP process enables the creation of complex UV-SMP composite structures, allowing selective metal deposition via lectroless plating to form 3D thermoplastic SMP/metal heterointerfaces, Macro-scale construction of thermoplastic SMP/metal heterointerfaces on functional substrates for programming 4D electronic shape memory structures, Upon UV exposure, PCL embeds in a cross-linked network, enabling shape memory effects via PCL crystal-to-amorphous phase transitions when heated (Reproduced with permission.[224] Copyright 2025, Elsevier B.V.); c) Schematic and scanning electron microscope (SEM) images demonstrating shape memory response for sinusoidal prints of PCL/TPU shape memory filament (Reproduced with permission.[225] under a Creative Commons Attribution license 4.0); d) Multi-material VPP can occur in the x–y and z directions, lithography-based printing can be combined with methods like microfluidics, extrusion printing, melt-electrowriting, and multi-photon laser ablation, VPP can use multiple wavelengths of light and 4D-printed hydrogels can dynamically change size or shape over time in response to external triggers (Reproduced with permission.[229] Copyright 2024, Springer Nature Limited).


Precise soft structures/devices
CAD models
4D printed original shape
Heating and shape programming
New shape retained after cooling
Heating to regain the original shape
(a1)
(a2)
80 °C
Deforming
Heating
Cooling
25 °C
Original shape
Programmed shape (Intermediate shape)
30 g
30 g
1.2 g
Hot airgun
80 °C
25 °C
Hot airgun
10 mm
Programming
Heat + Deforming
Heat + Deforming
Heat + Deforming
Heat + Deforming
Recovery
Programming
Recovery
(b1)
Reconfiguration
Programming
Recovery
Welding &
Reconfiguration
Programming
Recovery
200 g
(b2)
Welding &
Reconfiguration
Programming
Recovery
P
R
1 mm
Reconfiguration
P: Programming
R: Recovery
10 s
30 s
40 s
50 s
60 s
70 s
10 s
20 s
30 s
40 s
50 s
55 s
105
95
85
75
65
55
45
35
25
(°C)

fields such as biomedicine, AI-based flexible electronics, robotics, aerospace, and smart manufacturing. Shape memory materials are a broad class of materials that includes shape memory alloys, LCE, SMP, and SMP composites.[258] SMPs have emerged as leading smart materials due to their unique features, as outlined below and summarized in **Figure 12**.

4.2.1. Insights into SMP for Exhibiting Potential Shape Memory Behavior

SMPs exhibit their unique SME through the interplay of two distinct phases with different mechanical and physical properties: a ductile phase that facilitates deformation and transition, and a more rigid phase responsible for restoring the material to its original shape. These phases often referred to as "switching domains" interact physically and chemically, enabling a programmable shape memory process. The ductile phase becomes flexible under specific stimuli to allow temporary shape change, while the rigid segments, typically associated with higher transition temperatures, guide the material back to its permanent form. SMPs undergo thermal transitions, primarily the Tg and the melting temperature (Tm), where Tg is linked to molecular mobility in the amorphous phase and Tm to semicrystalline thermoplastics.[259] These transitions span a broad temperature range and are critical to SMP functionality. During cooling, the deformable phase solidifies, fixing the temporary shape by restricting polymer chain movement.[260] Upon reheating, chain mobility is restored, enabling shape recovery. Low-temperature treatment helps set the temporary form while heating above the transition temperature activates shape restoration.[261] Notably, higher transition temperatures can lead to improved elasticity and greater deformation, as the material's permanent shape is more effectively retained. Disabling chain movement at the molecular level allows for immediate fixation of the original shape, ensuring stability until external activation. The performance of shape-morphing devices based on SMPs depends not only on the material's intrinsic properties but also on actuation methods, design architecture, and control systems. Wang and Chortos[262] identified nine key performance metrics for evaluating such devices: actuation rate, load-to-weight ratio, maximum deformation curvature, shape variability, surface complexity, fabrication speed, actuation decoupling, number of actuators, and degree of under-actuation. These metrics provide a comprehensive framework for assessing and optimizing the efficiency and functionality of SMP-based adaptive systems.

SMPs have the ability to transform between various predefined shapes triggered by external stimuli[263–265] as discussed in **Table 4**. The phase transition approach or the viscoelastic approach are the main approaches currently used for SMPs for analyzing and modeling behavior.[266,267] Tremendous research has been done in broadening and optimizing the transforming functions of SMP to limit them with bare dual shape-memory transitions.[268] So far, thermoresponsive 3D/4D printed SMPs are enormously used for many applications.[269,270] Recently, Alsaadi et al.[271] investigated the shape memory (recovery/fixity) and fracture toughness of a UV-DLP 3D-printed epoxy resin, both before and after hydrothermal aging. Using dynamic mechanical thermal analysis, they characterized the shape-memory behavior through glass transition dynamics and demonstrated sequential deployment in flat and circular structures as shown in **Figure 13a**. This work enables the development of reconfigurable (one-way), high-deformation SMP structures capable of repeated reshaping under large strains, suitable for durable application. In another work by McLellan et al.[272] designed novel SMP composites using TPU:PLA polymer blend system embedded with MXene (Ti_3C_2) flakes through FDM-based 3DP. The results showed that MXene at various loading 0.5 wt.%. Around 2 wt.% demonstrates an impressive SME (referring to Figure 13b) such as fast recovery (≈98%) to its original position in under 14s. This large deformation is attractive for deployable structure applications.

The 4DP creates 3D structures indirectly from 2D configurations allowing them to fold, curl, unfold, or bend autonomously under stimulant conditions.[273] SMPs are categorized based on how responsive they are to external stimuli. For instance, one-way SMPs revert to their permanent shape upon activation and maintain this configuration after stimulus removal. This property makes them particularly suitable for single-use applications such as controlled drug delivery systems. In contrast, two-way SMPs exhibit reversible shape-switching between two states during heating and cooling, a property leveraged in dynamic applications such as artificial muscles, smart textiles, and actuators, driven by temperature-dependent molecular chain realignment.[274] Beyond these, three-way and multiple SMPs can memorize several temporary shapes by functioning as copolymers of one-way SMPs with varying transition temperatures, enabling sequential transformations classified as dual, triple, or multi-shape memory effects. The underlying mechanisms whether irreversible one way or reversible two way depend on the polymer structure. Advances in SMPs with superior mechanical and shape-memory performance hold significant potential for future innovations, particularly in fields requiring programmable, multi-stage actuation and adaptive materials. Recently, Mohan et al.[275] investigated the 4DP behavior of cellulose with graphene nanoplatelets (GNP). To improve the cellulose bio ink shear-thinning behavior and to promote smooth extrusion, partial dissolution of cellulose was done. The results demonstrated that 4D-printed GNP/cellulose demonstrated excellent shape-changing behavior and mechanical properties. The shape-changing behavior of cellulose/GNP was observed as a result of folding into a cube and transferring into a flat surface upon dehydration and hydration stimulus respectively. Wang et al.[276] developed various biomass furan-based complicated structures from poly (trimethylene furanoate) (PTF), polyesters poly (ethylene furanoate) (PEF),

Figure 8. a_1-a_2) Demonstration of Shape memory performance of various objects such as foldable box, smart packaging morphing, 3D-printed fiber with a high load-bearing capacity of the programmed flower-shaped 3D-printed structure and the adaptability of the proposed printing method for 2D and 3D structures (Reproduced with permission.[237] Copyright 2023, The Author(s), Published by Springer Nature); b_1-b_2) Demonstration of a shape-changeable high-heel shoe using SMP's reconfigurability and weldability, printed flat SMP hinge with microchannels, flat hinge assembled with resistance wire, folded temporary shape of the flat hinge and infrared images, right-angle hinge reconfigured from a flat hinge, the folded temporary shape of the right-angle hinge and infrared images all images under 5 mm scale bar(Reproduced with permission.[239] under a Creative Commons Attribution license 4.0).

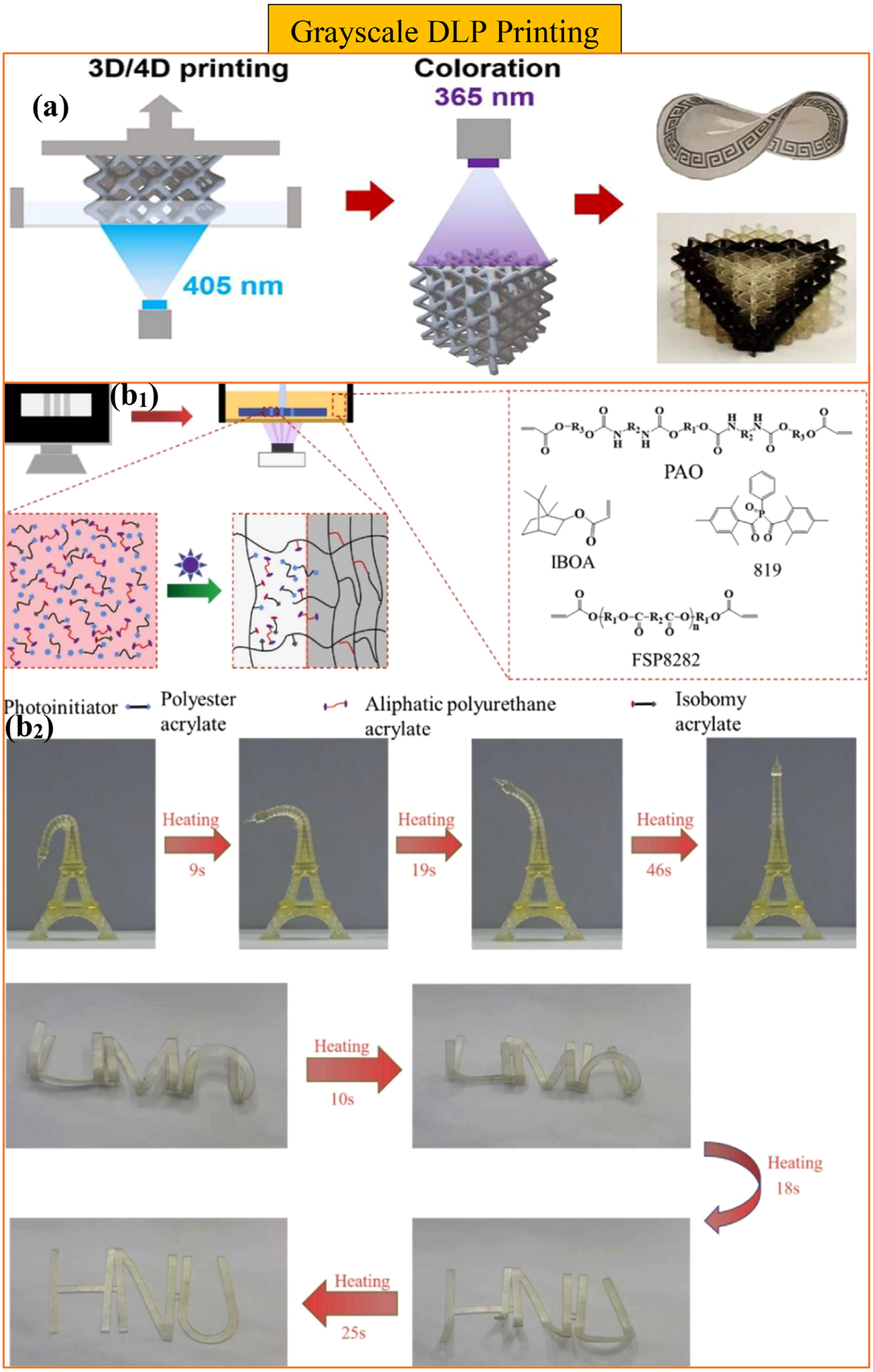


Figure 9. a) Demonstration of the grayscale fabrication process including the principle of coloration for producing complex multilayer structures having shape memory properties (Reproduced with permission.[244] under a Creative Commons Attribution license 4.0); b_1-b_2) Schematic illustration of the SMPs using liquid crystal display 3D printing technique for Eiffel tower and Text "HNU" 3D printed structures (Reproduced with permission.[245] Copyright 2024, Elsevier Ltd.).

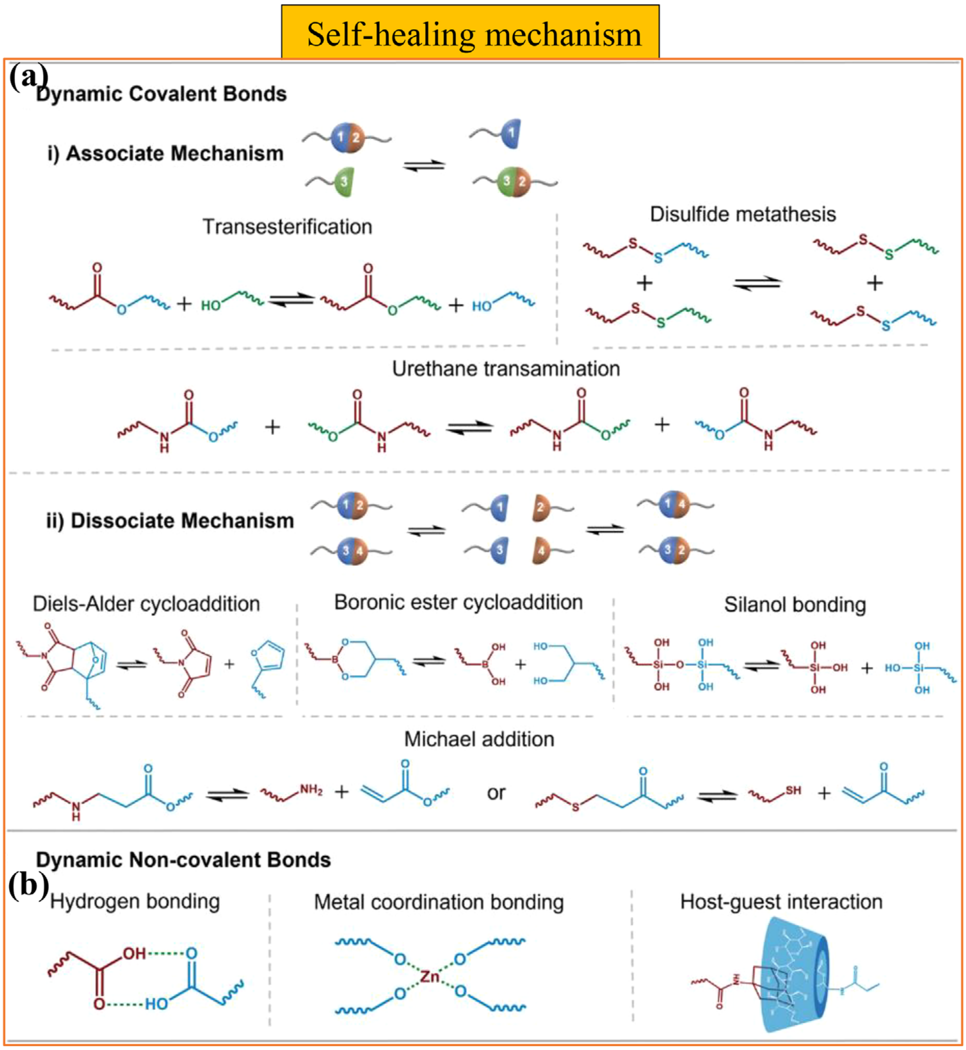


Figure 10. Representation of dynamic bonds in polymeric materials such as a) Dynamic covalent bonds exchange mechanism using i) associative and ii) dissociative mechanism, and b) Dynamic non-covalent bonds (Reproduced with permission.[250] Copyright 2023, The Authors, published by Wiley-VCH GmbH).

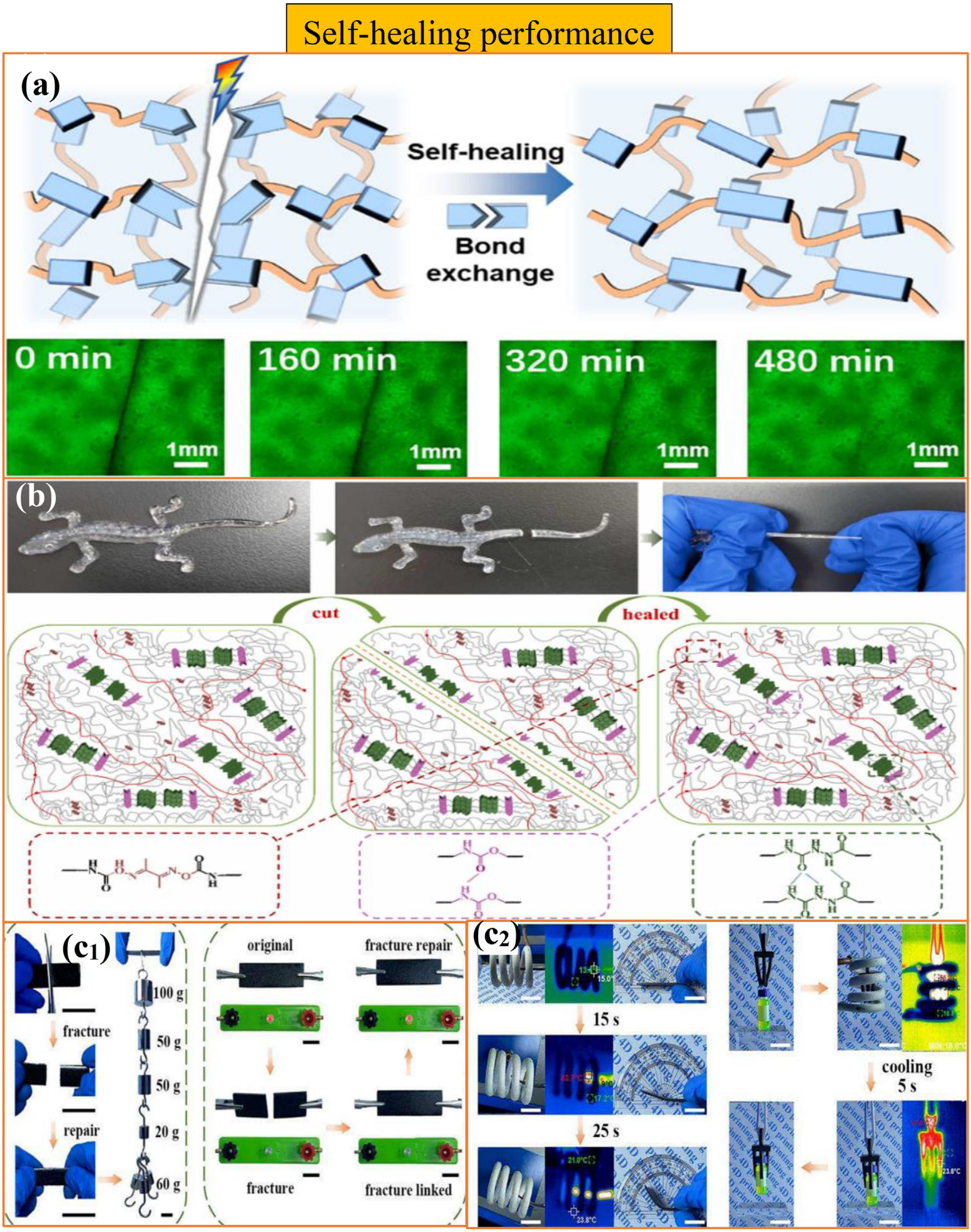
and poly (butylene furanoate) (PBF) using 3DP. Results showed that the 3D-printed PTF and PEF structures demonstrated satisfactory mechanical properties with the ability to carry 80 kg weight. Besides this, the furan-based polyesters PTF and PBF exhibited remarkable thermal-responsive shape memory behavior performance as illustrated by the deformation-recovery cycle curves (Figure 13c_1) as well as various complex structures such as gyroid lattice, the bionic flow and cross-structural as presented in Figure 13c_2. This study emphasizes the potential of various furan-based biomass materials as emerging SMPs, showcasing their novel shape-memory capabilities and responsiveness to diverse stimuli.

SMPs usually classified into thermoplastic and thermoset. Among them, thermosets demonstrate good shape memory performance along with excellent thermal and structural stability. The shape memory performance of SMP is typically determined by the shape fixity ratio, (R_f) and the shape recovery ratio, (R_r). R_f represents how well the switching domains can fix a temporary deformation, while Rr describes how well the material can regain its permanent shape after a temporary deformation.

$$R_f = \varepsilon / \varepsilon_{\mathrm{load}} \times 100\% \tag{2}$$

$$R_r = \left(\varepsilon - \varepsilon_{\mathrm{rec}}\right) / \varepsilon \times 100\% \tag{3}$$

where ε, ε_{load}, and ε_{rec} show the fixed deformation strain, deformation strain after loading, fixed deformation strain, and the deformation strain after recovery to the SMP at a fixed temperature, the deformation temperature, and recovery temperature, respectively.[285,286] Recently, Zhao et al.[287] adopted an interesting approach for epoxy/acrylate hybrid material for demonstrating various shape memory performances from DLP-based 3DP. Insights of this study showed that the unique two-phase molecular microstructure and the interpenetrating polymer network imparted good shape memory properties such as the average shape fixity 95.8 ± 0.4% and shape recovery ratios (99.6 ± 0.6%)


Self-healing performance
(a)
Self-healing
Bond exchange
0 min
160 min
320 min
480 min
1mm
(b)
cut
healed
(c1)
fracture
repair
100 g
50 g
50 g
20 g
60 g
original
fracture repair
fracture
fracture linked
(c2)
15 s
25 s
cooling
5 s

during eleven consecutive cycles. Moreover, various complex objects were printed to demonstrate their role in exciting applications in self-deploying antennas, intelligent mechanical grippers, and switches as shown in **Figure 14a**. Tekey et al.[288] studied novel heat-responsive properties of various blends from ethylene-vinyl acetate (EVA) copolymer and poly(butyl methacrylate-co-isobutyl methacrylate) from FDM-based 3DP. The results revealed that the proposed hybrid SMP exhibited satisfactory shape memory performance, with a shape recovery of 94.5% and shape fixing of 94.1% at a transition temperature (Ttrans) of 55 °C, particularly in a blend comprising 60 wt% EVA and 40 wt% poly(butyl methacrylate-co-isobutyl methacrylate). Besides their excellent shape recovery characteristics, the 4D printed parts shape memory performance in both hot oven and hot water environments are ideal for various engineering applications in designing robotic grippers, self-assemble rivets, movable cog-wheel teeth, surface traps, and finger splints as detailed in Figure 14b.

The entire 4DP process involves transforming an SMP object between multiple shapes or functions through "program-stimulate" actions.[176] The two basic components of this process are permanent and temporary shapes. There are various methods to transfer between these shapes, each offering unique applications. For instance, the transformation can be triggered by temperature changes, light exposure, or mechanical stress. These methods enable the SMP object to adapt to different functions and environments, making the process highly versatile and suitable for many intriguing applications. Recently, Huang et al.[289] studied the reversible microphase separation behavior of thermally responsive hydrogels by establishing a photo-chemistry-based molecular design. The temperature of the photo dimerization between the nitro cinnamate moieties governed the phase separation feature size which can be either increased or reduced depending upon heating. Thus, phase separation kinetics affects autonomous shape memory behavior as a result of this recovery onset can be regulated between 0 to 85 min. By utilizing light attenuation to encode gradient onset times, off-equilibrium and multiple temporary shapes were achieved, enabling precise control over shape-morphing pathways through simple stretching programming. This photo patterned network heterogeneity combined with 4DP via DLP or masked light was highly effective for demonstrating high controllability of shape-changing response of SMPs with automatic multi-paths recoveries as presented in Figure 14c.

Wang et al.[290] developed an eco-friendly SMP by melt-blending of poly(propylene carbonate) and poly(vinyl alcohol), enhanced with an effective compatibilizer, poly(vinyl acetate) for interfacial hydrogen bonding. The blend achieved high strength, >95% shape fixing, and ≈90% recovery, along with 91% self-healing and triple shape memory process in the stretching-recovery experiment as highlighted in Figure 14d. Its multifunctionality enables applications in biomedical structures, sensors, and soft robotics.

Beyond the basic one- and two-way SME, the three-way SME is appealing for practical applications, offering a balanced combination of shape fixation and recovery performance.[291] On the other hand, multiple stimuli responsiveness is useful in creating intelligent systems that adapt various properties to changing environments.[292] Liang et al.[293] developed a 3D-printed SMP design enabling smooth transitions between soft and stiff states for dynamic deformation and structural locking. The system uses multiple Kresling origami modules with selective heating to achieve programmable, customizable motion patterns and multimodal actuation as shown in **Figure 15a**. The proposed system shows potential for applications such as selective bending in continuum robots and performing functional tasks like bottle opening and load-bearing.

Lin et al.[25] designed multi-responsive SMP composites using shape memory PLA filled with Fe_3O_4 nanoparticles and MWCNTs functional fillers. The results showed that the proposed SMP is highly enriched with tripled programmability and demonstrated excellent thermal, light, and magnetic responsiveness. This work sheds new light on the efficient encrypted transmission of multiple types of information, for broader applications in, highly programmed metamaterials, flexible robots, and information encryption carriers. Likewise, Da Cunha et al.[294] studied the SME of polyethylene terephthalate glycol (PETG)/TPU blends using 3DP. The insights of this study showed that PETG/TPU (50/50) blend impressive shape memory behavior (referring to Figure 15b) such as a high recovery ratio (93%) and fixity ratio (97%) in bending mode, while remarkable recovery ratio (87%) and fixity ratio (100%) under torsion mode. Li et al.[295] investigated the temperature-driven controllable deformation of the heterogeneous laminated bilayer structure comprised of PLA/TPU using FDM-based 3DP. The reported results demonstrated four cross-shaped printed components such as rosette structure exhibited programmability as presented in Figure 15c and controllable deformation under the heating stimulus.

5. Evaluating Multifunctional Performance in Extreme Environmental Conditions

A comprehensive understanding of the multifunctional performance of 3D-printed SMPs is essential for their widespread adoption across advanced applications. The integration of multifunctional capabilities, particularly in soft electronics, enables these materials to operate effectively under external environmental conditions that closely mimic real-world scenarios, allowing them to generate appropriate and responsive behaviors.[296–298] For example, in wearable electronics, achieving a highly stable and conformal interface with biological tissues is critical for

Figure 11. a) Demonstration of the self-healing PU and dynamic oxime-carbamate bonds schematic and actual photos of self-healing behavior with the assistance of the appropriate molecular chain mobility and self-healing process using a notched self-healing PU-3 film at room temperature (Reproduced with permission.[252] Copyright 2024, American Chemical Society); b) Representation of the self-healing behavior and self-healing mechanism of the gecko model (Reproduced with permission.[256] Copyright 2024, Elsevier B.V.); c_1) Self-healing performance of soft materials such as a load of 280 g weight diagram is applied after fracture self-healing and self-healing ability is expressed by the switch of light emitting diode (LED) lamp, c_2) Magnetic-stimuli behavior of proposed smart materials demonstrating the magneto-thermal effect of Fe_3O_4, and the angle deflection is precisely controlled under the action of magnetic torque for exhibiting the practical application as a gripper for spreading out to grab and carry out the object (Reproduced with permission.[257] Copyright 2023, Elsevier B.V.).

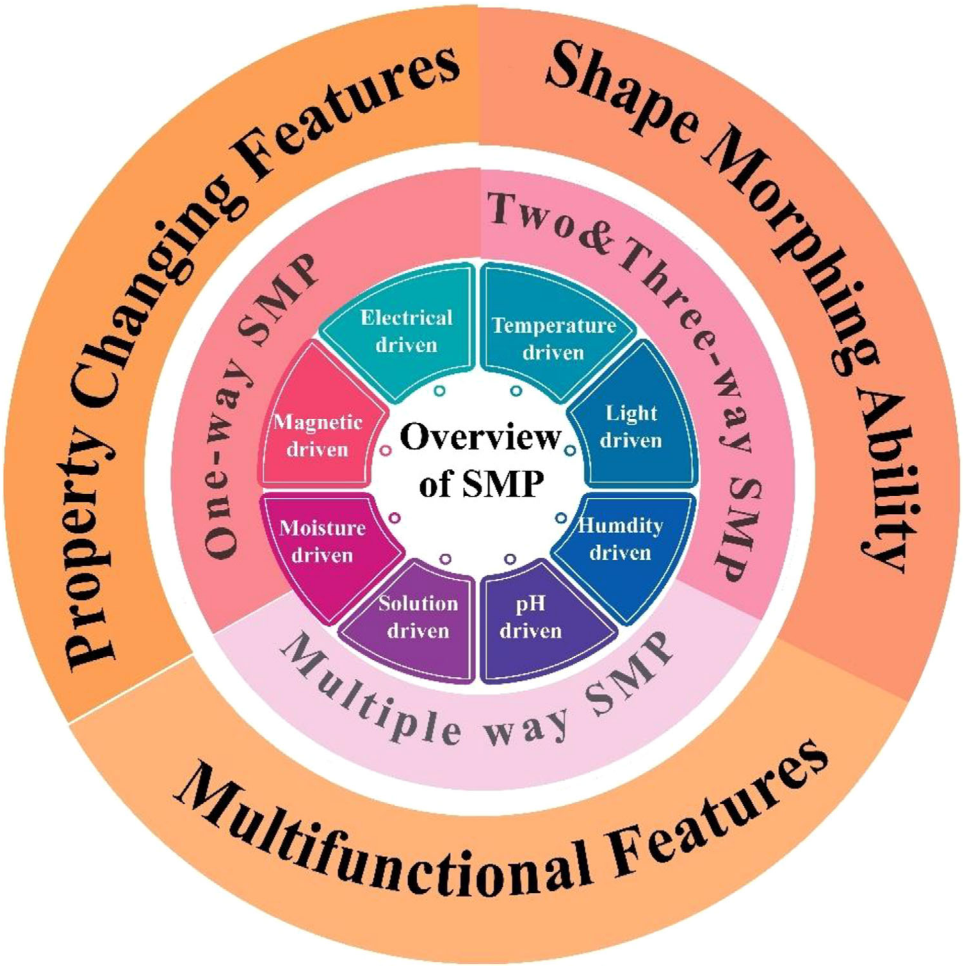


Figure 12. Overview of 4D-printed SMP.

Table 4. Overview of various stimuli employed for SMP-based 4DP technology.

Types of stimuli [Ref.]	3DP process	Smart materials	Functional components	Deformation mechanism
Temperature driven [32,278]	• DLP • SLA • FDM • DIW	• PLA • PCL • TPU	• MXene • GO • GNP • CNT	Phase change, built-in stress
Electrical driven [279]	• FDM • DIW • SLA	• PLA • PCL	• Carbon black (CB) • CNT • carbon fibers	Phase change
Magnetically driven [280]	• DIW • FDM • SLA • DLP	• PLA • TPU	• Fe nanoparticles • Fe_3O_4 particles • NdFeB microparticles	Phase change
Light-driven [281]	• FDM • DIW • SLA • DLP	• PLA	• Graphene • CNT	Photoisomerization; Phase change
Water driven [282–284]	• DIW • SLA • DLP	• PEG • PLA	• CNC • CNF	Swelling

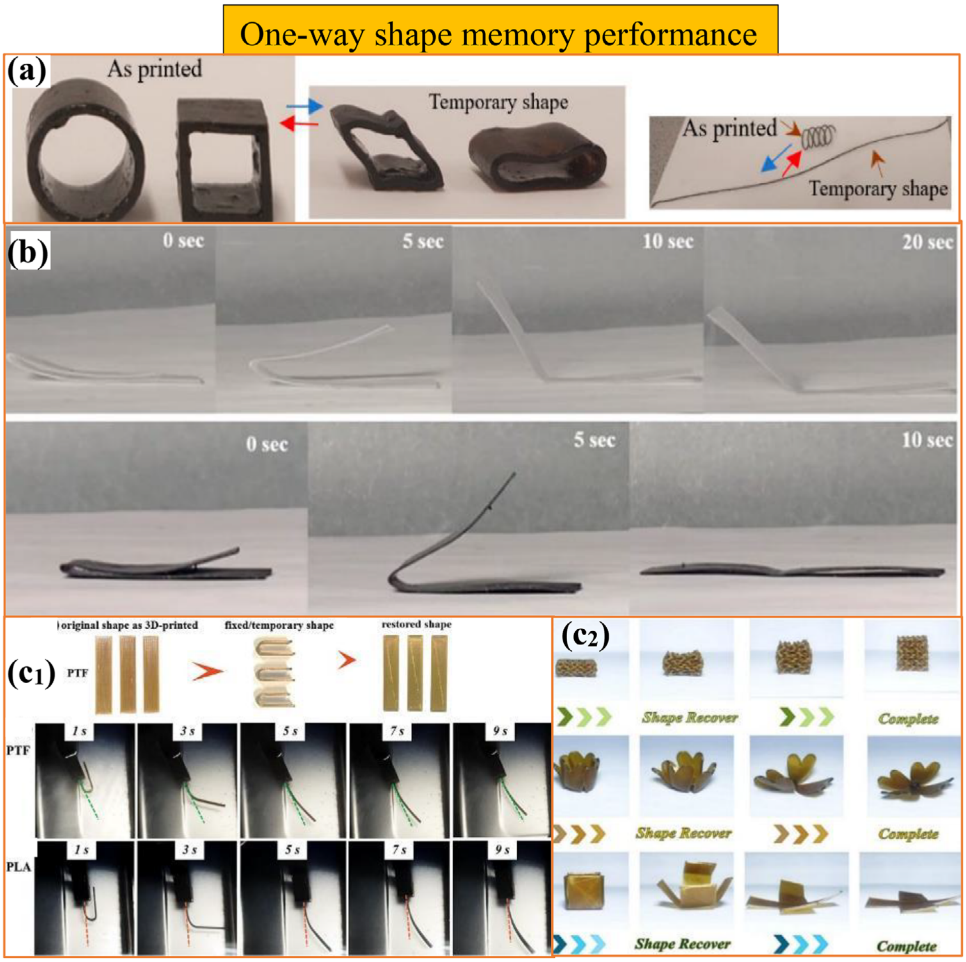


Figure 13. a) 3D printed epoxy-based structures showing temporary and recovery shapes (Reproduced with permission.[271] under a Creative Commons Attribution license 4.0); b) Demonstration of shape memory performance of various 0 wt % MXene and 2 wt % MXene composite activation images at 0, 5, and 10 s (Reproduced with permission.[272] Copyright 2022, American Chemical Society); c_1-c_2) Illustration of 4DP of free-standing LCE structures achieving various reversible shape transformations upon heating and cooling for various structures such as a cubic, hexagonal prism, conical cylindrical ring triangular prism (all images are under 5 mm scale bars), (c_2) Actuation of the LCE ring structure demonstrating under heating stimulus, LCE spring from gel matrix, linear expansion of LCE spring under heating stimulus (Reproduced with permission.[277] under a Creative Commons Attribution license 4.0); (c_1) Demonstration of the shape memory and recovery performance of PTF samples, and 3D-printed PLA samples under thermal field, (c_2) Representation of sequential shape memory recovery performance of various strictures such as Gyroid structure, bionic flower structure, and cube structure (Reproduced with permission.[276] Copyright 2023, Elsevier B.V.).

ensuring consistent performance and user comfort in practical applications.[299] Recently, 3D-printed SMP-based soft robots have demonstrated advanced functionalities such as environmental sensing, contextual decision-making, and the execution of physical tasks in real-world environments.[300] Beyond their well-known self-healing and shape memory properties, other key functionalities such as self-assembly and self-adaptability are vital to enhancing performance in demanding settings. Self-assembly enables SMPs to form complex 4D structures from simple 3D-printed components, which is particularly beneficial in challenging applications like satellite deployment and antenna systems. These structures can also autonomously reassemble to restore or repair damaged functionalities, and flexibly serve as adaptive joints in structural systems. Meanwhile, the self-adaptability of SMPs allows them to respond dynamically to environmental stimuli for instance, altering their assembly speed or changing shape in response to temperature fluctuations showcasing their potential for versatile, responsive deployment in smart systems.[301]

The rapid development of smart devices with improved functionalities particularly in the last decade has given birth to many smart devices that are fully integrated with many multifunctionalities such as autonomous sensing, monitoring, and deformation for novel sensing and smart displaying applications.[302,303] Liu et al.[304] developed smart structures from an FDM-based 4DP technique using a dynamically crosslinked shape memory TPU system. PCL-triol and polyethylene glycol (PEG) make up the majority of the dynamic TPU system, while Diels-Alder (DA)-diol extends the chain. Dynamic TPU was printable due to its thermally reversible DA reaction. As the active layer, the 2D flat laminated patterns are made up of high-swelling dynamic TPU, while the passive layer is made up of low-swelling dynamic TPU.

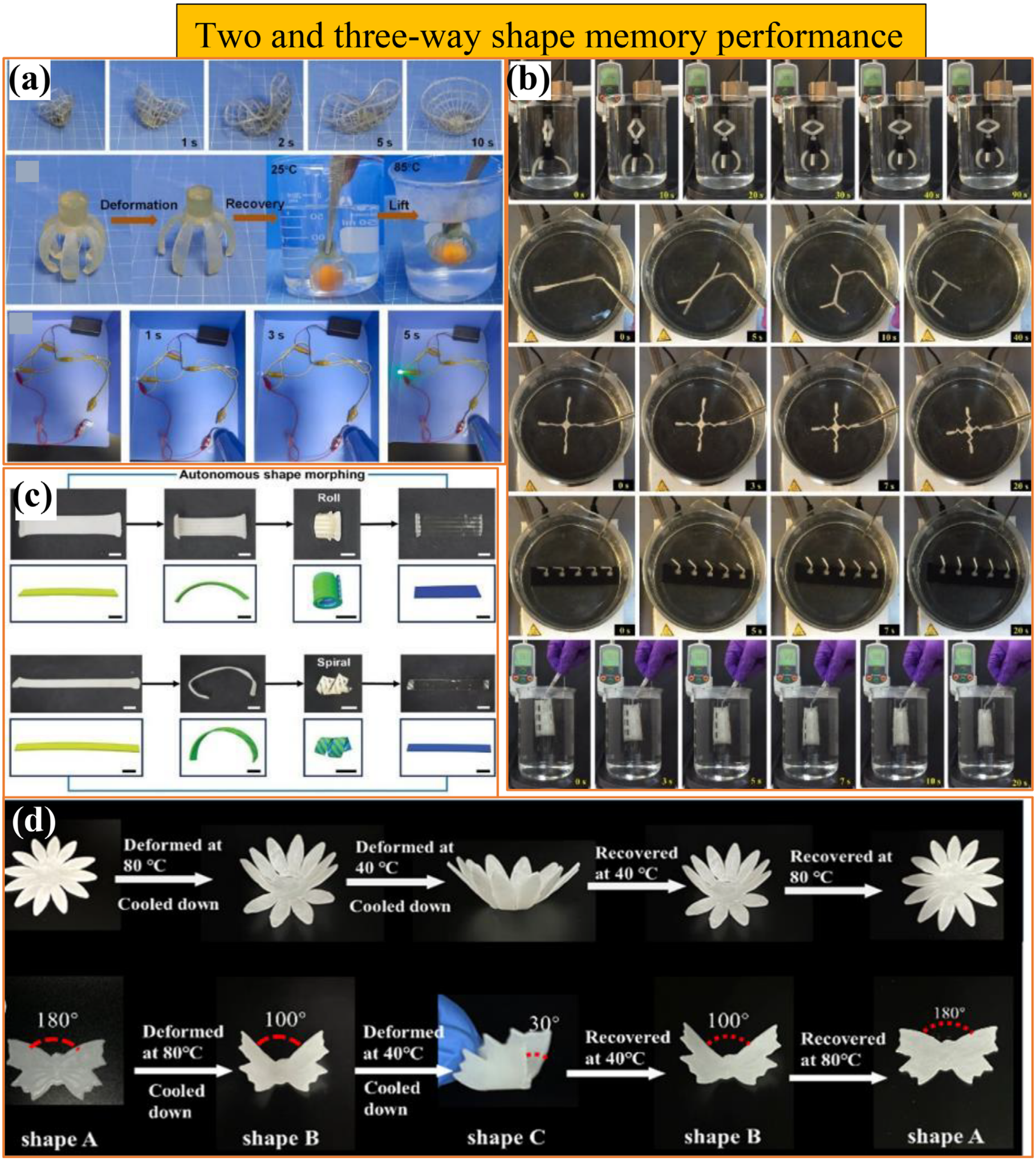


Figure 14. a) Various shape performance of printed structures enriched with shape memory performance for engineering applications first the printed antenna which folded and recovered to its original shape under heating stimulus by a dryer (1600 W) in 10 s, next mechanical gripper in a water bath to lift a ball during the its deformation and recovery to its original shape and finally an intelligent switch in which the surface of the shape memory polymer was covered with an electrical tape (3 M Copper Foil Shield Tape 1181) (Reproduced with permission.[287] Copyright 2023, Elsevier B.V.); b) Demonstration of shape recovery performance of the 4D printed parts gripper, rivet, cog wheel, surface trap and finger splint in 55 °C-water (Reproduced with permission.[288] Copyright 2024, Elsevier Ltd.); c) Illustration and simulations of multiple shapes developing in the autonomous shape morphing process (Reproduced with permission.[289] Copyright 2024, Wiley-VCH GmbH); d) Illustration of smart driving devices: multiple shape memory bionic flower and artificial butterfly with triple-SME (Reproduced with permission.[290] Copyright 2025, American Chemical Society).

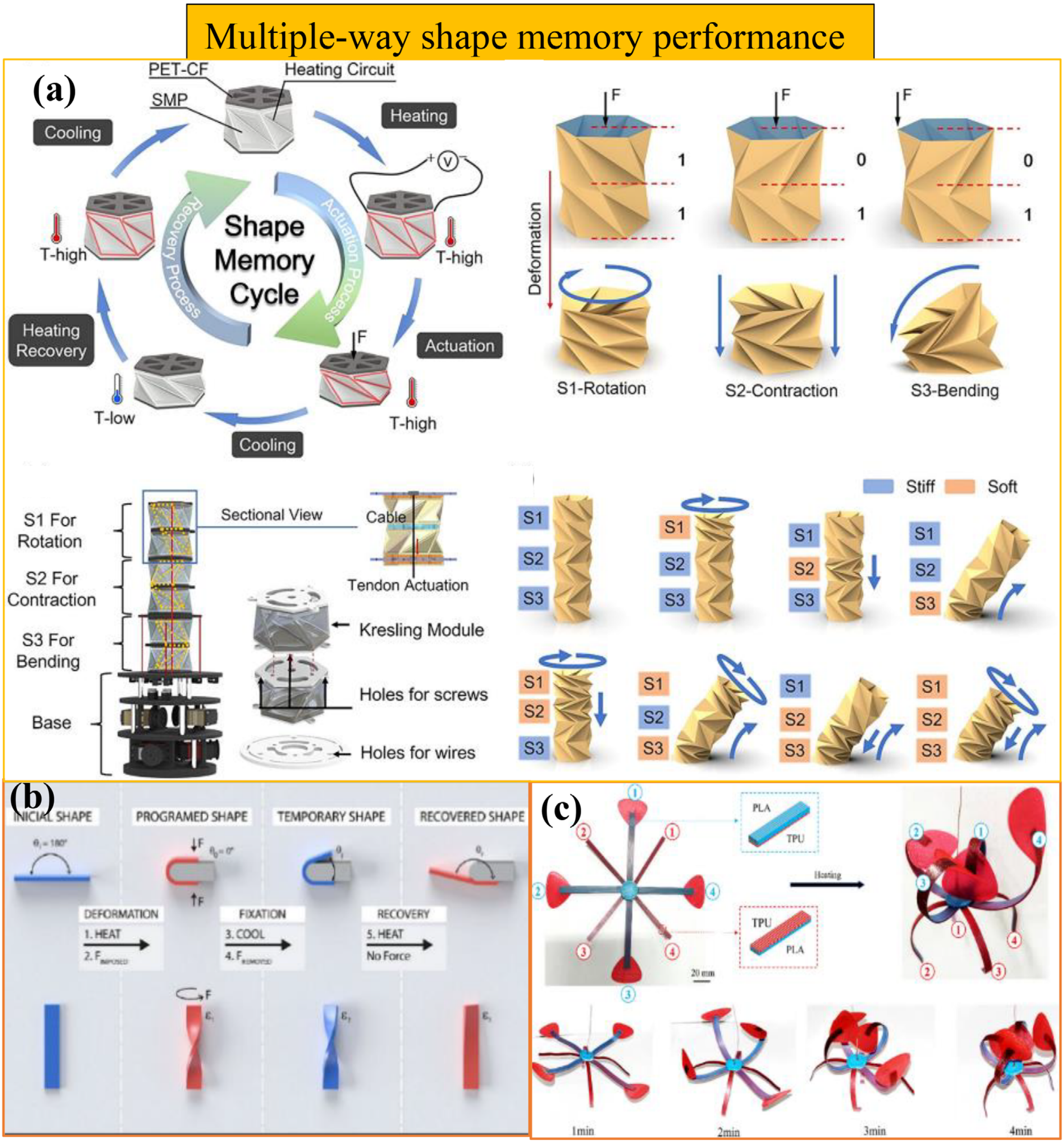


Figure 15. a) A variable-stiffness Kresling actuator system is illustrated as follows: the cycle of stiffness variation and actuation process, the deformation mechanism of three distinct segments S1 (responsible for rotation), S2 (responsible for contraction), and S3 (responsible for bending), a structural diagram of the continuum robot composed of three serially connected segments S1, S2, and S3 arranged from top to bottom alongside a schematic of a Kresling module with its ends connected via intermodular rings and demonstration of how the selective actuation of the three segments enables the generation of eight distinct deformation modes (Reproduced with permission.[293] Copyright 2025, American Chemical Society); b) Illustration of the shape memory cycle in sequential steps for characterizing the SME under bending and torsion modes (Reproduced with permission.[294] Copyright 2024, The Society of Manufacturing Engineers, Published by Elsevier Ltd.); c) Programmable 4D printed rosette structure with controllable bending deformation during the heating process (Reproduced with permission.[295] Copyright 2024, Springer-Verlag London Ltd., part of Springer Nature).

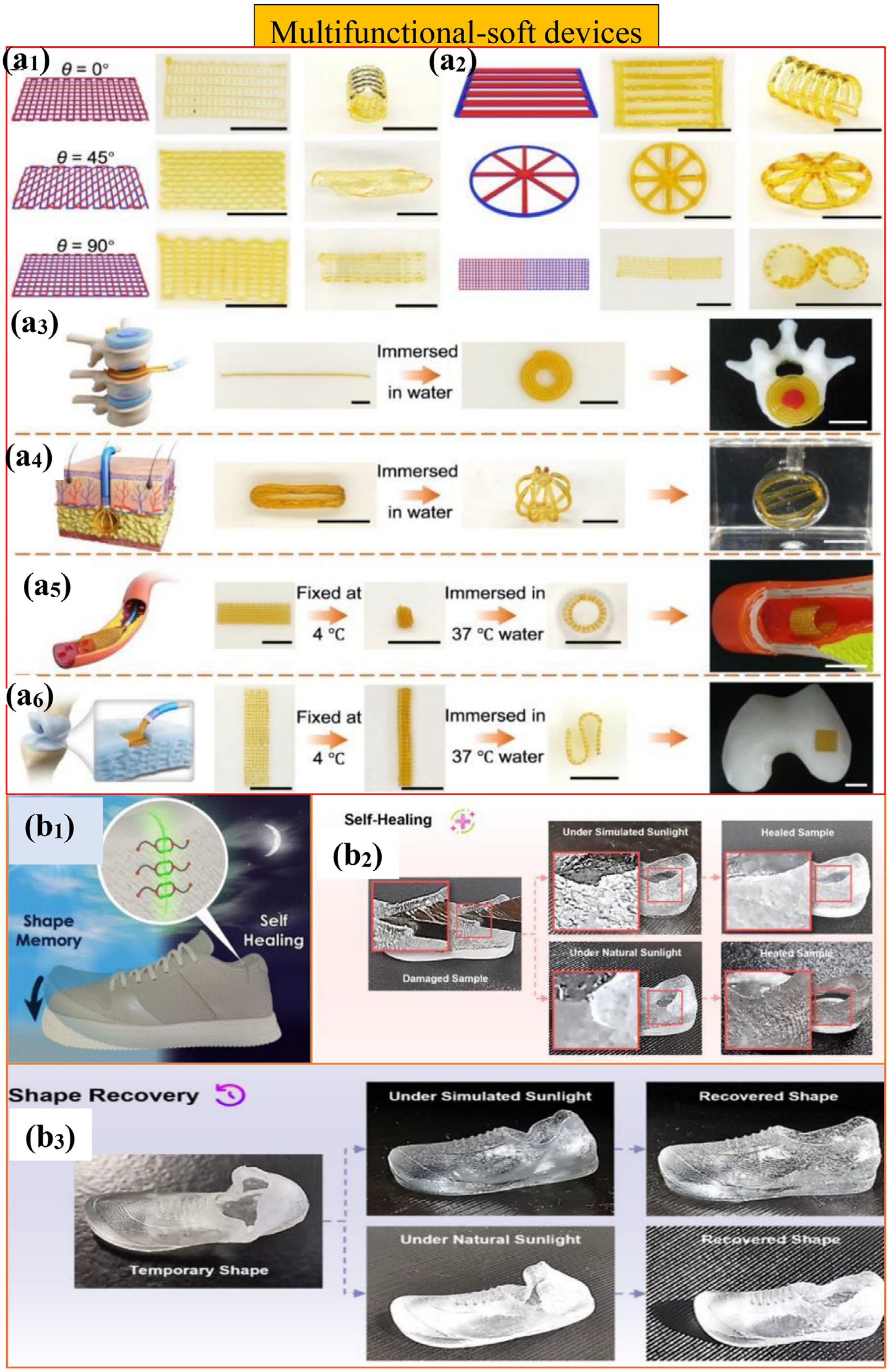


Figure 16. a_1) Programmable deformation of multi-material 4D-printed two-layer grids, highlighting different alignments of the active layer. a_2) Programmable deformation of specially designed 2D flat patterns. In both (a_1) and (a_2), the left column shows the initial configuration, the middle column displays the as-printed 2D patterns, and the right column illustrates the resulting deformed 3D structures. a_3_a_6) Detailed schematic illustrations and photographs of printed structures undergoing multi-dimensional deformation. These structures have potential applications such as fibrous ring replacements (a_3), supports for soft tissue defects (a_4), vascular scaffolds (a_5), and scaffolds for cartilage defects (a_6). The deformations in (a_3) and (a_4) are programmable in response to water, while those in (a_5) and (a_6) involve body temperature-triggered shape memory and programmable deformation in response to water (Reproduced with permission.[304] Copyright 2024, The Author(s), Published by Springer Nature); (b_1–b_3) (b_1) Smart 4D-printed sneaker, (b_2) self-healing performance of sneaker (crack highlighted in red) under simulated and natural sunlight and (b_3) Shape memory performance under (temperature of sneaker surface and natural sunlight intensity over time) (Reproduced with permission.[305] Copyright 2024, American Chemical Society).

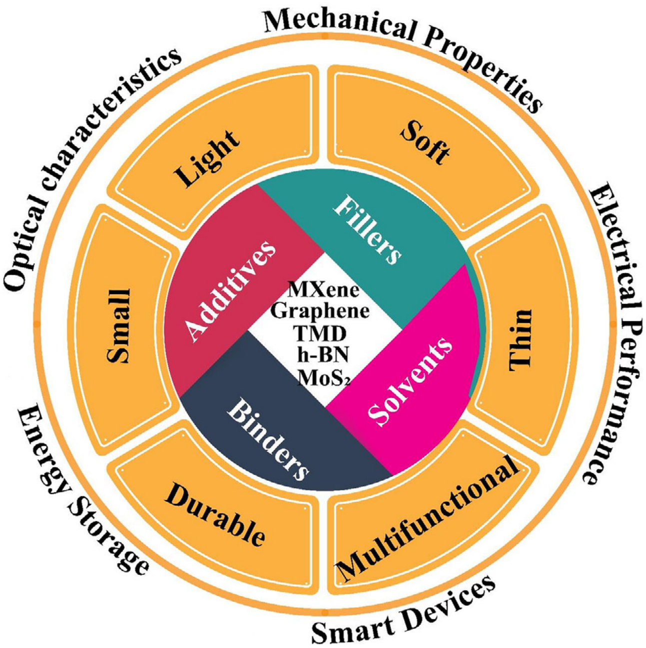


Figure 17. The 2D materials are characterized by their unique physical, mechanical, and chemical properties, expanding the horizons of SMP in various forms for imparting their multifunctionality and amplifying their impact in various domains (Figure drawn with the help of Refs. [325,326]).

Moreover, the dry 2D pattern is fixed into a temporary 1D roll-up shape based on the temperature-sensitive properties of PCL which finally demonstrates programmable deformations as presented in **Figure** 16a_1–a_6. Besides this, the 1D roll recovered to the initial 2D pattern and absorbed water to realize programmed deformation. Finally, after immersion in 37 °C water swelling–and stiffening properties of multimaterial 4D printed scaffolds were achieved along with the multi-dimensional deformability allowing them to be used in minimally invasive treatment of tissue defects.

Loo et al.[305] introduced a novel smart sneaker (Figure 16b_1) from 4DP of high-performance photothermal-responsive shape memory and self-healing polymer based on PU methacrylate. The study revealed that the 4D-printed SMP exhibited impressive self-healing efficiency of 93.4% at a comfortable actuation temperature (35.2 °C) and shape recovery of 98.7% under sunlight, as shown in Figure 16b_2,b_3. The proposed 4D-printed sneaker holds significant potential for smart wearables with personalized comfort.

6. Strategies to Improve Mechanical Strength and Toughness

Most 3D-printed SMPs suffer from poor mechanical strength, leading to sluggish and inefficient shape memory performance. The intrinsic mechanical properties of 4D-printed materials particularly their strength and toughness remain a major limitation for practical applications.[306] In fact, improving mechanical performance while maintaining optimal shape memory capabilities remains an unresolved challenge. To address this issue, researchers have explored several strategies, broadly categorized into material design, process optimization, and architectural innovation.[307] Moreover, parts made from 4DP have residual stress, similar to any manufactured object. Despite the absence of a load, residual stress remains in an object. In some cases, it develops during the printing process, while in others, it develops afterward. These residual stresses have a strong effect on the mechanical performance of 4D-printed SMP. For instance, it can cause deformation, deterioration, fissuration, among other damages.[308] Various material design approaches can enhance stiffness and fracture resistance, such as tuning crosslink density and crystallinity to improve toughness and energy dissipation.[309] Optimizing printing parameters including nozzle temperature and layer thickness can strengthen interlayer adhesion and reduce anisotropy.[310–312] Post-processing techniques such as annealing help relieve residual stresses and enhance crystallinity. Additionally, bioinspired structural designs, such as lattice and hierarchical architectures, can effectively redistribute stress and suppress crack propagation, offering a promising solution to the brittleness of 3D-printed materials. Zhang et al.[313] developed a multi-material 3D printing method for soft actuators, embedding pre-stretched SMP, silver nanowires electrothermal layer, and coolant/air channels to enhance performance. The result showed that the proposed modified SMP demonstrated improved mechanical strength, shape recovery, and layer bonding, thus solving key challenges in multi-material 4DP. Moreover, the actuator achieved two driving modes: stress-release (slow, precise deformation) and pneumatic (fast, high-force actuation), enhanced by active cooling for tunable control for showing a promising role in grasping and load-bearing applications, with potential uses in aerospace.

Yousuf et al.[314] incorporated $La_{1-x}Sr_xMnO_3$ manganite into a SMP via solution mixing, followed by extrusion into 3D-printable filaments. Their study revealed that $La_{1-x}Sr_xMnO_3$ addition significantly enhanced the elastic modulus, yield strength, and ultimate tensile strength. Additionally, all composites exhibited favorable magnetic properties in their ground state, including magnetic moments close to 3.5 μB per Mn ion. Bulk strain measurements of auxetic structures for 0 wt% and 20 wt% $La_{1-x}Sr_xMnO_3$/SMP nanocomposites showed that while shape fixity remained unchanged, the shape recovery ratio decreased slightly (from 88% to 81%), and the shape recovery rate increased sharply (from 124.3 to 179.5% min^{-1}).

Adding natural fibers, to polymer matrices enhances mechanical properties, such as stiffness and shape retention, in a sustainable and environmentally friendly manner. Recently, Bouguermouh et al.[315] developed flax fiber-reinforced PLA/PETG blends for 4DP aiming to improve mechanical, thermal, and shape memory properties with a focus on sustainability. The results showed that at optimal formulation of PLA-75/PETG-25 with 10% flax showed 92% shape recovery and ≈100% fixity after 10 thermal cycles with stiffness of 4 GPa and tensile strength of 44 MPa. These eco-friendly composites, suitable for complex auxetic and adaptive designs, demonstrate strong potential for automotive, aerospace, and biomedical applications.

7. 2D Materials for Enhanced Robustness

2D materials are an up-and-coming class of nanomaterials consisting of one or a few atomic layers, with strong covalent

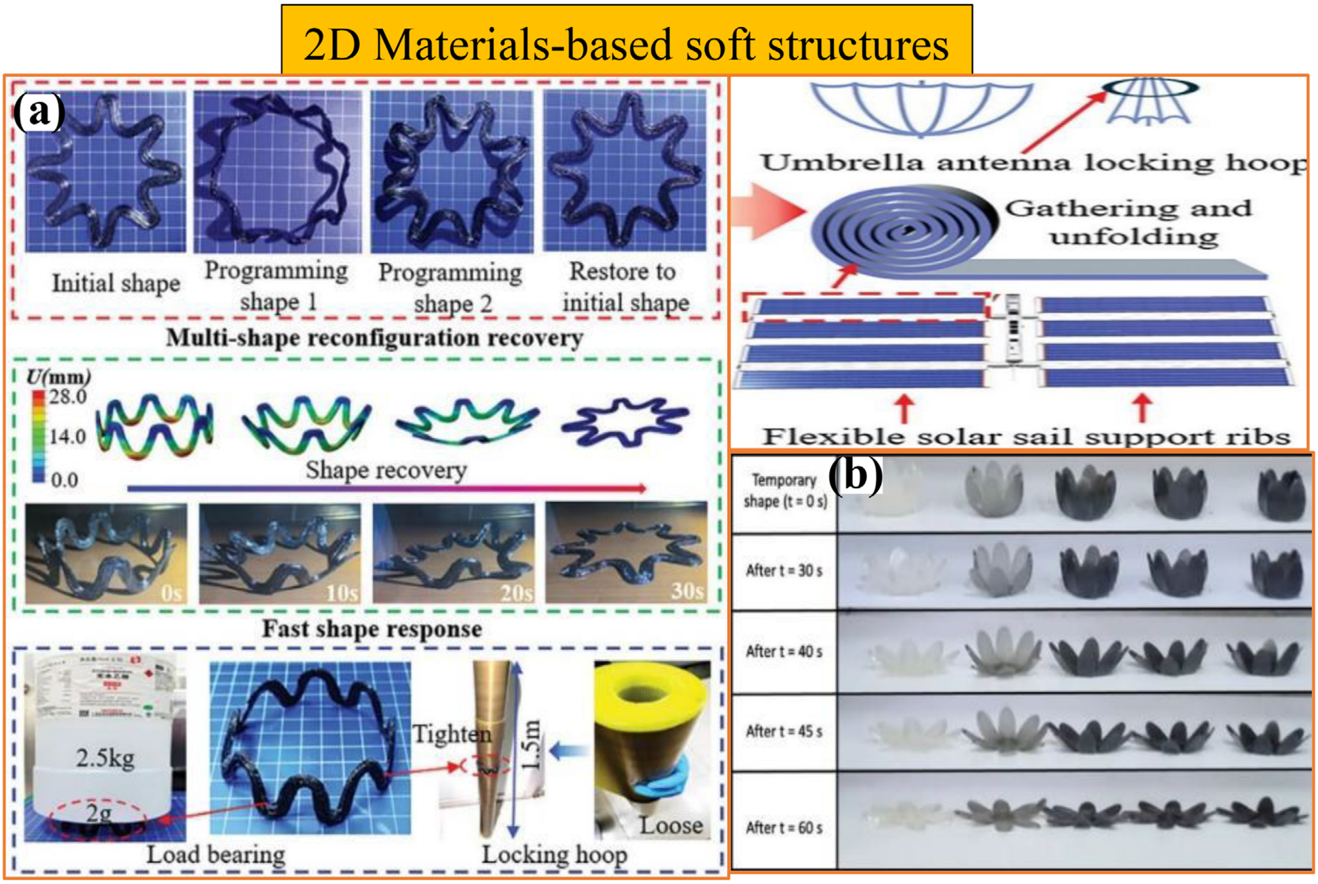


Figure 18. a) Demonstration of multi-shape reconfiguration performance with rapid shape response recovery extraordinary mechanical load-carrying ability large space-expandable antennas locking rings and flexible solar wings support ribs (Reproduced with permission.[327] Copyright 2024, Wiley-VCH GmbH); b) Illustration of shape recovery behavior in furnace images at 0, 30, 40, 45, and 60 s for pure PLA and PLA-MXene composites at 85 °C (Reproduced with permission.[328] Copyright 2024, Wiley-VCH GmbH).

bonds within each layer and weak van der Waals forces between the layers. Graphene, Mxene, transition-metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), and Molybdenum disulfide (MoS_2) all belong to the 2D materials. 2D materials are highly attractive particularly when considering SMP for 3DP of flexible electronics.[316] Advancements in atomic-scale additive manufacturing for 2D materials have attracted a deal of attention across various applications.[317,318] The integration of 2D materials (**Figure 17**) with SMP has led to the development of a compelling class of electronic devices. These devices are robust, offering both high mechanical strength and the ability to maintain sensing performance (e.g., sensitivity and linearity) under varying environmental conditions. The integration of MXene-based composites with SMP materials through 4DP has unlocked transformative potential for creating intelligent and adaptive structures capable of shape-shifting, environmental adaptation, and self-assembly. These advancements are particularly promising for soft robotics and energy storage applications, where MXenes contribute enhanced conductivity, mechanical strength, and environmental stability. This integration allows for precise structural control through meticulous 3DP processes, optimizing overall device performance.[319] Integrating the time-dependent shape transformation capabilities of 4DP with MXene-based SMP further enhances the complex functional requirements for biosensing applications. Moreover, the selectivity and sensitivity of MXene-based SMP make them viable biomedical diagnostics for various environmental monitoring applications.[320] There are, however, significant challenges to overcome, including uniform dispersion of MXene nanosheets within complex printing matrices, scaling production for industrial adoption, and addressing material limitations such as the scarcity of stimuli-responsive materials. There are also inherent difficulties in integrating MXenes, especially their dispersion stability, compatibility with other smart materials, and scalability, which can compromise the desired functional performance as a result of inconsistent dynamic properties during transformation. It is imperative that these barriers are addressed in order to move the field toward large-scale, practical implementations.[321]

MoS_2 improves the performance of soft electronics in inkjet printing by improving conductivity, flexibility, and biocompatibility. With its 2D layered structure, it ensures stretchable, conformable devices while being highly mobile and mechanically strong.[322,323] Recently, a novel approach for defining structures with micron resolution on rigid and flexible substrates has been demonstrated by Sargeni et al.[324] using both additive and subtractive manufacturing techniques. Due to its high-precision

Table 5. Various functional particles in 3DP for soft electronics applications.

3DP	SMP	Functional materials	Flexible electronics applications	Refs.
FDM/FFF	PLA/azodicarbonamide	–	Shock-absorbing materials with programmable properties	[330]
FDM/FFF	TPU	MWCNT	γ-Irradiation driven smart structures	[331]
FDM/FFF	PETG	Fe_3O_4	Sensors, actuaries, and deployable structures	[332]
FDM/FFF	PLA	CB	Smart structures	[333]
Multi-material extrusion	PLA/TPU	–	Soft frog-shaped robot	[334]
FDM/FFF	PLA	lignin-derived carbon quantum dots	Innovative designs for various applications	[335]
FDM/FFF	PU	–	Soft actuators	[336]
FDM/FFF	Polycarbonate	Aerosil 300	Aersoapce applications	[337]
FDM/FFF	TPU	–	Smart soft grippers	[338]
FDM/FFF	PLA	Fe_3O_4	Treatment of left atrial appendage occlude	[339]
FDM/FFF	TPU	–	Origami-inspired soft encapsulating gripper	[340]
FDM/FFF	PCL	Fe_3O_4	Medical devices	[341]
FDM/FFF	TPU	–	Soft gripper	[342]
FDM/FFF	polymethyl methacrylate(PMMA)Acrylic acid/TPU	Fe_3O_4	Magnetic actuated grippers	[343]
FDM/FFF	Nafion	–	Macro-scale soft robotic systems	[344]
FDM/FFF	PLA/PMMA	Fe_3O_4	Regenerative medicines	[345]
FDM/FFF	PLA/TPU	NdFeB	Smart grippers	[346]
FDM/FFF	NinjaFlex (NinjaTek)	–	Soft gripper	[347]
FDM/FFF	Cu-PLA	–	Flexible gripper	[348]
DIW	Poly(L-lactide-co-trimethylene carbonate)	MXene	peripheral nerve injury treatment	[349]
DIW	Silicon oil and gels and SiO2	NdFeB	Smart structures	[350]
DIW	PU	CNF	Smart wearable structures	[351]
SLA	Glucose//PDMS	CNT	Soft wearable sensor	[352]
SLA	PCL	Fe_3O_4	Micro-actuators	[353]
DLP	Soft conductive resin	–	Soft actuators	[354]
DLP	TPU	–	Frog-shaped soft robot	[355]
DLP	PUA		Dielectric elastomer actuators for vibrotactile device	[356]
IJP	Urethane and epoxy	–	Soft robotic	[357]
–	Benzoxazine-urethane	Fe_3O_4	Applications in the electric circuit	[358]
IJP	Tangoblack	–	Bellows actuators	[359]

mechanical stages, the proposed printer prototype can define conductive tracks with high spatial resolution when used with the dip pen nanolithography. As a result, they build and characterize MoS_2-flakes field effect transistors, demonstrating the potential of this prototype for rapid prototyping of highly dense electronic circuits based on 2D materials.

In wearable electronics, the precise 3DP process can revolutionize mass production, enabling the creation of intricate structures and advanced multifunctional performance at the atomic level. A unique synergy of 2D materials with SMP facilitates the design of wearable electronics for realizing energy storage ability making the device soft, thin, light, and durable. Moreover, 2D materials are ideal for 3D-printed flexible electronics due to their high electron mobility, and minimal thickness. Particularly, graphene and TMDs improve soft electronics device performance and can withstand significant strain without breaking. Wang et al.[327] developed graphene-continuous carbon fiber synergistically reinforced thermoset SMP composite structures from 4DP. This unique synergy of graphene with high thermal conductivity and high strength from continuous carbon fibers imparted multidirectional thermal conductivity and the load-bearing ability for thermoset SMP. The 4D printed composite structures exhibited multifunctional performance including remarkable shape memory performance (shape recovery ratio and shape fixation ratio, of 99.07% and 98.62%. respectively) bending strength of 676.99 MPa, and fast response shape

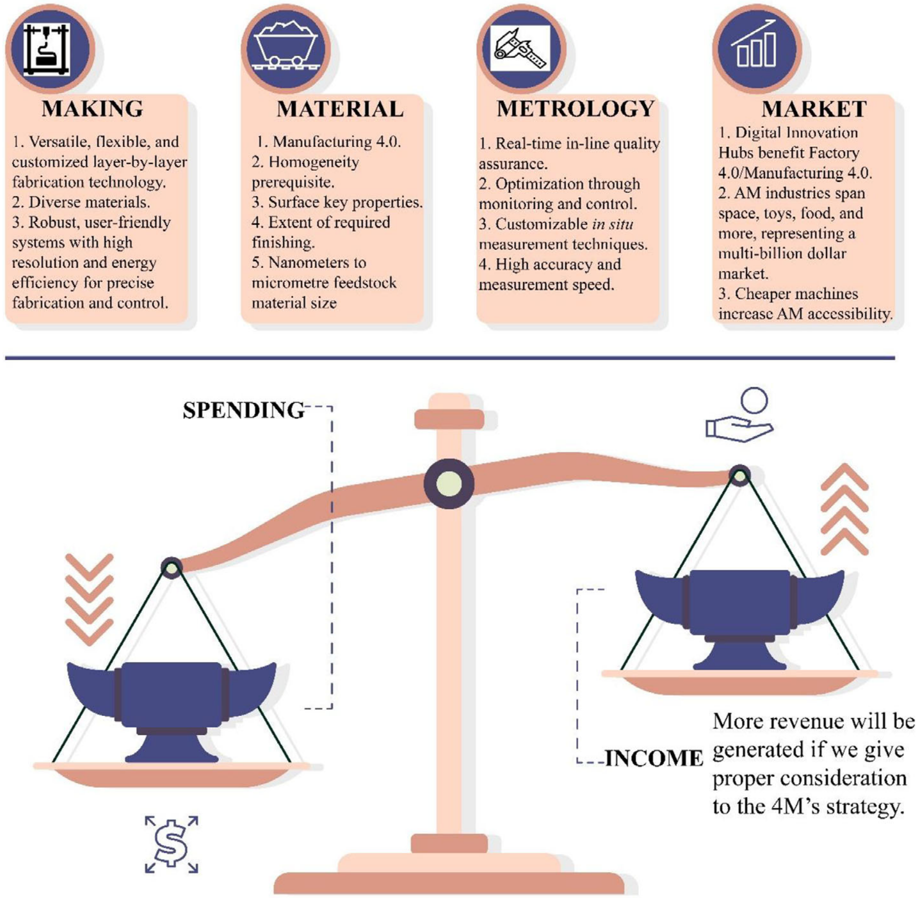


Figure 19. Role of the 4 M's in 3DP for taking it from lab to fab (information is collected.[360]).

reconfiguration within 6 s under NIR light excitation. This facile integrated manufacturing has broad application prospects in large space-expandable antenna locking rings and flexible solar wings support ribs as presented in **Figure 18a**. Sirinivas et al.[328] investigated the shape memory properties of novel SMP composites comprised of PLA and MXene from FDM-based 3DP. Results showed that the addition of 0.25-0.5 wt% of MXene to the PLA displayed excellent shape memory behavior where deformed samples were shown to recover their shape when submerged in hot water as shown in Figure 18b for numerous engineering applications.

7.1. Role of Other Functional Particles

Apart from 2D materials, various functional particles at the nanoscale play a significant role in advancing 3DP. Conductive inks for 3D printed electronics commonly incorporate conductive metal nanoparticles and nanowires. These materials enable efficient conductivity and have been widely used in fabricating diverse electronic components for applications include electrical circuits, and transparent electrodes. Advancements in 3D-printed electronics and nanomaterials are paving the way for large-scale production of flexible, stretchable, and eco-friendly devices. These technologies offer benefits such as low cost, lightweight, and suitability for wearable applications. The global printed electronics market is projected to reach approximately USD 23 billion by 2026.[329]

They also support flexible technologies like thin-film transistors and touch panels. The functional offers unique advantages such as surface effects and quantum effects, resulting in improved or novel properties in mechanics, thermal conductivity, magnetism, electronics, optics, and catalysis.[326] For example, iron particles, cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), carbon nanotubes (CNTs), and gold nanoparticles provide properties like size- and shape-dependent optoelectronic characteristics, a large surface-to-volume ratio, outstanding biocompatibility, and minimal toxicity.[325] In 3DP, functional particles can modify rheology, introduce multiple functionalities, and enhance mechanical properties. Thus expanding its frontiers toward advanced manufacturing systems at commercial scale. **Table 5** summarizes some recent works on various functional particles in 3DP for wearable electronics applications.

8. The Market: Evolving from "Lab" Innovations to "Fab" Applications

Today's, 3DP is rapidly transforming into functional prototyping and is considered a multi-billion dollar industry in various regions spanning from China to Europe to the USA. Modern 3D

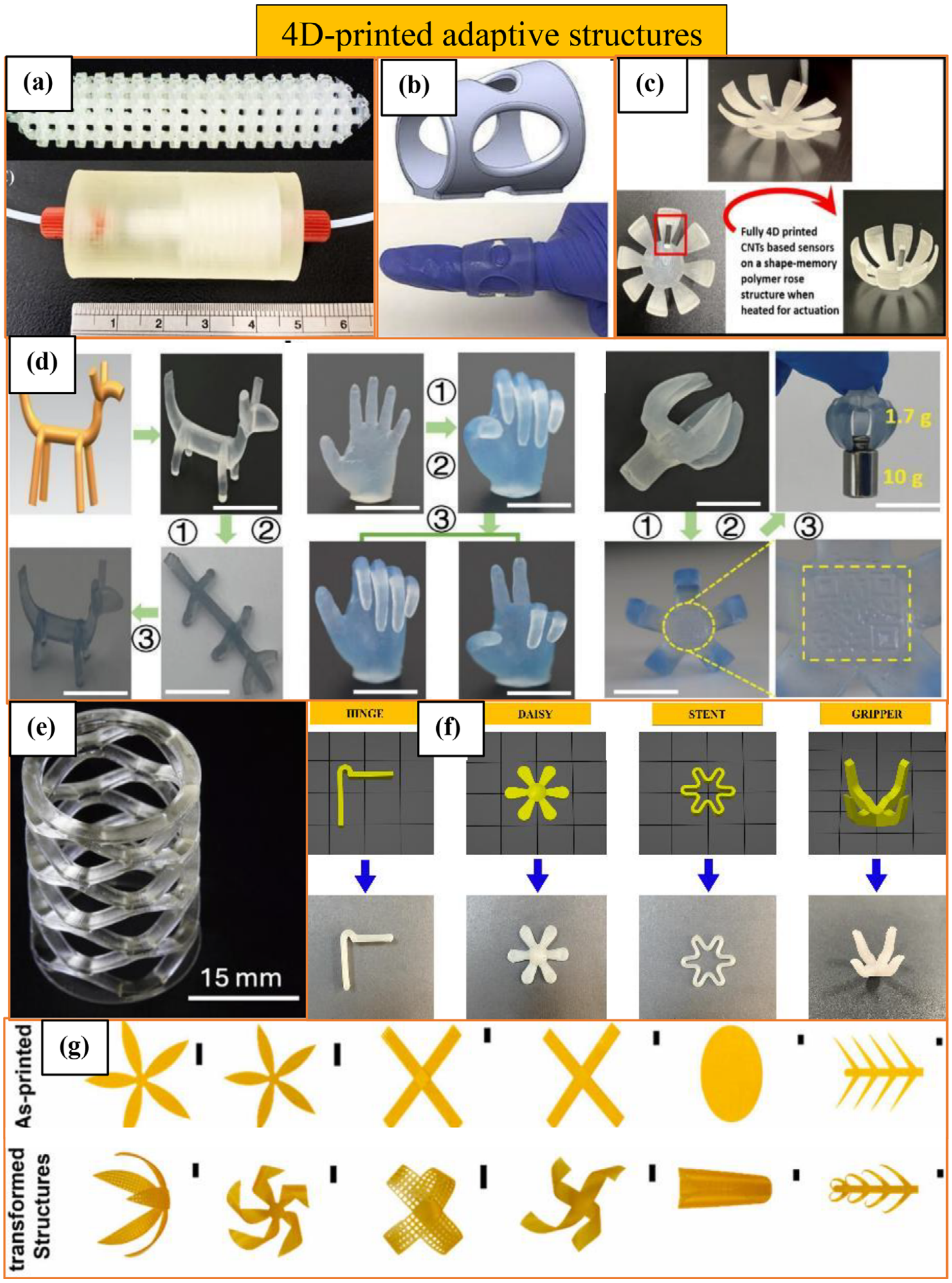


Figure 20. a) Images of the 4D-printed elution-peak-guided dual-responsive monolithic packing and fitted with two flat-bottom male connectors for facilitating the analyses of the metal ions in complex real samples (Reproduced with permission.[369] under a Creative Commons Attribution license 4.0); b) the DLP-based 3D printed Pluronic F-127 diacrylate/mecelle-based hydrogels with lithium chloride-based conductive tactile sensors for ideal sensing applications in real-time human motion even in a −20 °C low-temperature environment (Reproduced with permission.[370] Copyright 2024, American Chemical Society); c) DIW-based 4D-printed flower structure from CNT-based smart hybrid materials for fascinating soft robotic applications (Reproduced with permission.[371] under a Creative Commons Attribution license 4.0); d) Representation of DLP-based 4D printed SMP nanocomposites demonstrating the photoswitchable shape memory behaviors under NIR irradiation of the various designed and printed structures such as puppy, temporarily curved fingers and multifunctional gripper with confidential information (Reproduced with permission.[372] Copyright 2024, Wiley-VCH GmbH); e) 4D-printed intricate spiral structure (Reproduced with permission.[373] under a Creative Commons Attribution license 4.0); f) Demonstration of various designs as adaptive structures including hinge, daisy, stent and robotic gripper (Reproduced with permission.[374] Copyright 2025, Elsevier B.V.); g) DLP 3D-printed shape-morphing structures transform during thermal curing. Bionic flowers bend into compact or twist into pinwheel-like shapes. A mechanical gripper performs grasping or twisting. An oval leaf curls inward, while a biomimetic fern exhibits gradient curling in its leaflets (all images under a 5 mm scale bar) (Reproduced with permission.[375] Copyright 2025, Elsevier B.V.).

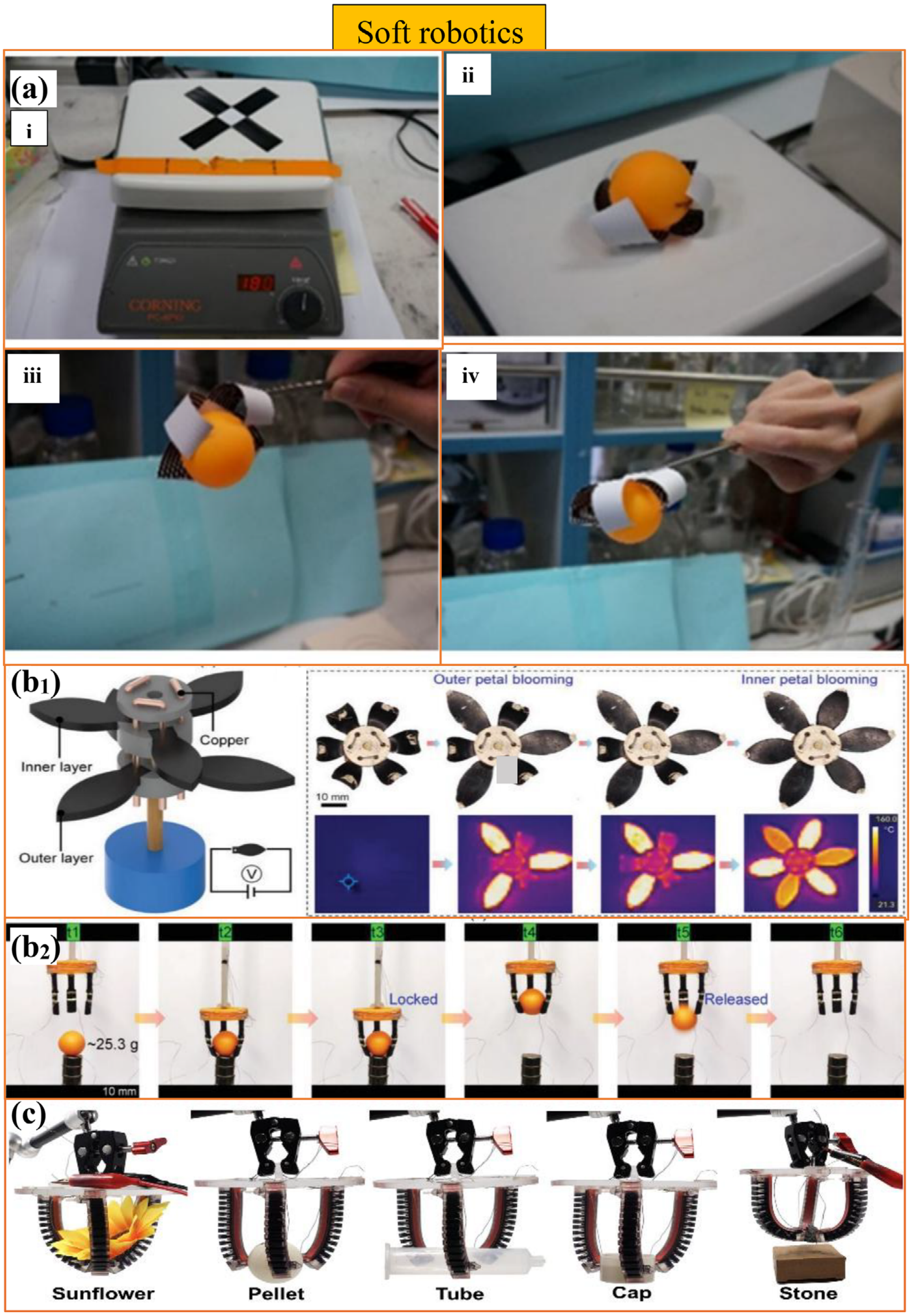
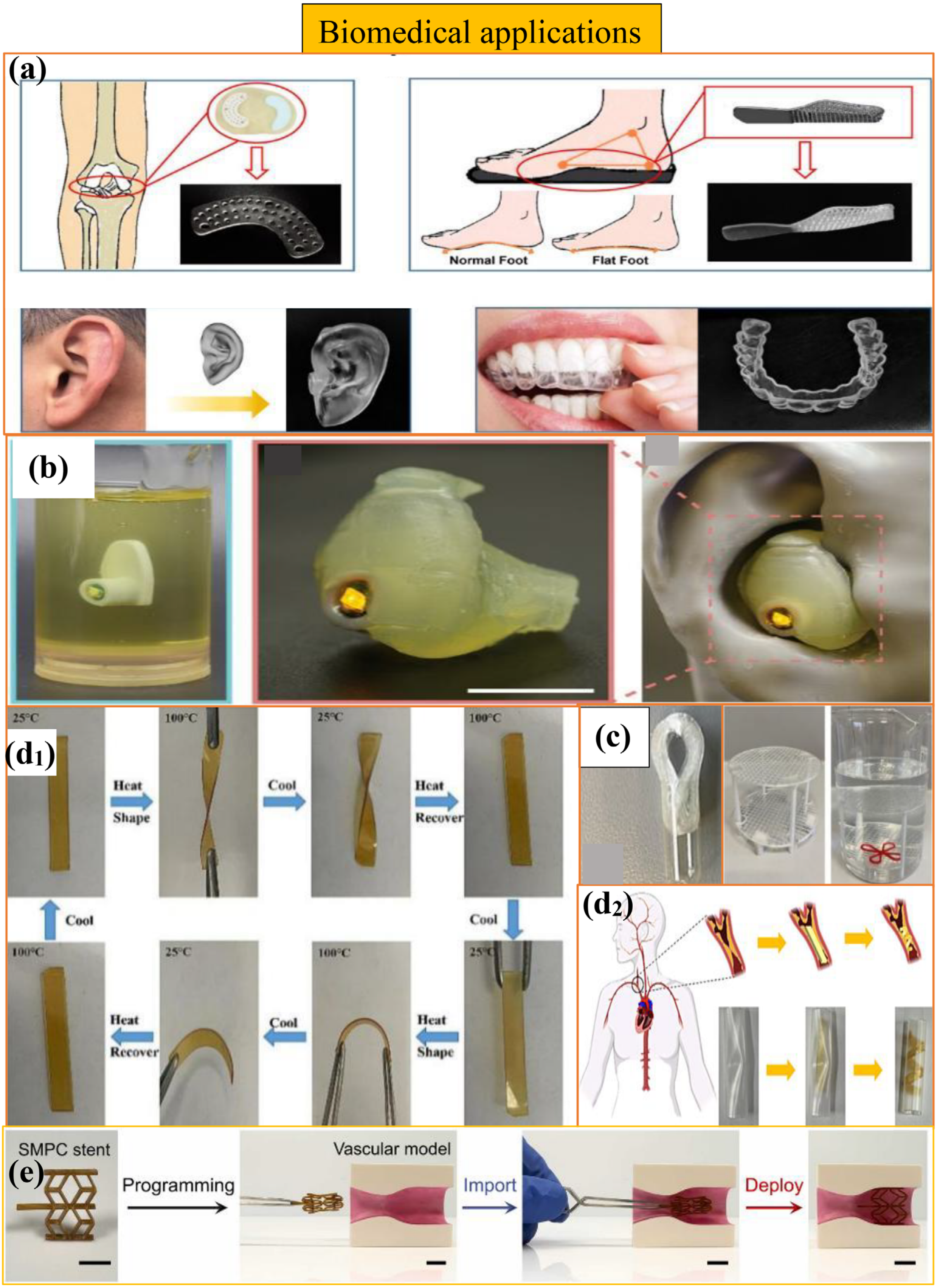


Figure 21. a) Demonstration of claw gripper of soft robot and its grasp behavior such as (i) heating situation and (ii) cooling situation on the hot plate, (iii) using the tweezer to pick up the ball from the hot plate and slowly turn upside down, (iv) successfully grabbing the tennis ball (Reproduced with permission.[385] Copyright 2024, Society of Plastics Engineers, Published by John Wiley and Sons); b_1-b_2) (b_1) The two-layered petal structures design and the blooming process of the artificial petals under sequential DC voltage activation due to the SME, (b_2) Sequential photos of the electric and magnetic actuation performance of developed gripper (Reproduced with permission.[389] Copyright 2024, Wiley-VCH GmbH); c) Demonstration of grasping of various objects such as a sunflower, a small ball, a test tube, a bottle cap, and a small stone by the multifunctional gripper in the stress-release drive mode (Reproduced with permission.[313] Copyright 2025, Elsevier B.V.).


Biomedical applications
(a)
Normal Foot
Flat Foot
(b)
(c)
(d1)
25°C
100°C
Heat
Shape
Cool
Heat
Recover
Cool
(d2)
(e)
SMPC stent
Programming
Vascular model
Import
Deploy

printers, now available for as little as $500 compared to over $100 000 in the 1990s, have seen significant advancements. In 2011, Stratasys, Z Corporation, and 3D Systems accounted for 62.8% of commercial/industrial AM units. The 3D printing industry is projected to grow to $50 billion by 2029–2031 and $100 billion by 2031–2044.[360] This is expected by giving proper consideration to the 4′Ms strategies as shown in **Figure 19**. Generally, a good balance between printability and mechanical properties is vital for printed parts which are widely investigated in laboratories. Transitioning from lab-scale to large-scale production requires a thorough investigation of key factors such as preparation, transportation, storage, and supply, as well as economic and environmental considerations, including reducing carbon emissions and printing costs.[361] It is worth noting that with the wide availability of 3D printers, many students and senior researchers now have experience using them both in universities and at home, leading to significant knowledge and expertise with these tools. Currently, many institutional 3DP centers are collaborating with various R&D sectors and multiple clinical departments. This collaboration is crucial for designing tailored and practical tools, improving overall efficiency, and creating structures adopted to real applications.[362,363] Currently, there are two main approaches to constructing 3D structures for wearable electronics by printing: first is printing 2D traces or 3D structures onto a preformed 3D structure second is directly printing functional or composite materials onto a planar substrate. 3DP for wearable electronics has potential benefits such as a simple cost-effective setup and continuous fabrication process that offers rapid prototyping, multimaterial compatibility, and the creation of flexible hybrid electronics, particularly at an industrial scale.

Extrusion-based printers allow for the creation of objects without the constraints of a formwork.[364] During extrusion, optimizing printing ink parameters such as droplet extrusion, substrate spreading, and ejection speed ensures controllable, uniform thickness, enhancing the miniaturization of printed soft devices. Moreover, layer-by-layer stacking during the printing process also ensures perfect alignment accuracy.[365] Thus giving proper consideration durability and reliability can be achieved for high-performance soft devices from an industrial-scale perspective.[366] Recently, Kim et al.[367] proposed a large-scale and ultrafast manufacturing method for customized wound patches aimed at advanced tissue regeneration. This technology features an autonomous robot arm with a computer vision system for rapid image recognition, integrated with extrusion-based 3DP. Three different types of inks are printed on flexible substrates to enhance the production process, accelerating the healing process in clinical wound therapy. Likewise, Leschok et al.[368] conducted various experiments on large-scale 3DP to investigate features such as bridging, nonplanar printing, and cantilevering. They demonstrated that 3D prints could be manufactured with hollow extrusion beads. Also, they found that the size of the extruded cross-section was controlled by the positive air pressure used to inflate the beads. As a result, multiple samples were printed by only adjusting the width and layer height without any changes to the hardware setup.

8.1. 3D-Printed SMP: Enabling Next-Gen Wearables and Soft Electronics

In the last decades, technological advances and frontiers for both 3DP/4DP techniques and SMP have triggered state-of-the-art innovations for mankind. As discussed above, 4D printed SMPs enable complex, customized architectures with precise control over spatial functionality. This synergy facilitates the development of adaptive structures also highlighted in **Figure 20** in fields such as soft electronics (e.g., morphing actuators and grippers) and biomedical devices (e.g., self-expanding stents or minimally invasive surgical tools). Here in this section, we overviewed some recent wearable and flexible electronics applications.

8.1.1. Sensors, Actuators, and Soft Robotics

With 4D-printed SMP, a variety of applications can be realized that are not possible with rigid counterparts, such as sensors, actuators, and soft robots that can be programmable and adaptable. Soft robots are highly versatile robots made from soft materials and can interact with fragile or soft objects/organisms over their rigid counterparts.[376,377] On the other hand, when interacting with fragile or soft objects, rigid robots face significant challenges due to their lack of flexibility and difficulty in precisely controlling applied force. It is often difficult for them to detect subtle changes in an object's properties, which increases the risk of damage.[378] Additionally, handling soft or irregularly shaped objects necessitates advanced algorithms and sensors, which are challenging to integrate into rigid robots. These challenges highlight the potential of soft robotics since they can adapt to various shapes, apply gentle forces, and provide greater sensitivity, making them ideal for handling delicate and soft objects.[379–381]

Soft robotics are especially well-suited for reversible shape change due to their mechanical deformability and morphological response to controlled stimuli such as heat, temperature, pH, light, magnetic and electric fields, or biomolecules in aqueous environments.[382–384] For instance, Lin et al.[385] optimized the grasping ability of an FDM-based 4D-printed soft robot. They employed PLA ribbons as SMP on cross-shaped bamboo sheets for designing a four-claw gripper of soft. The resultant 4D printed soft robot under heating stimulus grabbed the table tennis ball demonstrating its grasping ability as highlighted in **Figure 21a**.

Electro and magneto-active programmable SMPs offer fast, precise control and high energy efficiency compared to

Figure 22. a) 3D printed model of the knee meniscus and stent, orthopaedic insole models, ear prosthesis model, and highly transparent invisible braces (Reproduced with permission.[396] Copyright 2024, American Chemical Society); b) Insert suspended in gel photoresist before printing, overprinted model, and 3D-printed model of the outer ear with the auditory device fitted into the ear canal (Reproduced with permission.[400] Copyright 2023, Wiley-VCH GmbH); c) The cloverleaf, fitted into a size 00 capsule demonstrating the folding mechanism, opening and unfolding time testing based on mesh inserting left: 3D printed meshs insert, mesh insert in a 1 L beaker (Reproduced with permission.[401] Copyright 2022, Elsevier B.V); d_1- d_2) (d_1) Representation of shape memory programming data and (d_2) Representation of a spiral stent for cardiac vascular support for 0.4S-BDB@M–PMVS sample (Reproduced with permission.[402] Copyright 2024, Elsevier B.V.); e) Demonstration of deployment of the SMP composites stent within blood vessel phantom at 1 cm scale bars (Reproduced with permission.[403] Copyright 2025, The Authors, Published by Elsevier B.V.).

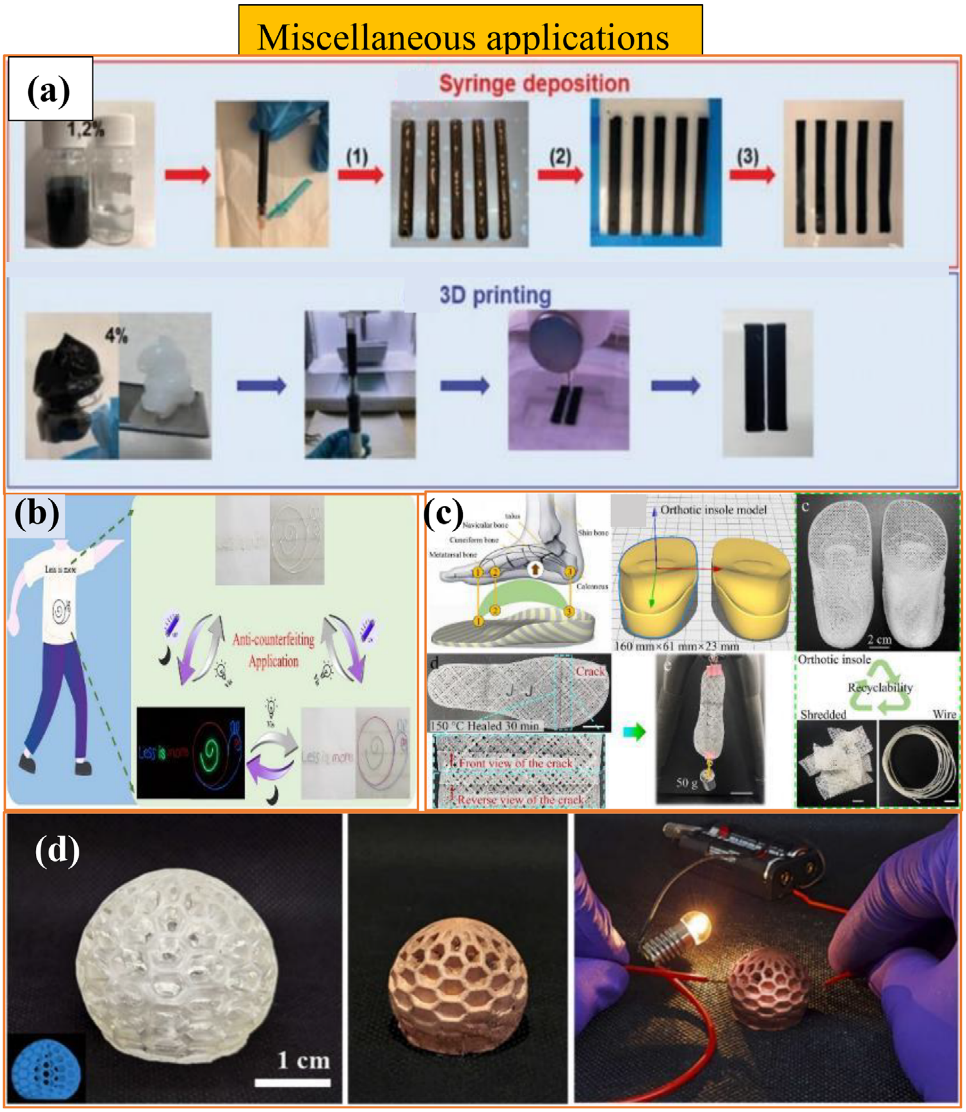


Figure 23. a) Schematic of fabrication of electronic patterned papers using syringe deposition and 3DP (Reproduced with permission from[412] under a Creative Commons Attribution license 4.0); b) Real image and the schematic diagram depicting the anti-counterfeiting design using photo-stimuli-responsive fibers (Reproduced with permission.[413] under a Creative Commons Attribution license 4.0); c) Representation of 4D printed foot orthopedics with the orthotic insole with superior performance such as recyclability, self-healing of the cracked 3D-printed sample (160 × 61 × 0.66 mm) after being healed at 150 °C for 30 min (images are under 2 cm scale bar) (Reproduced with permission.[414] Copyright 2024, Elsevier B.V.); d) Demonstration of a 3D hollow object after metallization and showing high conductivity Reproduced with permission.[151] Copyright 2024, Elsevier B.V).

other mechanical actuation methods (heat and light), making them human-friendly versatile lightweight, and compact applications.[386–388] Recently, Wu et al.[389] explained the working mechanism of smart grippers using multi-layer electrically/magnetically dual-driven shape memory composites based on a magnetic field-assisted DLP-based 4DP. This study revealed that 4D printed smart structures had magnetic responsive layers (10.7 emu g^{-1}) and electric conductive layers (up to 5.37 × 10^{-3} S cm^{-1}) which triggers and high-frequency magnetic field induction-based and Joule heat-based stimuli for demonstrating shape memory properties as presented in Figure $21b_1$. Moreover, these dual electrically/magnetically dual-driven and photocurable SMP composites showcased exceptional actuators and sensor performance as highlighted in Figure $21b_2$ with multiple functionalities.

Zhang et al.[313] proposed a multi-material UV-cured 4DP process for soft actuators, focusing on the integration of pre-stretched SMPs and their deformation behavior under stress-release and pneumatic drives. Insights of this study showed that by strategically embedding SMPs and silver nanowires electrothermal layers, the actuators achieved sequential and reversible deformations for demonstrating potential as highlighted in Figure 21c applications, including a foldable device and multi-modal gripper, highlighting the potential of 4D-printed soft actuators in diverse environmental conditions.

8.1.2. Biomedical Applications

4DP of soft functional materials with unique capabilities is expected to open new opportunities in various fields, enabling the development of advanced multifunctional sensing platforms for wearable technology applications.[390–392] Moreover, the dynamic response of SMP during 4DP adapts to various physical, chemical, and biological stimuli for creating biomimetic scaffolds that can dynamically adapt to complex tissue environments.[393,394] The 3D-printed soft actuators can mimic the movements of muscle tissue and organs such as the heart, skeletal muscles, and lungs.[395] Recently, Cao et al.[396] investigated photocurable glycerol polyether-based elastomer for demonstrating glycerol polyether acrylate oligomer using a one-step esterification method. After that elastomer's photo resin was developed having a low viscosity (258 mPa·s) while maintaining high performance by incorporating biocompatible isobornyl acrylate and N-vinylpyrrolidone. The insights of this study showed that the proposed photocurable elastomer can be used as a printing resin under 365 and 405 nm UV lights for DLP and SLA printers. The glycerol polyether acrylate elastomer demonstrated high biocompatibility, evidenced by low cytotoxicity, minimal dermal irritation, and negligible skin sensitization, highlighting its potential for wearable and biomedical applications (**Figure** 22a).

Wearable devices are expected to dominate biomedical monitoring applications due to various advanced technologies, including 3DP, which offers unique benefits such as highly conformable designs for detecting human motions.[397–399] Toombs et al.[400] fabricated three-component transparent using ethyl cellulose (EC)-based thermoreversible through DLP-based 4DP techniques. The results demonstrated that overprinted models—produced by printing over a pre-existing object were optimized and evaluated for an auditory device, achieving good shape conformation when fitted into the outer ear of a 3D-printed model, as depicted in Figure 22b. Thus, the proposed methodology using unfolding and expanding dosage forms has enormous potential to be used in emerging medicinal devices or sustained drug delivery concepts. Großmann et al.[401] produced various shapes and foldable objects using 3DP TPU filaments. Furthermore, their shape memory behavior was studied in water-soluble hard gelatin capsules. Depending on the shape and material, the unfolding time and dimensional recovery of the 3D-printed dosage forms were explored for possible gastric retention, as presented in Figure 22c. Guo et al.[402] investigated polysiloxanes using N-acetylcysteine and photosensitive molding with a dynamic borate ester crosslinker (S-BDB) for demonstrating antibacterial properties, self-healing properties, and fluorescent marker printing capabilities. The findings revealed that N-acetylcysteine and S-BDB's dynamic borate ester bonds exhibited self-healing (99.2%) and shape memory capabilities, facilitated by rapid hydrogen bond exchange at high temperatures and borate ester fixation, allowing for shape manipulation, as depicted in Figure $22d_1$. Moreover, when heated, the stent ring returned to its helical shape after initially being rigid and straight as shown in Figure $22d_2$ thus, supporting a blocked blood vessel with its shape memory performance. With its shape memory capabilities, this flexible helical support structure offers great potential for cardiovascular stenosis stents. Huang et al.[403] developed a novel thermoplastic polymer system for DLP-based 4DP, featuring self-healing and highly stretchable shape-memory capabilities. The system integrates a reinforcing polymer framework with a hydrogen bond-rich elastic lubricant, enhancing both flexibility and shape recovery. Notably, a lignin-containing PU acrylate-based SMP composite was synthesized using a biomass lignin-based cross-linker, imparting light-responsive properties and ensuring biocompatibility. These 4D-printed SMP composites demonstrate various adaptive structures such as active stent suggesting potential for applications in intelligent healthcare systems as illustrated in Figure 22e.

8.1.3. Miscellaneous Applications

The advent of 4DP technology has reinvigorated the development of SMP,[404] thus facilitating the precise and rapid novel intricate smart structures with enhanced functionalities suggesting its applicability to the food industry,[405–407] artificial muscles,[408] electronic switches,[409] protective devices[410] and anti-counterfeiting devices.[411] Recently, Lay et al.[412] prepared 2D and 3D electronic patterned paper from DIW of PEDOT:PSS/nanocellulose as presented in **Figure** 23a. Insights of this study revealed that printed supercapacitor has excellent mechanical stability for practical handling and good conducting for high-power devices and can be employed in smart packaging and wearable electronics. Shen et al.[413] prepared stimuli-responsive fibers having various colors of luminescent and reversible photochromic characteristics. Red, green, and blue-based three photochromic pigment colors distributed uniformly in fibers. The developed fibers exhibited a broad emission spectrum with full-color output and demonstrated reversible, rapid photochromic response under ultraviolet light, as shown in Figure 23b.

Li et.al.[414] developed a shape memory reconfigurable and self-healing poly(urethane-ureaamide) elastomer (sPUUA) through FDM-based 4DP. A series of sPUUA elastomers containing thiocarbamate, disulfide, and carbamate dynamic bonds was synthesized via an extrusion reaction using a twin-screw extruder. The process involved copolymerizing isocyanate-terminated PU prepolymer, polyetheramine, and amino-terminated oligomeric PA-12. The sPUUA was prepared by granulation, drying, extrusion, and hot pressing into a 1.75 ± 0.05 mm wire for FDM printing. This study revealed that 4D-printed sPUUA samples exhibited self-healing efficiency (69%) after thermal treatment at 150 °C for 30 minutes, along with tensile strength (9.6 MPa) and elongation at break (402.3%). This unique 4DP self-healed sPUUA is employed for foot orthopedics with the orthotic insole as presented in Figure 23c with other potential applications in biomedicine and robotics.

Multifunctional SMP as a new-generation intelligent device is expected to have wide application scenarios in challenging applications with multiple functions and mechanical deformation.[415,416] You et al.[151] prepared a novel formulation of photocurable PU acrylate (PUA) resin containing a symmetric polymer structure of 1,3-adamantanediol for reducing the dielectric constant. The improved PUA demonstrated excellent mechanical properties such as tensile strength (12.02 MPa) and elongation break at 111.35%. Moreover, the dielectric properties of PUA further reduced to 0.006 by adding a small amount of BN powder (1 wt.%) which was feasible for be for 5G device applications. The PUA resin is also employed for the printing of

Table 6. Highlights of recent works on various stimuli activated 3D printed SMP for soft electronics applications.

Stimuli	3DP technique	SMP	Smart behavior	Soft electronics/adaptive structures	Refs.
Temperature	DIW	PUA	Bending	Novel reconfigurable structures	[418]
Temperature	FDM/FFF	CNC/Poly(ε-caprolactone-co-lactide)-PEG-Poly(ε-caprolactone-co-lactide)	Bending	Biomedical scaffolds	[419]
Temperature	SLA	Poly (N-vinyl caprolactam)	Swelling	Biomedical applications	[420]
Temperature	FDM/FFF	PLA/CNC	Folding	Wearable electronics	[421]
Temperature	FDM/FFF	PLA/PBS	Compressive behavior	Smart structures	[422]
Temperature	FDM/FFF	CNC/PU/ball milled nanocellulose	Bending	Smart devices	[423]
Temperature	FDM/FFF	PLA/PBS	Self-deformation	Smart structures	[424]
Temperature	DIW	CNC/Acrylic acid (AA)	Self-healing	Wearable sensors	[425]
Temperature	FDM/FFF	TPU/elastomers	Self-folding	pre-configurable shape-memory textiles	[426]
Temperature	FDM/FFF	Recycled PETG	Bending	low-priced lightweight resettable actuators	[427]
Temperature	FDM/FFF	CNC/PU	Bending	smart biomaterials-based various applications	[423]
Temperature	FDM/FFF	PLA/PMMA	Bending	Biomedical devices	[428]
Temperature	FDM/FFF	PLA/PCL	Bending	Soft actuator	[429]
Temperature	FDM/FFF	PU/PLA	–	Smart grippers	[430]
Temperature	FDM/FFF	PCL/PLA	Folding	Medical protective devices	[431]
Temperature	FDM/FFF	TPU	Bending	Functional gripper-like structure	[432]
Temperature	FDM/FFF	PLA/Hydroxyapatite	Self-healing and bending	Self-healing bone implants	[433]
Temperature	FDM/FFF	PLA	Bending	Smart actuator	[434]
Temperature	FDM/FFF	Acrylonitrile–butadiene–styrene (ABS)	Origami and shrinking	Self-assembly structures	[435]
Temperature	FDM/FFF	PDMA/n-octadecyl acrylate	Bending	Skin-like sensors	[436]
Temperature	VPP	Polymer derived ceramics	Folding	Smart structures	[437]
Temperature	FDM/FFF	PCL/TPU	Bending and grasping	Bionic grippers	[438]
Temperature	FDM/FFF	PLA/PCL/PU	Shrinking	Soft robotics	[439]
Temperature	DLP	Poly(β-aminoesters) and C18-acrylate	Self-expansion	Biodegradable intestinal drug delivery devices	[440]
Temperature	DLP	cyanate esters/triethoxytriazine and diols.	Folding and bending	Smart structures	[441]
Temperature	FDM/FFF	PETG/Poly(ethylene-co-octene)	Bending	Smart structures	[442]
Temperature	FDM/FFF	PLA/poly(ethylene-co-vinyl acetate	Bending	Smart structures	[443]
NIR light	FDM/FFF	PETG/Poly(dopamine)	Curling, folding, and twisting	Smart devices for the biomedical field	[444]
Light	DIW	PU/lignin nanotubes	Bending and shrinking	Soft robots	[445]
Light and heat	FDM/FFF	PLA	Bending	Microfluidic control devices	[446]
Light and heat	FDM/FFF	TPU/PLA/polyaniline	Shrinking and bending	Smart actuators	[447]
Light	FDM/FFF	PLA/CB	Shrinking and origami	Smart electronics, origami structures, and robot precision control.	[448]
Light	VPP	Poly(N-isopropyl acrylamide) (PNIPAM/AA	Changing color	Soft robots	[449]

(Continued)

Table 6. (Continued)

Stimuli	3DP technique	SMP	Smart behavior	Soft electronics/adaptive structures	Refs.
Light and temperature	VPP	azobenzene-based acrylates	Bending	Smart structures	[450]
Light + magnetic field	DIW	PNIPAM/PEG/Fe_3O_4	Shrinking, swelling, and flipping	Soft carriers	[451]
Heat	FDM/FFF	PCL/Polybutylene adipate terephthalate/CNFs	Bending and folding	Bionic soft gripper	[452]
Heat	FDM/FFF	PETG/SEBS	Bending, and twisting	Adaptive structures	[453]
Heat	FDM/FFF	PLA	Bending	two-sieve filtering device for small objects	[454]
Heat	FDM/FFF	CNC/polyester	Bending	Bioinspired structures	[455]
Heat	FDM/FFF	Carbon fibers/PEKK	–	High-temperature smart structures/actuators	[456]
Heat	FDM/FFF	PLA	Bending	Grippers	[457]
Heat	SLA	Acrylate-epoxy hybrid photopolymer	Shrinking	Deployable structures	[458]
Heat	FDM/FFF	PLA	Spiralling	Self-spiralling pattern-driven actuator	[459]
Heat	SLA	polyetherimide or polysulfone	–	Smart structures	[460]
Heat	SLA	Acrylic resin	Shrinking and folding	Biomedical devices	[461]
Heat	SLA	hexadecyl acrylate hydrophilic N,N-dimethyl acrylamide, and methacrylic acid	Shape memory and self-healing performance	smart packaging and drug delivery systems.	[462]
Heat	SLS	Thermoplastic polyamide elastomer	Bending and folding	Smart architectures like soft robots	[463]
Heat	FDM/FFF	ABS	Bending	Smart structures	[464]
Heat +Magnetic field	FDM/FFF	PLA/Fe	Bending and folding	Medical implantable devices, and flexible electronic devices	[465]
Heat and ionic	DIW	PCL methacryloyl chloride/sodium alginate methacrylate	Self-rolling	Vascular stent	[466]
Heat and mechanical	FDM/FFF	PLA	Shrinking and origami	Energy absorbing devices	[467]
Humidity	FDM/electrospinning	PCL/Polyethylene oxide/CNC	Swelling	Bioinspired soft robot	[468]
Humidity	FDM/FFF	PU/elastomer	Folding and twisting	Origami structures	[469]
pH	DLP	LCiquid resin (PlasClear)	Swelling	Soft Actuators	[470]
pH	2PP	Acrylic acid/PNIPAM	Bending	untethered micro-robots	[471]
Magnetic field	FDM/FFF	PCL/PHB/CNFs/Fe_3O_4	Bending	Smart actuators	[73]
Magnetic field	FDM/FFF	PLA/hematite (α-Fe_2O_3)nanoparticles	–	Cardiovascular stents	[472]
Heat and water	DIW	PU/PVC	Swelling and bending	Soft gripper	[473]
Heat and magnetic field	DIW	Poly(D,L-lactide-co-methyl carbonate/Poly(trimethylene carbonate/Fe_3O_4	Bending	Multi-functional devices like soft robots	[474]

(*Continued*)

Table 6. (Continued)

Stimuli	3DP technique	SMP	Smart behavior	Soft electronics/adaptive structures	Refs.
Magnetic field	SLS	PA-12/γ-Fe_2O_3	Bending and grasping	Smart grippers	[475]
Heat and magnetic field	DIW	TPU/PCL/Fe_3O_4	Bending and grasping	Flexible robotics	[476]
Magnetic field	FDM/FFF	PLA/TPU/Fe_3O_4	Folding and gripping	Smart actuators	[477]
Magnetic field	SLS	TPU/Nd2Fe14B	Sequential shape change	Smart grippers	[478]
Magnetic field	FDM/FFF	PLA/iron particles	Bending and gripping	Smart grippers	[479]
Magnetic field	FDM/FFF	PCL/Polyhydroxybutyrate (PHB)/CNFs/Fe_3O_4	Bending	Smart actuators	[73]
Electric field	FDM/FFF	Polypyrrole/gold	Rolling and gripping	Soft micro-actuators	[480]
Electric field	FDM/FFF	PLA/CNTs	Bending and folding	Embeddable sensors	[481]
Electric field+temperature	FDM/FFF	CB/PLA	Bending	Soft actuators	[482]
Electric field	FDM/FFF	PLA/TPU/CNT/carbon fibers	Shrinking	Adaptive energy absorption devices	[170]
Electric field	FDM/FFF	PLA/polyester urethane/MWCNTs	Bending and grasping	Soft robotics and actuators	[483]
Electric field	FDM/FFF	PLA/CNTs	Folding	Electroactive deformable devices	[484]
Electric field	DLP	Poly(acrylic acid)	Folding and gripping	Soft robotic actuator	[485]
Electric field	DIW	PEEK	Bending and crawling	Reversible actuators, deployable structures, and soft robotics	[486]
Electric field	IJP	PCL/CNTs	Folding	Flexible electronic devices	[487]
Electric field	FDM/FFF	CNC/TPU/PCL	Bending	Biomimetic skin and conductive devices	[488]
Solvent	DLP	PUA/acrylamide/AA	Stretching and compression	Soft lattice structures	[489]

complex and flexible 3D structures as presented in Figure 23d for 5G flexible circuit board applications with low dielectric constant values enabling them to be used as a promising replacement for traditional rigid substrates for 5G flexible board applications.

Tang et al.[417] investigated the color and flavor behavior of white radish and potato gels with a lipid-soluble natural pigment, micro-encapsulated using gum Arabic, maltodextrin, and β-cyclodextrin through 3DP. Under microwave-infrared heating, the brightness of these smart 3D-printed structures decreased, while their yellowness and redness increased with longer heating times. The proposed 3DP technique has enormous scope in the foods industry for developing various colors and unique flavors-based foods.

For the purpose of competing for new SMP and novel applications also discussed in **Table 6**, 4DP and stimuli-responsive polymers must be considered as integral components, when considering a multi-process system or a series of integrated processes.

9. More Focus on Sustainability

Sustainable 3D printing relies on strategies like cellular structures and part consolidation in the design phase to minimize material usage effectively.[490] Moreover, utilizing recycled materials decreases waste and costs, while post-manufacturing self-repairing techniques extend the product lifespan.[491] Traditional, synthetic polymers from renewable fuels deplete valuable resources and cause serious environmental issues.[492] For instance, producing plastics in a lab requires a significant amount of both natural and synthetic materials. This process often involves extracting raw materials from the environment, which can deplete natural resources. Additionally, synthesizing these materials into usable plastics demands a considerable amount of energy. This energy is necessary to achieve the desired properties, such as strength, flexibility, and durability, which are essential for various applications. The high energy consumption and resource use can contribute to environmental concerns, including increased carbon emissions and resource scarcity. Moreover, their waste adversely affects ecosystems, directly impacting biodiversity and contaminating oceans through wildlife ingestion.[493,494] It is noteworthy that some synthetic SMPs are toxic, unsuitable for long-term use, and generally limited to specific applications.[495] For instance, PU-based SMPs can release harmful isocyanates during their synthesis and degradation processes, which are known to be toxic and can cause respiratory issues. Another example is certain epoxy-based SMPs, which can contain bisphenol which is a chemical that has been linked to various health concerns, including endocrine disruption. In this context, biomaterials can be a promising solution.[496] In biodegradable materials, sustainable additive manufacturing is crucial for ensuring cost-effectiveness, availability, and flexibility, thereby enhancing long-term biocompatibility.[497,498] 3DP, particularly FFF uses additive processes that build parts layer by layer, resulting in lower energy consumption. Recent studies have shown that 3DP can lower energy usage by up to 50% compared to the discussed processes.[499,500]

The integration of sustainability into 4DP provides an innovative path toward reducing environmental impact while advancing smart material technologies. These bio-based materials such as natural materials both plant-based (such as wood, natural fibers, cellulose, lignin, alginate, agarose, starch, pollen, and plant oil-derived polymers) and animal-based (including xanthan gum, chitosan, keratin, silk, and bovine serum albumin offer unique properties and responsiveness that make them ideal for fabricating dynamic objects capable of adapting to environmental stimuli.[501] Thus, energy-efficient 4DP technology, combined with biomaterials as potential feedstock, is becoming increasingly important for soft electronics which not only supports the goals of a circular bioeconomy but also paves the way for innovative advances in the design of intelligent, multifunctional systems.[502] These responsive biocomposites hold significant potential in fields like soft robotics, tissue engineering, drug delivery, smart packaging, architecture, and wearable electronics. Jung et al.[503] investigated the role of bio-based TPU derived from corn sugar polyester polyols as a sustainable SMP for FDM 3D printing. The proposed SMP exhibited shape recovery after deformation (**Figure 24a**) along with favorable mechanical properties, including a tensile strength of 15–21 MPa and elongation at a break of 534–585%. The study underscores bio-based TPU sustainability and its potential for shape-memory applications, contributing to advancements in 4D printing technology. Likewise, Lu et al.[504] investigated the multi-stimuli behavior of cellulose/PCL/Fe_3O_4 composite. Results showed that the "hard" and "soft" interactive structures lifted a weight of approximately 21 200 times their mass and had mechanical strength of 25.7 MPa and toughness of 107.0 MJ/m^3. Furthermore, the composite demonstrated shape memory behavior with a shape recovery ratio above 96% under temperature stimulus. NIR light-triggered shape memory characteristics of composites are highlighted in Figure 24b_1,b_2 for promising applications in heavy-lifting weight, self-tightening knots, and object transportation.

Boonnao et al.[505] adopted a sustainable approach to high-performance 4DP by blending biobased eugenol-furfuryl amine benzoxazine with a photoreactive acrylic resin, using dual UV printing and thermal curing method as shown in Figure 24c. Insights of this study showed that the 15 wt.% eugenol-furfurylamine benzoxazine improved mechanical properties such as flexural strength of 146.84 MPa, tensile strength of 81.80 MPa, and a 16 °C increase in 5% weight loss temperature. The optimum blending of the proposed resins system also improved shape memory properties including shape recovery ratio (97.8%), shape fixity ratio (99.6%), and stability for up to 15 shape memory cycles highlighting its potential for advanced engineering applications.

Table 7 provides an overview of natural materials used in smart and sustainable manufacturing and their related applications.

10. AI-Driven Technology for Practical Applications Scenarios

To accurately predict and optimize the time- and temperature-dependent mechanical behavior of SMPs during 4D printing, developing a robust constitutive model is critical, as the evolution behavior of the polymer object is usually complex and diverse.[516] To date, various thermo-mechanical viscoelastic constitutive models integrated with finite element analysis, and computational tools have been employed for predicting and optimizing the shape memory behavior of 4D-printed SMPs, enabling the precise design of SMP-based structure.[517] To fill this gap, constitutive models related to SMP and finite element analysis have been developed with more general applicability, which can be used to optimize design parameters for 4D printing with better efficiency and economics.

Now AI and machine learning (ML) can further enhance this modeling process by learning complex material responses, accelerating parameter calibration, and enabling real-time adaptive control for precise 4D-printed structure performance. Moreover, the intelligent 3DP system employs ML and computer vision for real-time monitoring, control, and analysis[518] thus can be beneficial for achieving Manufacturing 4.0 or Factory 4.0, significantly enhancing competitiveness and productivity. This method is particularly advantageous for high-value, low-volume products, enabling flexible production and mass customization. ML models can provide extensive input-output data, which can train printing system models with artificial neural networks. The various ML models (also detailed in **Table 8**) simplify printer operation through feedforward control and serve as the basis for a closed-loop controller, ensuring reproducible results by minimizing output errors in real-time.[519] Moreover, ML-based models provide the robustness, flexibility, and scalability needed for process control of AM in uncertain and complex environments. It has been shown that online ML models process in-situ sensory data to detect and diagnose flaws in real-time during 3DP.[520,521] The ultimate goal of the ML model is to find the exact relationships between different types of response and input parameters of 3D-printed parts and predict the exact output response.[522] Thus, improving overall throughput and reproducibility for 3DP systems.[523] The ML and AI are expected to ensure reliable scalability from lab-scale 4D printing of SMP to real-world engineering solutions, bridging the gap between theoretical modeling and practical industrial adoption.

The flourishing AI technology will continue to expand and collaboration with transforming technology is poised to unleash the astonishing potential of AI[525] ML, a sub-field of AI, provides methods to address the challenges related to experimental and computational time and costs.[526] The integration of ML in 3DP processes has attracted a great deal of attention for various reasons such as improving the printing of complex patterns from large datasets, controlled microstructure analysis, and easy material formulation.[524] Moreover, ML algorithms can optimize SMP 3DP parameters by predicting and adjusting material properties,[527] enhancing performance efficiency, reliability, and adaptability.[528] Moreover, ML techniques remarkably improved the 3DP process also summarized in **Figure 25** in various aspects by leveraging data-driven approaches.[529] Thus, AI with intelligent manufacturing is considered a contemporary in-

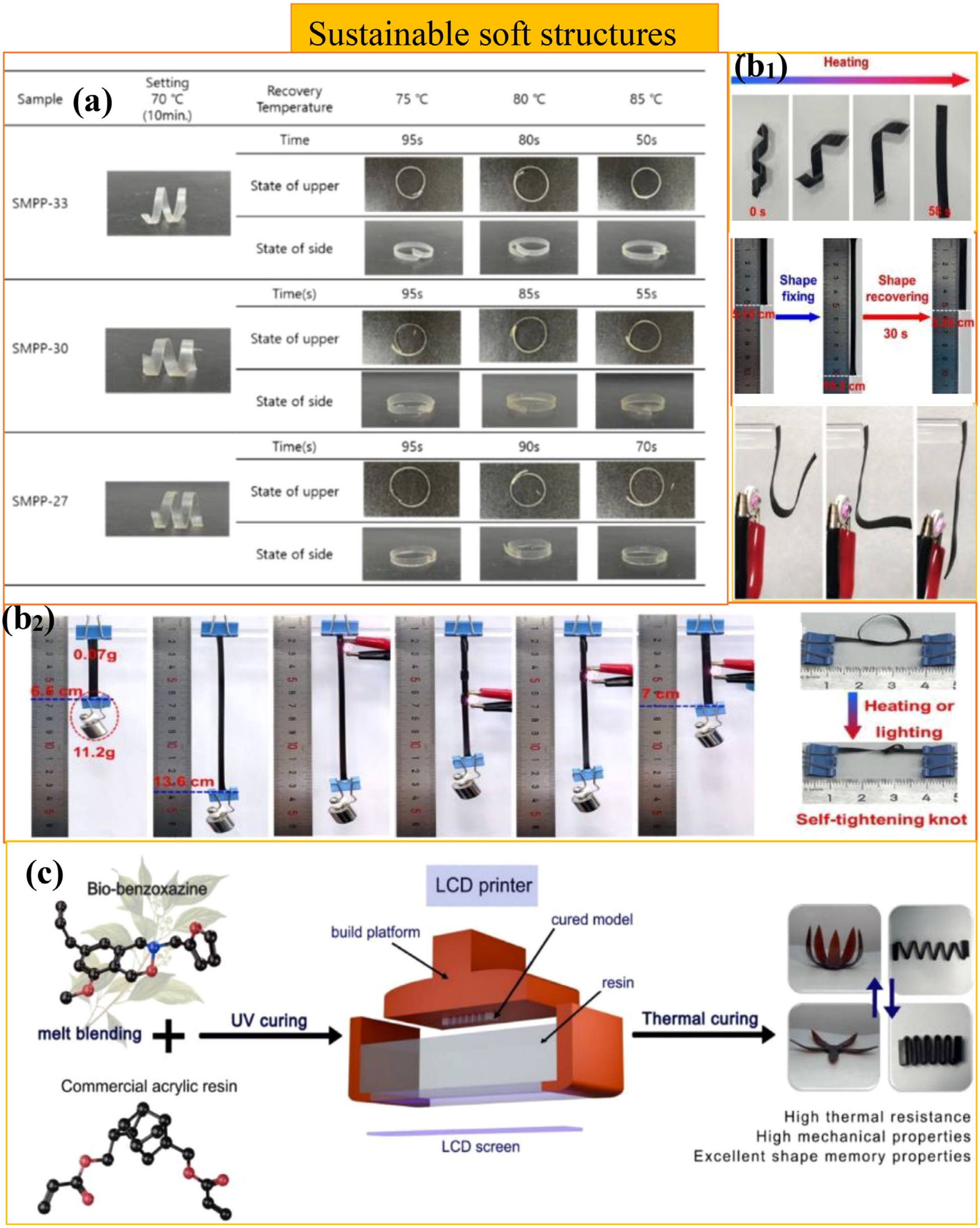


Figure 24. a) Images demonstrating the shape memory process of shape memory TPU films (Reproduced with permission.[503] under a Creative Commons Attribution license 4.0); b_1-b_2) The shape memory performance of composites under temperature stimulus (b_1) spiral-shaped sample and stretched sample, shape memory performance under NIR light stimulus, and V-shaped sample and (b_2) stretched sample and self-tightening knots application of the proposed composites (Reproduced with permission.[504] Copyright 2022, Elsevier B.V.); c) Demonstration of 3DP and dual-curing process for biobased eugenol-furfurylamine benzoxazine with a photoreactive acrylic resin for producing smart structures (Reproduced with permission.[505] Copyright 2025, Elsevier B.V.).

Table 7. Summary of recent works on smart and sustainable manufacturing.

Smart and sustainable manufacturing			Applications	Refs.
3DP	Bio SMP	Stimulus		
FDM/FFF	Banana and orange peel, cinnamon, neem leaf fibers/ABS	Temperature	Smart structures	[506]
FDM/FFF	PCL-PLA copolymer	Temperature	Protection of elbow	[431]
FDM/FFF	PBAT/carbon black	Temperature	Smart structures	[507]
FDM/FFF	Fe_3O_4/bioactive glass/PCL	Magnetic	Bone tissue scaffolds	[508]
FDM/FFF	PLA/CNC	–	Biomedical applications	[509]
FDM/FFF	PLA	Temperature	Protective visors frame	[510]
FDM/FFF	PLA/TPU	Temperature	Meta structures	[511]
FDM/FFF	PLA	Temperature	Smart structures	[512]
FDM/FFF	PLA/Fe_3O_4	Magnetic	Tracheal stents	[513]
DIW	PLA/Fe_3O_4/benzophenone	Magnetic	Cardiovascular implant	[38]
SLA	PLA/methacrylic anhydride	–	Smart structures	[514]
SLA	PCL/Fe_3O_4	Magnetic	Tissue scaffolds	[515]

dustrial need from both economic and social perspectives. This AI technology can be seamlessly integrated with IoT technology, propelling the evolution of wearable electronics applications and fostering an intelligent world with various interconnected activities.[530]

3DP processes can encounter defects at various stages, affecting the quality and performance of components. These defects include geometric and surface irregularities, porosity, inadequate fusion, inclusions, residual stresses, and microstructural issues. However, optimizing process parameters can significantly benefit manufacturers by reducing manufacturing costs. By fine-tuning these parameters, manufacturers can enhance the quality of the finished product in several ways: reducing porosity, improving surface finish, and increasing dimensional accuracy. Effective process parameter optimization allows manufacturers to minimize defects and ensure their products meet required specifications. Recently, Ma et al.[532] implemented a novel data acquisition strategy and a training routine to reproduce the small-

Table 8. Overview of various types of ML techniques (Reproduced with permission.[524] Copyright 2024 The Authors. Advanced Materials published by Wiley-VCH GmbH.).

Types	Techniques
Reinforcement Learning	Monte Carlo Methods Policy Gradient Methods Actor-Critic
	Deep Q Networks (DQN)
	Q-learning
Supervised Learning	Support Vector Machine (SVM)
	Linear Regression
	Logistic Regression
	Decision Trees (Classification and Regression Tree)
	Gradient Boosted Trees (LightGBM, XGBoost, CatBoost)
	Random Forest
	Neural Networks (DNN, U-Net, RNN, LSTM, RandLA-Net,) Gaussian Process Modeling K-Nearest Neighbors (K-NN) Ensemble learning (Adaboost, bagging, Bayes optimal classifier, stacking)
Semi-supervised Learning	Generative Adversarial Networks (GANs) Domain Adversarial Neural Network (DANN)
	Multi-view Training
	Self-training
Unsupervised Learning	Principal Component Analysis (PCA)
	Hierarchical Clustering
	K-means Clustering
	Autoencoders (variational autoencoders)
	Gaussian Mixture Models
	Independent Component Analysis (ICA)

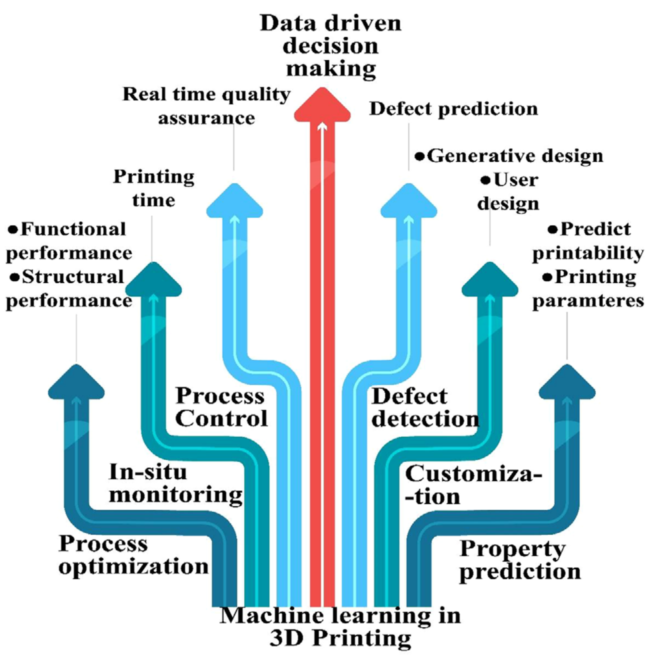


Figure 25. ML and 3DP have a unique synergy for improving the efficiency of the 3DP system (Figure drawn with the help of Ref. [531]).

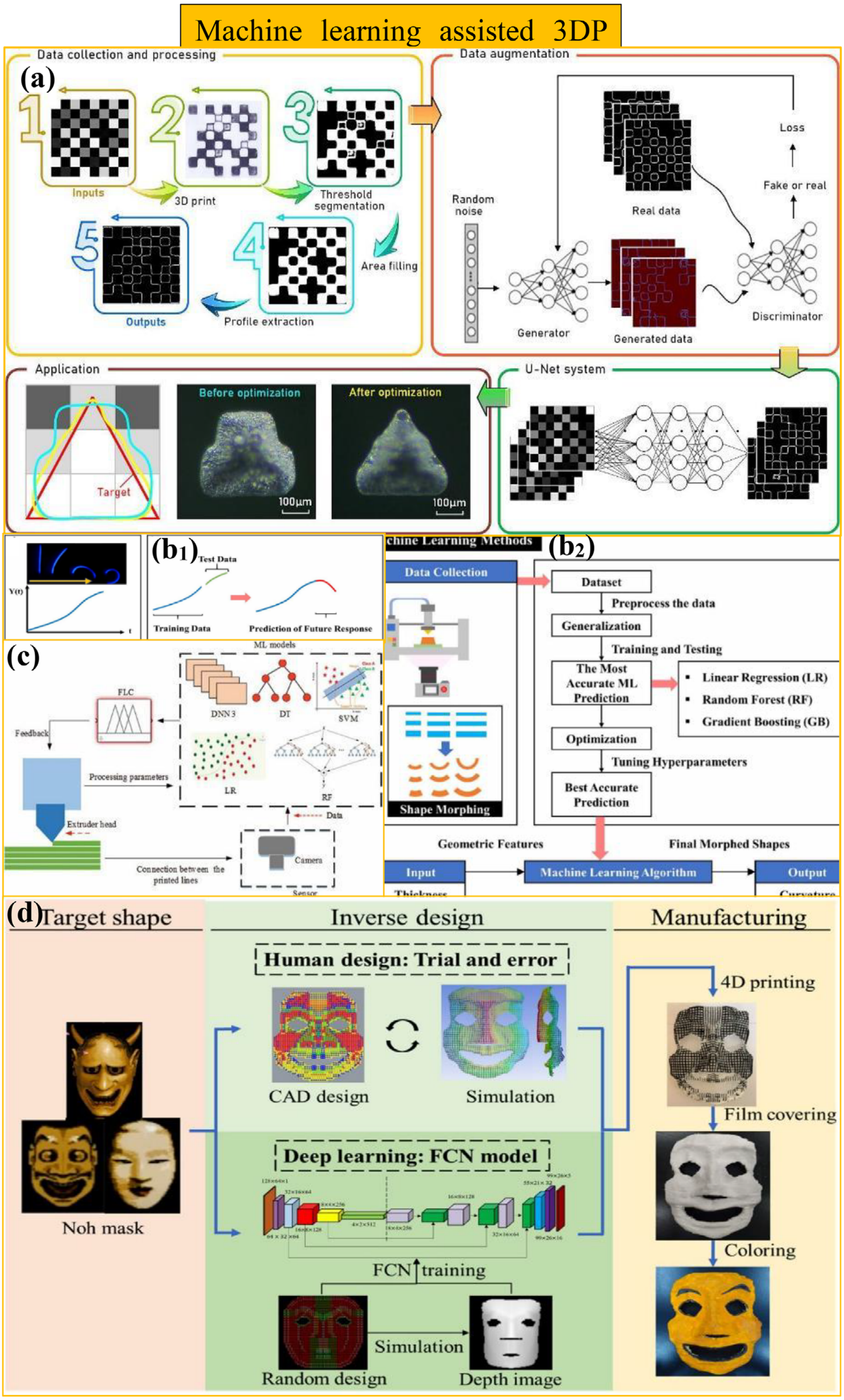


Figure 26. a) A lab-built VPP-3DP device with a digital micromirror UV projector creates various solidification profiles by adjusting greyscale pixels and light intensity, data acquisition and conditional generative adversarial network-based augmentation trained a model to correlate projection and curing patterns, assessed through a U-Net system with their performance (Reproduced with permission.[532] under a Creative Commons Attribution license 4.0); b) Dynamic response and illustration of training and testing of the sequential data for prediction their response with a flow chart for data-driven modeling to predict shape-morphing behaviors in printed active structures, it encompasses data collection, preprocessing, and hyperparameter tuning

est shape of an intended DLP-based object by automatically tuning the distribution of localized grey pixels of various intensities as presented in **Figure 26**a. A chessboard pattern-based strategy improved understanding of conditional generative adversarial network models for curing effects, enhancing efficiency, and reducing deviation by ≈30%. Likewise, Su et al.[533] studied a data-driven approach by incorporating an ensemble of ML algorithms as shown in Figure 26b_1 for predicting the shape morphing behaviors of smart materials driven from 4DP. Particularly, three ML algorithms were used to correlate thickness with final morphing shapes as presented in Figure 26b_2, with remarkable improvement in gradient with high correlation factors (R^2 of 0.96 and 0.94) from 150 experiments. For forecasting the dynamic response of printed structures from forest model ranked, three-time series algorithms were employed, with exponential smoothing achieving an average mean absolute percentage error of 0.0139.

Recent breakthroughs in ML-assisted 3DP have shown that optimizing process parameters can significantly increase efficiency, reduce material waste, and minimize the need for post-processing.[534,535] This improvement greatly enhances overall high-volume production.[525] Tamir et al.,[536] integrated both closed-loop and open-loop ML models such as support vector machine, logistic regression, deep neural network, random forest, and decision tree for monitoring the effects of processing parameters on the quality of printed parts as highlighted in Figure 26c. Particularly, an open-loop classification model formulates the relationship between properties and processing parameters of printed parts. The deep neural network from all proposed ML models outperformed all other models and is considered the final classification model for optimizing the printing parameters. Moreover, optimizing processing parameters for better printed part properties governed by a closed-loop control algorithm combines open-loop ML models and fuzzy inference systems. **Table 9** summarizes some recent works on various ML-assisted 3DPs for optimizing various parameters and controlling the defects.

Chiu et al.[537] proposed a cost-effective, bi-material 4DP process to create 3D human face-like gridshells from 2D grids using fused deposition modeling. The approach combined SMP and PLA in bilayer rods, which morph into 3D shapes upon uniform heating due to pre-programmed material properties. Insights of this study showed that a fully convolutional network (FCN) was trained on 100 000+ simulated face designs using nonlinear finite element analysis, achieving over 90% accuracy in predicting 2D grid configurations from 3D depth images. The method was experimentally validated by fabricating intricate structures, including Japanese "Noh" masks, demonstrating its robustness as discussed in Figure 26d. This work significantly advances 4DP by enabling precise, data-driven inverse design for complex shell-like morphing structures.

11. Perspective and Outlook

It is hoped that this review will inspire researchers worldwide to collaborate and drive further breakthroughs in the diverse and expanding applications of SMPs. In recent years, SMPs have made significant progress and have been widely recognized by the scientific community for their unique capabilities. The emergence of 4DP marks a pivotal step toward realizing the practical potential of SMPs, as it enables dynamic, time-dependent functionality in printed structures. This integration of SMPs with 4DP significantly broadens their scope of application. However, despite this progress, several challenges and limitations remain unresolved. For instance, future real-world applications particularly next-generation systems will expose SMPs to extreme environmental conditions, which may compromise their performance and reliability during service. One of the key challenges is to develop SMPs capable of multi-mode and multi-level shape morphing. These hierarchical shape transformations are critical for enhancing physical intelligence and enabling greater functional diversity in advanced soft robotic systems.

Furthermore, 3DP, when combined with innovative design strategies and supported by AI and ML tools, offers new opportunities to create microstructures with increased complexity and functionality. Such advancements are expected to play a vital role in future engineering applications, especially within the framework of a circular economy, ultimately paving the way for an unprecedented era of smart manufacturing as illustrated in **Figure 27**. However, to the best of our knowledge, there are currently no specialized 3DP processes designed specifically for 4DP that fully harness the potential of smart materials. Therefore, moving forward, equal attention must be given to both material development and printing technologies. These should be co-designed to achieve superior performance by incorporating a wider range of printing techniques including material jetting, volumetric printing, micro-SLA, and 2PP to fully realize the transformative promise of 4D-printed SMP systems.

It is challenging to address all the practical aspects of 3D printed SMP, but in this section, we address some fundamental challenges related to all discussed areas and their associated solutions, with a focus on the large-scale production of wearable electronics.

11.1. Scalability and Programmability of Shape Memory Polymers (SMPs)

The in-depth understanding and research of various responsive soft materials such as SMPs, hydrogels, and LCEs will be imperative to support further soft structures or machines with adaptivity for embodied intelligence as well as natural environment conditions.[546–548] Moreover, the fundamental understanding of

for developing ML models (Reproduced with permission.[533] Copyright 2021, IOP Publishing); c) The proposed negative feedback control system in 3DP proposes using multi-input-multi-output Fuzzy logic-based control algorithm for generating optimized processing parameter (Reproduced with permission.[536] Copyright 2023, Taylor & Francis); d) Schematic workflow of the inverse design for face-like 3D surfaces using multi-material 4DP. Target-shaped 2D grids are designed through machine learning predictions and iterative trial-and-error adjustments. Random designs generate corresponding depth images based on finite element model simulations, forming the dataset for training the FCN deep learning model. The 3D grid shells are fabricated via 4DP, followed by film application to convert them into continuous curved surfaces. Lastly, film coloring is applied to accurately replicate the target shapes (Reproduced with permission.[537] Copyright 2025, Taylor & Francis).

Table 9. A summary of recent works on ML-assisted 3DP technology.

3DP process	Targeted objective	Input	ML technique	Output	Accuracy	Refs.
FDM/FFF	Defects during the printing of part	1900 image	Supervised: convolutional neural network (CNN)	Quality of printed layer	–	[538]
FDM/FFF	Fault diagnosis	128 × 128-pixel images	Semi-supervised: conditional (GAN), and DAN	Nozzle parameters such as flow rate and temperature	91.01%	[539]
FDM/FFF	Detect cracks in concrete surface	300 × 300-pixel images	Supervised: Mobile Net-SSD	Cracks	80%	[540]
FDM/FFF	Optimization of 3DP outcome	Printing parameters	Supervised: ad hoc optimized CNN and mathematical model	Extrusion multiplier	94.3%	[541]
FDM/FFF	Defection	Images of parts at specified checkpoints	Supervised: SVM	Classify good and defective parts	–	[542]
FDM/FFF	Improved mechanical performance	Image of PA12	Multi-Layer Perceptron	Mechanical properties	with larger sets (50–60%)	[543]
FDM/FFF	Reducing the manufacturing time and cost of products	Deposition angle	Supervised: Random Forest model	Product geometry	94.57%	[544]
IJP	Droplet monitoring	Droplet size, velocity, aspect ratio, presence of satellites	Supervised: Back propagation neural network	Normal dispensing, non-dispensing, and satellite modes	90%	[545]

the tunable chemistry, structure, and conformation of SMP will be critical for modulating their switchable functions and smart properties to predict their response more confidently based on their chemical structure.[549–551] Furthermore, the so-called “multifunctionality” in stimuli-responsive polymers implies their use for various purposes, including shape memory and self-healing properties. However, they often lack important characteristics such as biocompatibility, impressive mechanical properties, and electrical conductivity.[552] This will be one of the mainstream directions for future areas.

Highly processable and programmable SMP can be easily scaled up, regardless of their availability.[553] In this regard, SMP with multiple SMEs is crucial and considered an important breakthrough for the biomedical field in comparison to the common one-way effect, and two-way effect. Various steps need to be taken to develop the multi-SME of SMPs, including controllable recovery speed, recovery level, and stress programming controls.[23,554] Thus, more in-depth understanding is needed to comprehend this multiple-SME of SMP to truly unlock their potential in designing new possibilities for biomimicry of various biological materials for novel applications.[102] The future of SMPs is promising, with advancements in multifunctionality, mechanical properties, and biodegradability set to overcome technical challenges in dynamic scaffolds, biosensing devices, and implants.

11.2. Challenges in Current 3DP Processes for Wearable Devices

Before 3DP, the preparation routes for stimuli-responsive polymers involve, solvent evaporation/carbonization, crosslinking, and precursor production involving various toxic reagents. Thus the critical question will be how far this technology is considered as sustainable material from well-established 3DP technology. The versatility, affordability, simplicity of material requirements, and highly accessible printing methods such as FDM, SLA, and DIW are commonly employed for the wearable device whereas MJ, and powder bed fusion, are comparatively less utilized. FDM and DIW[555] gaining popularity these 3DP processes are commonly employed for wearable electronics and face challenges with material anisotropy and high temperatures, leading to polymer warping or melting.[556] Particularly, FDM has some prominent drawbacks such as printer speed, nozzle size, bandwidth requirements, material dependency, and extensive post-processing, resulting in significant time consumption. On the other hand, VPP achieves high accuracy for small parts, but lasers and toxic odors from photopolymers pose problems. The use of IJP 3DP addresses time consumption issues through immediate curing and the elimination of post-processing. However, IJP is significantly limited by material selection and print quality, which hinders its performance. Therefore, in each 3DP process for wearable electronics fabrication, it is crucial to critically evaluate the pros and cons before making an appropriate selection.[394]

While acknowledging the successful adaptation of 3DP at a small scale, there is still much to be done regarding the standardized guidelines related to the proportioning, composition, and performance requirements of resin and ink.[557] Moreover, understanding innovative additive manufacturing technologies and their applications prospect is of great interest to both academia and industry. 3DP as a powerful development manufacturing technology will be moving toward higher performance, in line with sustainability, and more environmentally friendly, providing a strong momentum as a futuristic manufacturing technology.[558] It continues to offer numerous opportunities for materials scientists and engineers to develop advanced printing materials. By incorporating novel fillers and combining various printing techniques, they can create more complex architectures that maintain high multifunctionality for a wide range of

Figure 27. The potential future area of this exciting and thriving research frontier on 3DP of stimuli response polymers for functional applications.

potential applications.[191] Moreover, the perfect combination of 3DP techniques with stimuli-responsive materials will create more sophisticated architectures and structural designs highly enriched with many biomimetic functions for soft robotics applications. Therefore, there is an urgent need to comply fully with soft actuators and robots for transformation in actual applications and leading toward commercialization especially considering their unprecedented demand in upcoming years.[559,560] It is envisioned that if scientific progress is given paramount importance regarding the wide availability of SMP in terms of their multifunctionality with cost-effective 4DP processes in line with the circular economy approach we can expect to see their practical applications in the near future.[561]

11.3. Hidden Costs of Hybrid 3D Printing

Due to the layer-by-layer nature of 3DP, micro/nano pores are produced in the printed structures, resulting in weakly bonded interfaces between adjacent layers, which significantly lowers mechanical performance. In this regard, composite or hybrid printing (additive + subtractive technologies) technologies such as multi-nozzle, composite lithography, freeze drying-IJP, and electrostatic spinning-DIW are practical for their rapid, low-loss, customized, and integrated printing features for improved precision, print speed, and high transparency, bigger build volume, and multi-material within the same layer.[562] Particularly, VPP-based multi-material system, uncured ink is cleaned during material switching using solvents, physical wiping, pressurized air, or by flushing with new ink. Thus, larger systems and efficient ink usage may become hotspots for future research for achieving commercial scalability.[221]

Mixing multi-material inks with varying viscoelasticities is critical for multi-layer printing. This ensures the accurate formation of different device layers, maintains shape fidelity, and achieves seamless interface integration. However, multi-material-based 3DP faces significant challenges, such as high costs, material compatibility issues, and larger system footprints due to the integration of multiple printing modalities. 3DP should be considered an integral part of a multi-process system or an integrated process involving multiple systems.[563,564] Moreover, while the multisystem-based 3DP approach could potentially address issues such as micro/nano pores, it also introduces significant challenges. This approach would increase the complexity of the 3DP system, leading to higher power consumption and increased material waste, which conflicts with the "sustainable" 3DP concept discussed earlier in the review. Additionally, if additive and subtractive fabrication techniques need to be combined, it would increase the time required to fabricate a single device. This contradicts the commonly stated advantage of 3DP as a time-efficient method. In fact, such a combination might require more time than either solely subtractive or solely additive fabrication methods. Thus, the multisystem 3DP approach solves some fundamental issues related to conventional 3DP, it also diminishes several of its core advantages.

11.4. Critical Considerations for Skin-Conformal Wearable Electronics

Notably, the printing techniques, smart materials, and wearable applications discussed in this review are still in development and often not commercially available. In spite of the major advances in the soft wearable field, there are some challenging tasks that require proper attention. First, the limited material performance such as self-adhesion, stretchability, self-healing, conductivity, printability, and achieving satisfactory mechanical properties remains a challenge. Secondly, on-skin wearability has always happened due to the mismatch in elastic modulus between the human skin and printed flexible skin. However, the novel design concept of kirigami-inspired substrates can mitigate this issue by offering skin-similar elasticity. Third, how can we achieve a highly comfortable design for wearable devices that are lightweight and skin-conformal, using 3D printing of bio and soft substrates, while ensuring the highest performance?[565] Lastly, breathability and long-term wearable monitoring parameters such as reliability, durability, and scalability must be given top priority before we can shift their translation into the real world for providing ideal wearable health solutions. In the context of 3DP, the multi-material-based printing from FDM, DIW, and SLA techniques seems to have an important impact on high-performance and practical wearable electronics applications. Moreover, the role of various conductive fillers in 3DP with adopting and conducting designs will considered as critical steps toward realizing novel wearable sensors with ideal performance in diverse environmental conditions.[150]

11.5. Integrating Bio-SMPs for Sustainable Wearable Devices

In light of the environmental crisis, biomaterials are being explored as potential SMPs for wearable electronics. Sustainable materials have become the cornerstone of the smart and sustainable manufacturing industry. Bio-SMPs will advance toward more innovation, social progress, and technological development. Their future applications will profoundly shape wearable technology due to ongoing sustainability issues. Apart from biocompatible materials other materials including binders, photosensitive resins, and additives, should be replaced with other biomaterials. Particularly to meet the strict robustness needs of industrial applications, furthers needs to be studied further such as upgrading and maintaining printing equipment is pivotal for accomplishing precise controllability with high accuracy. Three distinct approaches as synthesizing biodegradable polymers from biomass-derived resources, second is designing closed-loop recyclable polymers that degrade to small molecules and third is creating recyclable polymers based on existing systems to address current issues.[4] Moreover, it is welcome to see advances in materials, but it is challenging to manage excess materials when using 3D printers. These materials can be recycled or stored more effectively, but an optimal approach is to repurpose them for alternative applications. By integrating this method seamlessly into existing crafting practices and 3DP, we can reuse materials that are normally discarded.[566]

Several opportunities for future work exist in sustainable 3DP, such as using reclamation and recycling materials. This approach can also be extended to standard, single-material FDM.[567,568] It is worth mentioning that all 3D-printed wearable devices are usually confined to research facilities as they are usually evaluated on limited performance criteria while for their practical design, equal attention is needed to be paid to smart wearable device availability and suitability, long-term monitoring capability, robust performance (accuracy and precision) and adopting sustainability approach.[569,570]

11.6. Next-Gen Wearables: The Promise and Challenges of 2D Material Integration

The incorporation of 2D materials such as graphene, and MXene into wearable electronics will not only enhance conductivity, but it will remarkably improve the mechanical strength and highly tailored electrochemical properties. However, the synthesis and integration of 2D materials into SMP for effecting printing is the main bottleneck that hinders the commercial application of robust wearable electronics. Two factors such as the synthesis of high-quality 2D materials and their subsequent integration with 3DP.[103,571] Suitable rheological properties such as extrudability are an important aspect of 3DP of various 2D materials. For instance, preparing high-quality 3D printable graphene-based inks is challenging due to the difficulty in dispersing pristine graphene in solvents due to their inherent hydrophobic and oleophobic properties which produced degraded slurry flowability and resulted in poor rheological properties. Thus, developing additive-free, high-quality graphene ink for 3DP flexible devices, without cryogenic assistance or post-processing reduction, is scientifically and practically valuable.[572] Advancements in 2D materials-based 3DP at smaller scales and higher speeds will overcome current challenges in miniaturized, efficient wearable devices, accelerating the evolution of this technology in daily life.

11.7. Multifunctional Material Design for Autonomous Wearable Devices

Wearable electronics consist of a soft, wearable substrate, functional electrical components, and highly conductive interconnects.[573] For widespread adoption, mitigating these scalability and cost issues is indispensable. Particularly, scalability and cost issues of 3D-printed SMPs for wearable electronics stem from several factors such as high material costs and complex printing processes increased expenses with extensive post-processing requirements add to the challenges.

3D printed SMPs for wearable electronics still need advanced processes for achieving material/structure/function integration with self-deforming, self-sensing, triboelectric nanogenerator performance (that requires no external power source), self-healing, and self-learning functions. Self-healing materials are designed to achieve high healing efficiency without requiring additional chemicals. The essence of self-healing of stimuli-responsive polymers lies in their chemistry and is achieved through dynamic exchange reactions which involve breaking and creating new bonds.[574] To further improve their self-healing efficiency, it is critical to advance toward dynamic reactions, Vitrimer chemistry,[575] and double covalent bonds with proper understanding to ensure 100% self-healing ability without adding any outside chemical reagent.[576] In addition to that, various external stimuli, such as light, pH, or magnetic fields, will shed new light on advanced self-healing applications. Furthermore, we envisage a not-too-far-distant future where multifunctional behavior such as shape memory and self-healing will be fully integrated. Moreover, practical wearable technology must meet higher requirements with functional architectures/interface layers and gradient porous frameworks which play a vital role in ensuring their conductivity during working conditions, fostering advancements in smart textiles and on-body devices.

11.8. Integrating Smart Structures and Novel Locomotion for High Performance Robotics

In this regard, advanced stimulus-responsive modes should be explored further including magnetic or electrical-driven feedback-controlled systems, for enhancing maneuverability. To enhance the performance of autonomous actuators, novel locomotion methods such as climbing, jumping, and flying should be integrated into self-sustaining systems. Embedding smart structures like bistable/multistable structures, topology structures, tensegrity structures, origami, and metamaterials into soft robots can provide unique mechanical properties, such as snapping motion and high degrees of freedom, enabling high frequency, strong actuation force, and remarkable load capacity.[577,578] Currently, there are no commercially available soft electronic products which can exploit the full potential of 3DP or 4DP to a significant extent. Thus, traditional electronics-fabrication processes remain easier, cheaper, and more reliable, 3D-or 4D-printed electronics tend to be found in research laboratories or as prototypes.[579]

11.9. Focus on AI/ML Integration and Intelligent Systems

In the past, physical intelligence systems such as actuation and control were limited only by our imagination and are now no longer constrained. For instance, making full use of other spontaneous physicochemical changes occurring in SMP systems with the assistance of 3DP techniques will allow us to gain control over the intelligence system for emerging applications. Moreover, dynamic stimulations can also play their part in providing more knowledge about the perception and self-control of the intelligence system. Higher-level intelligence systems for 3D printed SMP will broaden their applications in smart devices.[580] Precise optimization of structure through advanced AI or ML algorithms improves flexible electronics shape morphing capabilities.[581] This will pave the foundations of SMPs in practical applications of intelligent sensors, and flexible electronics for more innovative and durable materials.[258] ML algorithms have become prevalent in Industry 4.0, lowering labor costs and enhancing product quality. Particularly, advanced digitalization drives ML toward a smart and integrated manufacturing industry that adjusts errors in real-time, thus saving time and resources.[582]

Most ML algorithms, including deep learning, often require domain knowledge to uncover hidden insights about 3DP.[583] This is because modeling the mathematical relationships in the 3DP process is challenging due to the diverse factors from different perspectives and process stages.[584] Moreover, in order to accurately guide the dynamic deformation process of 4D printed SMP structures, theoretical models are urgently needed.[585,586] Programming deformation design is currently based on empirical methods without standardized guidelines.[587] It is also necessary to develop models to accurately control structural deformation because there is no theoretical support for dynamic recovery.[588,589] It is anticipated that with the advancement of data-driven approaches such as data acquisition and storage technologies, ML models will be extremely adopted to discover hidden knowledge and build highly complex relationships for futuristic 3DP systems.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M.Y.K. contributed to writing the original draft, writing the review and editing, validation, methodology, investigation, formal analysis, and conceptualization. A.O. contributed to writing the original draft, writing the review and editing, visualization, conceptualization, investigation, and formal analysis. O.S.M. contributed to writing the review and editing, visualization, validation, conceptualization, methodology, and formal analysis. K.A. contributed to writing the review and editing, validation, supervision, methodology, investigation, and conceptualization. M.B. contributed to writing the review and editing, validation, supervision, project management, methodology, investigation, and conceptualization.

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4D printing, adaptive structures, SMP, soft electronics, wearable electronics

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[1] B. Zhang, S. Li, Z. Zhang, Z. Meng, J. He, S. Ramakrishna, C. Zhang, *Curr. Opin. Biomed. Eng.* **2023**, *26*, 100454.
[2] M. Bodaghi, R. Noroozi, A. Zolfagharian, M. Fotouhi, S. Norouzi, *Materials* **2019**, *12*, 1353.
[3] S. C. Gauci, A. Vranic, E. Blasco, S. Bräse, M. Wegener, C. Barner-Kowollik, *Adv. Mater.* **2024**, *36*, 2306468.
[4] Y. Jia, H. Xie, J. Qian, Y. Zhang, H. Zheng, F. Wei, Y. Li, Z. Zhao, *Adv. Funct. Mater.* **2024**, *34*, 2307279.
[5] T. Kim, C. Bao, M. Hausmann, G. Siqueira, T. Zimmermann, W. S. Kim, *Adv. Electron. Mater.* **2019**, *5*, 1800778.
[6] L. Sun, Y. Wang, S. Zhang, H. Yang, Y. Mao, *Biomater. Adv.* **2023**, 213499.
[7] S. Panda, S. Hajra, M. Rajaitha, H. J. Kim, *Micro Nano Syst. Lett.* **2023**, *11*, 2.
[8] S. Zhang, Q. Wang, Z. Li, Y. Xu, B. Su, *J. Mat Chem. C* **2025**, *13*, 250.
[9] B. Tatár, L. Mészáros, *ACS Omega* **2024**, *9*, 46960.
[10] R. Lin, S. Xu, Z. Liu, *J. Appl. Mech.* **2024**, *92*, 011007.
[11] H. Gao, J. Li, F. Zhang, Y. Liu, J. Leng, *Mater. Horizons* **2019**, *6*, 931.
[12] Z. Guan, L. Wang, J. Bae, *Mater. Horizons* **2022**, *9*, 1825.
[13] P. Kumar, S. K Dwivedy, S. Banerjee, *Mater. Sci. Eng. B* **2025**, *317*, 118205.
[14] Z. U. Arif, M. Y. Khalid, A. Tariq, M. Hossain, R. Umer, *Giant* **2023**, *14*, 100209.
[15] I. Kopyeva, R. P. Brady, C. A. DeForest, *Nat. Rev. Bioeng.* **2024**, *13*, 159.
[16] Y. Xia, Y. He, F. Zhang, Y. Liu, J. Leng, *Adv. Mater.* **2021**, *33*, 2000713.
[17] J. Patadiya, M. Naebe, X. Wang, G. Joshi, B. Kandasubramanian, *Eur. Polym. J.* **2023**, *184*, 111778.
[18] J. Lee, D. Lee, C.-H. Ahn, T. A. Kim, *Adv. Funct. Mater.* **2024**, *35*, 2414842.
[19] P. Narayanan, R. Pramanik, A. Arockiarajan, *Smart Mater. Struct.* **2024**, *33*, 043001.
[20] T. Isogai, M. Hayashi, *Macromol. Rapid Commun.* **2024**, *45*, 2400125.
[21] D. Niu, D. Li, J. Chen, M. Zhang, B. Lei, W. Jiang, J. Chen, H. Liu, *Sensors Actuators A Phys* **2022**, *341*, 113516.
[22] L. Bonetti, D. Natali, S. Pandini, M. Messori, M. Toselli, G. Scalet, *Mater. Des.* **2024**, *238*, 112725.
[23] A. Y. Lee, J. An, C. K. Chua, *Engineering* **2017**, *3*, 663.
[24] Y. Bai, X. Zhang, Q. Wang, T. Wang, *J. Mater. Chem. A* **2014**, *2*, 4771.
[25] C. Lin, X. Xin, L. Tian, D. Zhang, L. Liu, Y. Liu, J. Leng, *Compos. Part B Eng.* **2024**, *274*, 111257.
[26] L. Sang, W. Wu, Y. Yao, X. Dong, H. Zhang, H. Zhang, *Virtual Phys. Prototyp.* **2024**, *19*, 2372620.
[27] S. Amukarimi, M. Mozafari, *Bioprinting* **2021**, *23*, 00161.
[28] S. Moroni, L. Casettari, D. A. Lamprou, *Biosensors* **2022**, *12*, 568.
[29] X. Lu, G. Liu, J. Lu, *Addit. Manuf. Front.* **2024**, *3*, 200158.
[30] A. Moheb Afzali, M. A. Kheradmand, S. M. Naghib, *Bioprinting* **2024**, *37*, 00325.
[31] J. Patadiya, A. Gawande, G. Joshi, B. Kandasubramanian, *Ind. Eng. Chem. Res.* **2021**, *60*, 15885.
[32] J. Zhang, Z. Yin, L. Ren, Q. Liu, L. Ren, X. Yang, X. Zhou, *Adv. Mater. Technol.* **2022**, *7*, 2101568.

[33] N. J. Castro, C. Meinert, Levett, D. W. Hutmacher, *Curr. Opin. Biomed. Eng.* **2017**, *2*, 67.
[34] S. Joshi, K. Rawat, K. C., V. Rajamohan, A. T. Mathew, K. Koziol, V. Kumar Thakur, B. A. S. S., *Appl. Mater. Today* **2020**, *18*, 100490.
[35] Y. Li, W. Zheng, J. Zhang, L. Xu, B. Li, J. Dong, G.-L. Gao, Z. Jiang, *Frontiers in Materials* **2023**, *10*.
[36] A. C. Pinho, A. P. Piedade, in *Nanotechnology-Based Additive Manufacturing*, Wiley, Hoboken, NJ **2023**, pp. 249–276.
[37] J. Zhang, M. Xu, N. Zhang, L. Tao, M. Shao, T. Wang, Z. Yang, Q. Wang, Y. Zhang, *Small* **2024**, *20*, 2406358.
[38] H. Wei, Q. Zhang, Y. Yao, L. Liu, Y. Liu, J. Leng, *ACS Appl. Mater. Interfaces* **2017**, *9*, 876.
[39] Y. Qin, J. Qiao, S. Chi, H. Tian, Z. Zhang, H. Liu, *Materials* **2024**, *17*, 5903.
[40] A. Asar, M. S. Irfan, K. A. Khan, W. Zaki, R. Umer, *Compos. Sci. Technol.* **2022**, *221*, 109219.
[41] W. Zhang, M. Yu, Y. Cao, Z. Zhuang, K. Zhang, D. Chen, W. Liu, J. Yin, *Bioact. Mater.* **2023**, *21*, 450.
[42] W. Yuan, S. Xu, C. Yu, M. Ding, Y. Zheng, J. Zhou, G. Shan, Y. Bao, P. Pan, *Chem. Eng. J.* **2022**, *446*, 137346.
[43] G. Kostopoulos, K. Stamoulis, V. Lappas, S. K. Georgantzinos, *Aerospace* **2024**, *11*, 134.
[44] Y. Lin, R. Yang, X. Wu, *RSC Appl. Polym.* **2023**, *1*, 132.
[45] R. E. Booth, C. Khanna, H. M. Schrickx, S. Siddika, A. Al Shafe, B. T. O'Connor, *ACS Appl. Mater. Interfaces* **2022**, *14*, 53129.
[46] Y. Liu, L. Wang, Y. Liu, F. Zhang, J. Leng, *Compos. Commun.* **2024**, *51*, 102062.
[47] Y. Guan, H. Guo, X. Jia, J. Qin, Y. Yang, K. Cao, T. Li, J. Liao, Y. Zhang, *J. Polym. Sci.* **2024**, *63*, 406.
[48] M. Słoma, *Nanoscale* **2023**, *15*, 5623.
[49] G. Gürlek, Ş. Özkan, M. Şener, B. O. Gürses, Y. Seki, *Solid State Sci.* **2024**, *158*, 107759.
[50] Y. Wang, X. Zhou, J. Zhong, J. Zhan, Y. Kong, J. Yin, H. Gong, Q. Chen, S. Li, H. Zhao, Y. Wu, W. Huang, *Adv. Funct. Mater.* **2024**, *34*, 2400208.
[51] T. Salo, A. Halme, J. Lahtinen, J. Vanhala, *Flex. Print. Electron.* **2020**, *5*, 045001.
[52] K. Liang, S. Carmone, D. Brambilla, J.-C. Leroux, *Sci. Adv.* **2024**, *4*, aat2544.
[53] J. Zhang, Q. Zhang, W. Pan, M. Jiao, Y. Chen, H. Pei, X. Li, Y. Qi, J. Zhao, *J. Elastomers Plast.* **2024**, *57*, 00952443241297450.
[54] M. P. Gaj, A. Wei, C. Fuentes-Hernandez, Y. Zhang, R. Reit, W. Voit, S. R. Marder, B. Kippelen, *Org. Electron.* **2015**, *25*, 151.
[55] K. Osouli-Bostanabad, T. Masalehdan, R. M. I. Kapsa, A. Quigley, A. Lalatsa, K. F. Bruggeman, S. J. Franks, R. J. Williams, D. R. Nisbet, *ACS Biomater. Sci. Eng.* **2022**, *8*, 2764.
[56] D. G. Tamay, T. Dursun Usal, A. S. Alagoz, D. Yucel, N. Hasirci, V. Hasirci, *Front. Bioeng. Biotechnol.* **2019**, *7*, 164.
[57] Z. Fu, L. Ouyang, R. Xu, Y. Yang, W. Sun, *Mater. Today* **2022**, *52*, 112.
[58] W. Su, Z. Wu, Y. Fang, R. Bahr, P. Markondeya Raj, R. Tummala, M. M. Tentzeris, in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, **2017**, pp. 544–547.
[59] J. Rajendran, R. Esfandyarpour, *Biomed. Mater. Devices* **2024**, *3*, 818.
[60] A. Mahmood, T. Akram, C. Shenggui, H. Chen, *Compos. Part B Eng.* **2023**, *266*, 110952.
[61] A. Kirillova, L. Ionov, *J. Mater. Chem. B* **2019**, *7*, 1597.
[62] M. Hassan, A. K. Mohanty, T. Wang, H. N. Dhakal, M. Misra, *Compos. Part C Open Access* **2025**, *17*, 100602.
[63] Z. Zuo, W. De Corte, Y. Huang, X. Chen, Y. Zhang, J. Li, L. Zhang, J. Xiao, Y. Yuan, K. Zhang, L. Zhang, V. Mechtcherine, *Virtual Phys. Prototyp.* **2024**, *19*, 2346821.
[64] K. Blanco, E. Navas, L. Emmi, R. Fernandez, *IEEE Access* **2024**, *12*, 30434.
[65] M. Y. Khalid, Z. U. Arif, A. Tariq, M. Hossain, K. A. Khan, R. Umer, *Eur. Polym. J.* **2024**, *205*, 112718.
[66] Z. Zuo, W. De Corte, Y. Huang, X. Chen, Y. Zhang, J. Li, L. Zhang, J. Xiao, Y. Yuan, K. Zhang, L. Zhang, V. Mechtcherine, *Nat. Rev. Mater.* **2024**, *9*, 754.
[67] J. S. Meena, S. Bin Choi, S.-B. Jung, J.-W. Kim, *Mater. Today Bio* **2023**, *19*, 100565.
[68] A. Osman, J. Lu, *Mater. Sci. Eng. R Reports* **2023**, *154*, 100734.
[69] Y. Xin, X. Zhou, H. Bark, P. S. Lee, *Adv. Mater.* **2024**, *36*, 2307963.
[70] S. Xu, S. Ahmed, M. Momin, A. Hossain, T. Zhou, *Device* **2023**, *1*, 100067.
[71] N. Shahrubudin, T. C. Lee, R. Ramlan, *Procedia Manuf.* **2019**, *35*, 1286.
[72] A. Su, S. J. Al'Aref, *3D Printing Applications in Cardiovascular Medicine*, (Eds. S. J. Al'Aref, B. Mosadegh, S. Dunham) Academic Press, Boston **2018**, pp. 1–10.
[73] C. Yue, M. Li, Y. Liu, Y. Fang, Y. Song, M. Xu, J. Li, *Addit. Manuf.* **2021**, *46*, 102146.
[74] B. Elder, R. Neupane, E. Tokita, U. Ghosh, S. Hales, Y. L. Kong, *Adv. Mater.* **2020**, *32*, 1907142.
[75] S. Park, B. Shi, Md. M. Islam, J. He, D. H. Sung, C. Zhang, Z. Cao, Y. Shang, L. Liu, K. Fu, *Adv. Funct. Mater.* **2024**, *34*, 2410164.
[76] W. Tuvayanond, L. Prasittisopin, *Buildings* **2023**, *13*, 429.
[77] G. Zhu, H. A. Houck, C. A. Spiegel, C. Selhuber-Unkel, Y. Hou, E. Blasco, *Adv. Funct. Mater.* **2024**, *34*, 2300456.
[78] P. Somers, A. Münchinger, S. Maruo, C. Moser, X. Xu, M. Wegener, *Nat. Rev. Phys.* **2024**, *6*, 99.
[79] G. Palmara, F. Frascella, I. Roppolo, A. Chiappone, A. Chiadò, *Biosens. Bioelectron.* **2021**, *175*, 112849.
[80] M. Trovato, P. Cicconi, *Procedia CIRP* **2023**, *119*, 1084.
[81] B. Yao, Y. Zhu, Z. Xu, Y. Wu, L. Yang, J. Liu, J. Shang, J. Fan, L. Ouyang, H.-J. S. Fan, *Polym. Eng. Sci.* **2023**, *63*, 3743.
[82] M. I. Farid, W. Wu, X. Liu, P. Wang, *Int. J. Adv. Manuf. Technol.* **2021**, *115*, 2973.
[83] P. Zarrintaj, F. Seidi, M. Youssefi Azarfam, M. Khodadadi Yazdi, A. Erfani, M. Barani, N. P. S. Chauhan, N. Rabiee, T. Kuang, J. Kucinska-Lipka, M. R. Saeb, M. Mozafari, *Compos. Part B Eng.* **2023**, *258*, 110701.
[84] A. Romani, R. Suriano, M. Levi, *J. Clean. Prod.* **2023**, *386*, 135779.
[85] M. Hassan, M. Misra, G. W. Taylor, A. K. Mohanty, *Compos. Part C Open Access* **2024**, *15*, 100513.
[86] A. Al Rashid, M. Koç, *Mater. Today Sustain.* **2023**, *24*, 100529.
[87] A. S. Finny, O. Popoola, S. Andreescu, *Nanomaterials* **2021**, *11*, 2358.
[88] Q. Tan, H. Chang, G. Liang, V. Luzin, Y. Yin, F. Wang, X. Cheng, M. Yan, Q. Zhu, C. Hutchinson, M.-X. Zhang, *Nat. Commun.* **2024**, *15*, 10077.
[89] R. Noroozi, Z. U. Arif, H. Taghvaei, M. Y. Khalid, H. Sahbafar, A. Hadi, A. Sadeghianmaryan, X. Chen, *Ann. Biomed. Eng.* **2023**, *51*, 1683.
[90] M. Adhami, A. G. Dastidar, Q. K. Anjani, U. Detamornrat, Q. Tarrés, M. Delgado-Aguilar, J. G. Acheson, K. Manda, S. A. Clarke, N. Moreno-Castellanos, E. Larrañeta, J. Domínguez-Robles, *Drug Deliv. Transl. Res.* **2024**, *15*, 2467.
[91] K. Huanbutta, K. Burapapadh, Sriamornsak, T. Sangnim, *Pharmaceutics* **2023**, *15*, 1877.
[92] L. Prasittisopin, *Smart Cities* **2024**, *7*, 3458.
[93] A. Al Rashid, S. A. Khan, S. G. Al-Ghamdi, M. Koç, *Autom. Constr.* **2020**, *118*, 103268.
[94] S. Grira, H. A. Khalifeh, M. Alkhedher, M. Ramadan, *Bioprinting* **2023**, *33*, 00291.
[95] V. Ekanayaka, A. Hürkamp, *PAMM* **2023**, *22*, 202200273.
[96] M. A. Rahman, L. Gibbon, M. Z. Islam, E. Hall, C. A. Ulven, *Polymers* **2024**, *16*, 2996.

[97] M. P. Sekar, H. Budharaju, A. Zennifer, S. Sethuraman, N. Vermeulen, D. Sundaramurthi, D. M. Kalaskar, *J. Tissue Eng.* **2021**, *12*, 20417314211027676.
[98] F. Gong, X. Cheng, B. Fang, C. Cheng, Y. Liu, Z. You, *J. Clean. Prod.* **2023**, *397*, 136551.
[99] R. Wagmare, R. Harshe, J. Pednekar, T. U. Patro, *Prog. Addit. Manuf.* **2024**, *10*, 1973.
[100] F. Ali, S. N. Kalva, M. Koc, *Discov. Mater.* **2024**, *4*, 53.
[101] K. Sood Monika, S. K. Sood, *Prog. Addit. Manuf.* **2024**, *10*, 3305.
[102] Y. A. Alli, H. Anuar, A. Bamisaye, M. R. Manshor, N. O. Etafo, M. O. Bamidele, M. A. Rasheed, S, K. Olatunde, A. S. Akinfenwa, A. Lawal, *Polymer (Guildf)* **2024**, *315*, 127823.
[103] M. Nadgorny, A. Ameli, *ACS Appl. Mater. Interfaces* **2018**, *10*, 17489.
[104] Z. X. Khoo, J. E. M. Teoh, Y. Liu, C. K. Chua, S. Yang, J. An, K. F. Leong, W. Y. Yeong, *Virtual Phys. Prototyp.* **2015**, *10*, 103.
[105] M. Falahati, P. Ahmadvand, S. Safaee, Y.-C. Chang, Z. Lyu, R. Chen, L. Li, Y. Lin, *Mater. Today* **2020**, *40*, 215.
[106] M. Castillo, R. Monroy, R. Ahmad, *J. Intell. Manuf.* **2024**, *35*, 3.
[107] M. Shahbazi, H. Jäger, R. Ettelaie, A. Mohammadi, P. A Kashi, *Addit. Manuf.* **2023**, *71*, 103598.
[108] A. Pavone, S. Terryn, H. Abdolmaleki, A. C. Cornellà, G. Stano, G. Percoco, B. Vanderborght, *Addit. Manuf.* **2024**, *95*, 104535.
[109] A. A. Mohammed, J. Miao, I. Ragaisyte, A. E. Porter, C. W. Myant, A. Pinna, *Heliyon* **2023**, *9*, 14682.
[110] D. Singh, Y. Sharma, D. Dheer, R. Shankar, *Int. J. Biol. Macromol.* **2024**, *261*, 129901.
[111] C. M. González-Henríquez, M. A. Sarabia-Vallejos, J. Rodriguez-Hernandez, *Prog. Polym. Sci.* **2019**, *94*, 57.
[112] F. Abedi, Ghandforoushan, F. Adeli, M. Yousefnezhad, A. Mohammadi, S. V. Moghaddam, S. Davaran, *Mater. Today Chem.* **2023**, *29*, 101372.
[113] M. A. Yousefi, D. Rahmatabadi, M. Baniassadi, M. Bodaghi, M. Baghani, *Macromol. Rapid Commun.* **2024**, *46*, 2400661.
[114] I. Khan, I. Barsoum, M. Abas, A. Al Rashid, M. Koç, M. Tariq, *Compos. Struct.* **2024**, *349–350*, 118490.
[115] O. Mehrabi, H. Sabri, M. Karamimoghadam, M. Khoran, G. Casalino, M. Moradi, *Smart Mater. Methods* **2024**, *1*, 119.
[116] S. Choi, B. Park, S. Jo, J. H. Seo, W. Lee, D.-G. Kim, K. B. Lee, Y. S. Kim, S. Park, *Adv. Eng. Mater.* **2022**, *24*, 2101497.
[117] B. Zhang, S. H. Chung, S. Barker, D. Craig, R. J. Narayan, J. Huang, *Prog. Nat. Sci. Mater. Int.* **2021**, *31*, 180.
[118] N. N. Kermani, S. G. Advani, J. Férec, *Addit. Manuf.* **2023**, 103781.
[119] M. A. S. R. Saadi, A. Maguire, N. T. Pottackal, Md. S. H. Thakur, M. Md. Ikram, A. J Hart, P. M. Ajayan, M. M. Rahman, *Adv. Mater.* **2022**, *34*, 2108855.
[120] Y. Hu, Z. Luo, Y. Bao, *Biomacromolecules* **2024**, *26*, 85.
[121] A. Enayati-Gerdroodbar, A. Khayati, M. Ahmadi, B. Pourabbas, M. Ali Aboudzadeh, M. Salami-Kalajahi, *Eur. Polym. J.* **2024**, *221*, 113552.
[122] O. W. Saadi, K. A. Khan, *Virtual Phys. Prototyp.* **2025**, *20*, 2505994.
[123] Z. Zhao, X. Tian, X. Song, *J. Mater. Chem. C* **2020**, *8*, 13896.
[124] S. Li, H. Li, X. Shang, J. He, Y. Hu, *MedComm – Biomater. Appl.* **2023**, *2*, 46.
[125] F.-C. Bin, M.-L. Zheng, *ACS Appl. Mater. Interfaces* **2024**, *16*, 51807.
[126] A. Selimis, V. Mironov, M. Farsari, *Microelectron. Eng.* **2015**, *132*, 83.
[127] F. Cantoni, D. Maher, E. Bosler, S. Kühne, L. Barbe, D. Oberschmidt, Ch. Marquette, R. Taboryski, M. Tenje, A.-I. Bunea, *Addit. Manuf.* **2023**, *76*, 103761.
[128] G. Minnick, B. T. Safa, J. Rosenbohm, N. V. Lavrik, J. Brooks, A. M. Esfahani, A. Samaniego, F. Meng, B. Richter, W. Gao, R. Yang, *Adv. Funct. Mater.* **2023**, *33*, 2206739.
[129] X. Liu, M. Wei, Q. Wang, Y. Tian, J. Han, H. Gu, H. Ding, Q. Chen, K. Zhou, Z. Gu, *Adv. Mater.* **2021**, *33*, 2100332.
[130] A. Jaiswal, C. K. Rastogi, S. Rani, G. P. Singh, S. Saxena, S. Shukla, *iScience* **2023**, *26*, 106374.
[131] D. O. Agumba, S. Panicker, D. H. Pham, J. Kim, *Adv. Sustain. Syst.* **2022**, *6*, 2200369.
[132] A. J. Boydston, B. Cao, A. Nelson, R. J. Ono, A. Saha, J. J. Schwartz, C. J. Thrasher, *J. Mater. Chem. A* **2018**, *6*, 20621.
[133] R. T. Shafranek, S. C. Millik, T. Smith, C. U. Lee, A. J. Boydston, A. Nelson, *Prog. Polym. Sci.* **2019**, *93*, 36.
[134] M. Bodaghi, A. Sadooghi, M. Bakhshi, S. J. Hashemi, K. Rahmani, M. K. Motamedi, *Adv. Mater. Interfaces* **2023**, *10*, 2300337.
[135] A. Firmanda, F. Fahma, K. Syamsu, S. Suprihatin, R. Purnawati, M. Mahardika, L. Suryanegara, Y. Saito, K. Wood, R. Sinaga, *J. Environ. Chem. Eng.* **2023**, *11*, 110359.
[136] P. Yang, F. Zhu, Z. Zhang, Y. Cheng, Z. Wang, Y. Li, *Chem. Soc. Rev.* **2021**, *50*, 8319.
[137] S. Ahmadzadeh, A. Ubeyitogullari, *Addit. Manuf.* **2023**, *69*, 103549.
[138] A. Prakash, R. Malviya, S. B. Sridhar, J. Shareef, *Bioprinting* **2024**, *44*, 00373.
[139] L.-Y. Zhou, J. Fu, Y. He, *Adv. Funct. Mater.* **2020**, *30*, 2000187.
[140] W. Xu, S. Jambhulkar, D. Ravichandran, Y. Zhu, M. Kakarla, Q. Nian, B. Azeredo, X. Chen, K. Jin, B. Vernon, D. G. Lott, J. L. Cornella, O. Shefi, G. Miquelard-Garnier, Y. Yang, K. Song, *Small* **2021**, *17*, 2100817.
[141] O. Gülcan, K. Günaydın, A. Tamer, *Polymers* **2021**, *13*, 2829.
[142] A. Elkaseer, K. J. Chen, J. C. Janhsen, O. Refle, V. Hagenmeyer, S. G. Scholz, *Addit. Manuf.* **2022**, *60*, 103270.
[143] M. Pagac, J. Hajnys, Q.-P. Ma, L. Jancar, J. Jansa, Stefek, J. Mesicek, *Polymers* **2021**, *13*, 598.
[144] F. Zhang, L. Zhu, Z. Li, S. Wang, J. Shi, W. Tang, N. Li, J. Yang, *Addit. Manuf.* **2021**, *48*, 102423.
[145] C. Liao, A. Wuethrich, M. Trau, *Appl. Mater. Today* **2020**, *19*, 100635.
[146] H. Liu, C. Wu, S. Lin, J. Lam, N. Xi, Y. Chen, *Adv. Intell. Syst.* **2025**, *7*, 2400699.
[147] S. Roy, K. A. Deo, H. P. Lee, J. Soukar, M. Namkoong, L. Tian, A. Jaiswal, A. K. Gaharwar, *Adv. Funct. Mater.* **2024**, *34*, 2313575.
[148] Z. Guo, Yu, B. Li, F. Xuan, J. Zhao, *Virtual Phys. Prototyp.* **2024**, *19*, 2286514.
[149] A. D. Valentine, T. A. Busbee, J. W. Boley, J. R. Raney, A. Chortos, A. Kotikian, J. D. Berrigan, M. F. Durstock, J. A. Lewis, *Adv. Mater.* **2017**, *29*, 1703817.
[150] Y. Wei, B. Li, M. Domingos, Z. Qian, Y. Zhu, L. Yan, L. Ren, G. Wei, *Commun. Eng.* **2023**, *2*, 80.
[151] J.-L. You, I.-T. Liu, Y.-H. Chen, R. Balaji, S.-H. Tung, Y.-C. Liao, *Addit. Manuf.* **2024**, *82*, 104047.
[152] A. Megdich, M. Habibi, L. Laperrière, Z. Li, Y. Abdin, *Appl. Mater. Today* **2025**, *44*, 102702.
[153] J. Zhang, S. Meng, B. Wang, Y. Xu, G. Shi, X. Zhou, *Machines* **2024**, *12*, 813.
[154] J. Huang, S. Xia, Z. Li, X. Wu, J. Ren, *J. Mater. Sci. Technol.* **2021**, *91*, 105.
[155] J. Sonatkar, B. Kandasubramanian, S. O. Ismail, *Eur. Polym. J.* **2022**, *169*, 111128.
[156] H. Daungsupawong, V. Wiwanitkit, *Formos. J. Surg.* **9900**.
[157] W. Wu, Y. Zhou, Q. Liu, L. Ren, F. Chen, J. Y. H. Fuh, A. Zheng, X. Li, J. Zhao, G. Li, *Adv. Sci.* **2023**, *10*, 2206486.
[158] A. Melocchi, N. Inverardi, M. Uboldi, F. Baldi, A. Maroni, S. Pandini, F. Briatico-Vangosa, L. Zema, A. Gazzaniga, *Int. J. Pharm.* **2019**, *559*, 299.
[159] L. Bonetti, A. Cobianchi, D. Natali, S. Pandini, M. Messori, M. Toselli, G. Scalet, *Soft Matter* **2024**, *20*, 4544.
[160] T. Y. Koh, A. Sutradhar, *Addit. Manuf.* **2022**, *56*, 102866.
[161] S. Lantean, I. Roppolo, M. Sangermano, M. Hayoun, H. Dammak, G. Barrera, Tiberto, C. F. Pirri, L. Bodelot, G. Rizza, *Adv. Mater. Technol.* **2022**, *7*, 2200288.

[162] S. Feng, J. Cui, Y. Guo, W. Gao, Y. Sun, C. Liang, Z. Lu, B. Zhang, *Compos. Sci. Technol.* **2024**, *260*, 110984.
[163] R. Gholizadeh Ledari, A. Zolfaghari, *Rapid Prototyp. J.* **2025**, *31*, 830.
[164] S. Cen, Z. Li, Z. Guo, H. Li, J. Shi, X. Huang, X. Zou, M. Holmes, *Addit. Manuf.* **2022**, *56*, 102925.
[165] M. Shahbazi, H. Jäger, R. Ettelaie, J. Chen, A. Mohammadi, P. A. Kashi, *Addit. Manuf.* **2024**, *81*, 103977.
[166] W. Zhao, C. Yue, L. Liu, Y. Liu, J. Leng, *Adv. Healthc. Mater.* **2022**, *12*, 2201975.
[167] R. Tao, L Xi, W. Wu, Y. Li, B. Liao, L. Liu, J. Leng, D. Fang, *Compos. Struct.* **2020**, *252*, 112663.
[168] D. Podstawczyk, M. Nizioł, P. Szymczyk-Ziółkowska, M. Fiedot-Toboła, *Adv. Funct. Mater.* **2021**, *31*, 2009664.
[169] S. Pandini, C. Pasini, D. Battini, A. Avanzini, A. Fiorentino, I. Bodini, S. Pasinetti, *Smart Mater. Struct.* **2024**, *33*, 105023.
[170] K. Dong, M. Panahi-Sarmad, Z. Cui, X. Huang, X. Xiao, *Compos. Part B Eng.* **2021**, *220*, 108994.
[171] C. Lin, Z. Huang, Q. Wang, Z. Zou, W. Wang, L. Liu, Y. Liu, J. Leng, *Adv. Healthc. Mater.* **2022**, *12*, 2201999.
[172] L. Bonetti, G. Scalet, *Prog. Addit. Manuf.* **2024**, *10*, 1913.
[173] L. Wang, F. Zhang, S. Du, J. Leng, *Sci. China Technol. Sci.* **2023**, *66*, 127.
[174] A. Megdich, M. Habibi, L. Laperrière, *Mater. Lett.* **2023**, *337*, 133977.
[175] F. Demoly, J.-C. André, *Applied Sciences* **2024**, *14*, 5669.
[176] P. Feng, F. Yang, J. Jia, J. Zhang, W. Tan, C. Shuai, *Int. J. Extrem. Manuf.* **2024**, *6*, 062011.
[177] J. A. Rodriguez-Morales, H. Duan, J. Gu, H. Zeng, H. Sun, *Smart Mater. Struct.* **2024**, *33*, 073005.
[178] S. Yan, F. Zhang, L. Luo, L. Wang, Y. Liu, J. Leng, *Research* **2024**, *6*, 234.
[179] C. Battaglia, C. Vite, R. Morbiducci, Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering) **2025**, pp. 68–82.
[180] S. Shinde, R. Mane, A. Vardikar, A. Dhumal, A. Rajput, *Eur. Polym. J.* **2023**, *197*, 112356.
[181] H. Ikram, A. Al Rashid, M. Koç, *Polym. Compos.* **2022**, *43*, 6355.
[182] T. Li, Q. Liu, H. Qi, W. Zhai, *Small* **2022**, *18*, 2204032.
[183] J. Gao, *4D Printing of Liquid Metals BT – Handbook of Liquid Metals*, (Eds. J. Liu, W. Rao), Springer Nature Singapore, Singapore **2024**, pp. 1–39.
[184] R. Liu, Y. Wang, Y. Yang, *Virtual Phys. Prototyp.* **2024**, *19*, 2434719.
[185] Z. Guo, Z. Hou, X. Tian, W. Zhu, C. Wang, M. Luo, A. V. Malakhov, A. N. Polilov, D. Zhi, H. Ding, H. Lan, *Compos. Part B Eng.* **2025**, *291*, 112039.
[186] S. Nam, E. Pei, *Prog. Addit. Manuf.* **2019**, *4*, 167.
[187] Y. Wang, H. Cui, T. Esworthy, D. Mei, Y. Wang, L. G. Zhang, *Adv. Mater.* **2021**, *34*, 2109198.
[188] J. Leng, X. Lan, Y. Liu, S. Du, *Prog. Mater. Sci.* **2011**, *56*, 1077.
[189] P. Liu, J. Yu, J. Guan, X. Zeng, Y. Zhang, *J. Intell. Mater. Syst. Struct.* **2024**, *36*, 1045389.
[190] J. Mauriello, R. Maury, Y. Guillaneuf, D. Gigmes, *Adv. Mater. Technol.* **2023**, *8*, 2300366.
[191] X. Deng, C. Qi, S. Meng, H. Dong, T. Wang, Z. Liu, T. Kong, *Adv. Mater.* **2024**, *36*, 2406825.
[192] M. Aberoumand, K. Soltanmohammadi, D. Rahmatabadi, E. Soleyman, I. Ghasemi, M. Baniassadi, K. Abrinia, M. Bodaghi, M. Baghani, *Macromol. Mater. Eng.* **2023**, *308*, 2200677.
[193] C. Bignardi, N. M. Pesqueira, Y. M. Shimizo, A. E. H. Machado, D. M. S. Araújo, O. R. Nascimento, V. P. Carvalho, J. Lalevée, B. E. Goi, *ACS Appl. Polym. Mater.* **2025**, *7*, 7429.
[194] S. Ma, Z. Jiang, M. Wang, L. Zhang, Y. Liang, Z. Zhang, L. Ren, L. Ren, *Bio-Design Manuf.* **2021**, *4*, 867.
[195] D. Rahmatabadi, A. Bayati, M. Khajepour, K. Mirasadi, I. Ghasemi, M. Baniassadi, K. Abrinia, M. Bodaghi, M. Baghani, *Mater. Chem. Phys.* **2024**, *325*, 129737.
[196] Y. Huang, Y. Tao, Y. Wang, *Crystals* **2024**, *14*, 717.
[197] S. Castañeda-Rodríguez, M. González-Torres, R. M. Ribas-Aparicio, M. L. Del Prado-Audelo, G. Leyva-Gómez, E. S. Gürer, J. Sharifi-Rad, *J. Biol. Eng.* **2023**, *17*, 21.
[198] Y. S. Alshebly, M. Nafea, *Smart Mater. Struct.* **2023**, *32*, 064008.
[199] S. Liu, X. Dong, Y. Wang, J. Xiong, R. Guo, J. Xiao, C. Sun, F. Zhai, X. Wang, *Adv. Mater. Technol.* **2023**, *8*, 2202004.
[200] L. Chen, Y. Wang, Z. Liu, Z. Liu, Q. Song, *Polym. Compos.* **2025**, *1-17*.
[201] V. K. M. G., S. Kumar, M. Doddamani, *Adv. Eng. Mater.* **2024**, *26*, 2401427.
[202] T. Zhou, Y. Zhou, Z. Hua, Y. Yang, C. Zhou, L. Ren, Z. Zhang, J. Zang, *Smart Mater. Struct.* **2021**, *30*, 115006.
[203] N. Ojha, S. Kumar, M. R. Ramesh, M. Doddamani, *Polym. Compos.* **2025**, *1-11*.
[204] Y. Zhou, L. Ren, J. Zang, Z. Zhang, *Polymers* **2022**, *14*.
[205] W. He, D. Zhou, H. Gu, R. Qu, C. Cui, Y. Zhou, Y. Wang, X. Zhang, Q. Wang, T. Wang, Y. Zhang, *Macromol. Rapid Commun.* **2023**, *44*, 2200553.
[206] L. Zeenat, A. Zolfagharian, Y. Sriya, S. Sasikumar, M. Bodaghi, F. Pati, *Adv. Mater. Technol.* **2023**, *8*, 2300200.
[207] Y. L. Tee, P. Tran, *Aust. J. Mech. Eng.* **2021**, 1.
[208] Ayushi, U. Kumar Vates, S. Mishra, N. Jee Kanu, *Mater. Today Proc.* **2021**, *47*, 3313.
[209] J. Lai, X. Wang, Q. Zhao, C. Zhang, T. Gong, L. He, Z. Wang, H. Xia, *ACS Appl. Mater. Interfaces* **2024**, *16*, 16880.
[210] H. Li, W. Fan, X. Zhu, *J. Biomed. Mater. Res. Part A* **2020**, *108*, 2217.
[211] D. Muhindo, R. Elkanayati, P. Srinivasan, M. A. Repka, E. A. Ashour, *AAPS PharmSciTech* **2023**, *24*, 57.
[212] Y. Wang, H. Ye, J. He, Q. Ge, Y. Xiong, *Nat. Commun.* **2024**, *15*, 2322.
[213] Y. Ma, C.-J. Shih, Y. Bao, *Responsive Mater.* **2024**, *2*, 20240008.
[214] Y. Jin, J. Liu, *Designs* **2024**, *8*.
[215] A. Nazir, O. Gokcekaya, K. Md. Masum Billah, O. Ertugrul, J. Jiang, J. Sun, S. Hussain, *Mater. Des.* **2023**, *226*, 111661.
[216] G. Pelliccia, F. Bianconi, M. Filippucci, D. Correa, *3D Print. Addit. Manuf.* **2024**, *12*, 141.
[217] D. Pokras, Y. Schneider, S. Zaidi, V. K. Viswanathan, *Journal of Manufacturing and Materials Processing* **2024**, *8*, 154.
[218] A. Chen, W. Wang, Z. Mao, Y. He, S. Chen, G. Liu, J. Su, Feng, Y. Shi, C. Yan, J. Lu, *Adv. Mater.* **2024**, *36*, 2307686.
[219] A. M. Shah, *Artif. Organs* **2024**, *48*, 1221.
[220] D. Yu, G. Chi, Xu Mao, M. Li, Z. Wang, C. Xing, D. Hu, Q. Zhou, Z. Li, C. Li, Z. Deng, Du Chen, Z. Song, Z. He, *Adv. Mater.* **2024**, *36*, 2403088.
[221] S. Subedi, S. Liu, W. Wang, S. M. A. Naser Shovon, X. Chen, H. O. T. Ware, *npj Adv. Manuf.* **2024**, *1*, 9.
[222] A. M. Bayoumy, A. Hessein, M. Ahmed Belal, M. Ezzat, M. A. Ibrahim, A. Osman, A. Abd El-Moneim, *J. Power Sources* **2024**, *617*, 235145.
[223] C. Pasini, Z. V. Soreño, D. Schönfeld, T. Pretsch, G. Constante, I. Sadilov, L. Ionov, *Macromol. Rapid Commun.* **2024**, *45*, 2400010.
[224] K. Song, C. Xiong, Ze Zhang, K. Wu, W. Wan, Y. Wang, S. Umezu, H. Sato, *Compos. Part B Eng.* **2025**, *295*, 112218.
[225] B. Tandon, N. Sabahi, R. Farsi, T. Kangur, G. Boero, A. Bertsch, X. Li, J. Brugge, *Adv. Mater. Technol.* **2024**, *10*, 2400466.
[226] M. Chen, R. An, F. Demoly, H. J. Qi, K. Zhou, *Mater. Sci. Eng. R Reports* **2025**, *163*, 100890.
[227] S. Liang, M. Huang, D. Jiang, J. Chen, L. Hu, J. Chen, Z. Wang, *ChemistryOpen* **2024**, *13*, 202300301.
[228] S. Huang, H. Zhang, J. Sheng, E. Agyenim-Boateng, C. Wang, H. Yang, J. Wei, G. Jiang, J. Zhou, J. Lu, J. Zhang, *Chem. Eng. J.* **2023**, *465*, 142830.

[229] A. P. Dhand, M. D. Davidson, J. A. Burdick, *Nat. Rev. Bioeng.* **2024**, *3*, 108.
[230] J. Son, H. Kim, Y. Choi, H. Lee, *Microsystems Nanoeng.* **2024**, *10*, 93.
[231] A. Solanki, M. S. Ranganath, A. K. S. Singholi, *Int. J. Interact. Des. Manuf.* **2024**, *19*, 3153.
[232] J. Zheng, Y. Niu, Z. Song, N. Li, S. Ju, *JOM* **2024**, *77*, 415.
[233] B. J. Ree, *Polymer (Guildf)*. **2024**, *308*, 127384.
[234] S. Jaganathan, R. Kandasamy, R. Venkatachalam, M. Gunalan, R. Dhairiyasamy, *Adv. Polym. Technol.* **2024**, *2024*, 3168252.
[235] I. Levchenko, O. Baranov, M. Keidar, C. Riccardi, H. E Roman, S. Xu, K. Alexander, *Adv. Funct. Mater.* **2024**, *34*, 2407602.
[236] K. R. Ryan, M. P. Down, C. E. Banks, *Chem. Eng. J.* **2021**, *403*, 126162.
[237] F. Alam, J. Ubaid, H. Butt, N. El-Atab, *NPG Asia Mater.* **2023**, *15*, 65.
[238] T. Cheng, Y. Tahouni, E. S. Sahin, K. Ulrich, S. Lajewski, C. Bonten, D. Wood, J. Rühe, T. Speck, A. Menges, *Nat. Commun.* **2024**, *15*, 10366.
[239] H. Li, B. Zhang, H. Ye, B. Jian, X. He, J. Cheng, Z. Sun, R. Wang, Z. Chen, J. Lin, R. Xiao, Q. Liu, Q. Ge, *Sci. Adv.* **2024**, *10*, adl4387.
[240] L. Wu, Y. Song, *Mater. Horizons* **2025**, *12*, 401.
[241] J. Nam, M. Kim, *Nano Converg.* **2024**, *11*, 45.
[242] G. Fei, C. Parra-Cabrera, K. Zhong, K. Clays, R. Ameloot, *Adv. Funct. Mater.* **2024**, *34*, 2314635.
[243] M. T. Kiker, E. A. Recker, A. Uddin, Z. A. Page, *Adv. Mater.* **2024**, *36*, 2409811.
[244] Y. Lu, C. Zhang, T. Xie, J. Wu, *Chem Bio Eng.* **2024**, *1*, 76.
[245] W. Shan, Liu, L. Liang, Z. Liu, T. Q. Bui, *Mater. Today Commun.* **2024**, *38*, 108145.
[246] W. Ji, X. Ji, L. Cao, W. Wang, S. Chen, *J. Colloid Interface Sci.* **2024**, *665*, 109.
[247] S. Pruksawan, Y. T. Chong, W. Zen, T. J. E. Loh, F. Wang, *Chem. – An Asian J.* **2024**, *19*, 202400183.
[248] Y. Wan, X.-C. Li, H. Yuan, D. Liu, W.-Y. Lai, *Adv. Funct. Mater.* **2024**, *34*, 2316550.
[249] S. Shin, Y. Kwon, C. Hwang, W. Jeon, Y. Yu, H.-J. Paik, W. Lee, M. S. Kwon, D. Ahn, *Adv. Mater.* **2024**, *36*, 2311917.
[250] G. Zhu, H. A. Houck, C. A. Spiegel, C. Selhuber-Unkel, Y. Hou, E. Blasco, *Adv. Funct. Mater.* **2023**, *34*, 2300456.
[251] J. Xu, Y. Li, T. Liu, D. Wang, F. Sun, P. Hu, L. Wang, J. Chen, X. Wang, B. Yao, J. Fu, *Adv. Mater.* **2023**, *35*, 2300937.
[252] F. Li, X. Wang, J. Zuo, C. Chen, J. Chen, J. Zhu, W. B. Ying, *ACS Appl. Polym. Mater.* **2024**, *6*, 4070.
[253] C. Li, Xu Zhang, Z. Ren, J. Wang, S. Sun, J. Fu, Y. Xu, W. Duan, *Micromachines* **2024**, *15*, 603.
[254] D. R. Yao, I. Kim, S. Yin, W. Gao, *Adv. Mater.* **2024**, *36*, 2308829.
[255] W. Yu, W. Zhao, X. Zhu, M. Li, X. Yi, X. Liu, *Adv. Mater.* **2024**, *36*, 2401920.
[256] H. Wu, X. Luo, C. Wang, Q. Jin, Y. Li, F. Guo, W. Guo, Y. Long, *Colloids Surfaces A Physicochem. Eng. Asp.* **2024**, *685*, 133248.
[257] B. Ma, Y. Zhang, J. Li, D. Chen, R. Liang, S. Fu, D. Li, *Chem. Eng. J.* **2023**, *466*, 143420.
[258] L. Luo, F. Zhang, L. Wang, Y. Liu, J. Leng, *Adv. Funct. Mater.* **2023**, *34*, 2312036.
[259] Y. Yue, *Eur. Polym. J.* **2024**, *221*, 113563.
[260] M. A. Kouka, F. Abbassi, M. Habibi, F. Chabert, A. Zghal, C. Garnier, *Adv. Eng. Mater.* **2023**, *25*, 2200650.
[261] A. Singhwane, A. Jaiswal, K. Chaturvedi, M. Mili, K. Pal, R. K. Mohapatra, M. A Khan, H. N. Bhargaw, A. K. Srivastava, S. Verma, *Polym. Adv. Technol.* **2023**, *34*, 3552.
[262] J. Wang, A. Chortos, *Nat. Rev. Mater.* **2024**, *9*, 738.
[263] Y. Huang, W. Zhao, H. Ren, L. Jiang, Y. Ouyang, W. Xu, Y. Liu, *Polym. Compos.* **2024**, *45*, 16916.
[264] W. Du, H. Ren, W. Xu, Y. Liu, *Compos. Commun.* **2024**, *48*, 101962.
[265] J. Gong, Z. Tang, H. Shen, X. Zhang, T. Wang, X. Pei, Q. Wang, Y. Zhang, *ACS Appl. Polym. Mater.* **2025**.
[266] A. Hameed, K. A. Khan, *Smart Mater. Struct.* **2024**, *33*, 105010.
[267] H. Duan, H. Sun, J. A. Rodriguez-Morales, X. Bai, *Polymer (Guildf)*. **2024**, *315*, 127786.
[268] S. Basak, *Smart Mater. Methods* **2024**, *1*, 48.
[269] L. Jingcheng, V. S. Reddy, W. A. D. M. Jayathilaka, A. Chinnappan, S. Ramakrishna, R. Ghosh, *Polymers* **2021**, *13*.
[270] J. Kim, D. A. Gouripriya, P. Saha, in *3D Bioprinting from Lab to Industry*, Wiley, Hoboken, NJ **2024**, pp. 231–250.
[271] M. Alsaadi, T. A. Sebaey, E. P. Hinchy, C. T. McCarthy, T. A. De M. de Lima, A. Portela, D. M. Devine, *Journal of Manufacturing and Materials Processing* **2025**, *9*, 46.
[272] K. McLellan, T. Li, Y.-C. Sun, M. B. Jakubinek, H. E. Naguib, *ACS Appl. Polym. Mater.* **2022**, *4*, 8774.
[273] J. Tian, C. Li, G. Nie, X. Zhao, Y. Zhao, *Eur. J. Mech. – A/Solids* **2025**, *111*, 105530.
[274] J. Zou, Y. Wang, J. Cheng, W. Cai, J. Li, L. Xu, W. Fan, R. Liu, *J. Appl. Polym. Sci.* **2025**, 57246.
[275] D. Mohan, T. Zee, M. Shaiful, H. Kaco, *Mater. Lett.* **2021**, *303*, 130522.
[276] B. Wang, W. Wu, H. Liu, L. Wang, M. Qi, Z. Wei, H. Zhang, L. Sang, *Int. J. Biol. Macromol.* **2024**, *254*, 127701.
[277] L. McDougall, J. Herman, E. Huntley, S. Leguizamon, A. Cook, T. White, B. Kaehr, D. J. Roach, *ACS Appl. Mater. Interfaces* **2023**, *15*, 58897.
[278] H. M. El-Husseiny, E. A. Mady, W. A. El-Dakroury, M. B. Zewail, M. Noshy, A. M. Abdelfatah, A. S. Doghish, *Appl. Mater. Today* **2022**, *29*, 101560.
[279] T. Liu, T. Zhou, Y. Yao, F. Zhang, L. Liu, Y. Liu, J. Leng, *Compos. Part A Appl. Sci. Manuf.* **2017**, *100*, 20.
[280] W. Wang, Y. Liu, J. Leng, *Coord. Chem. Rev.* **2016**, *320–321*, 38.
[281] L. Fang, W. Yan, S. Chen, Q. Duan, M. Herath, J. Epaarachchi, Y. Liu, C. Lu, *Macromol. Mater. Eng.* **2023**, *308*, 2300158.
[282] A. Cremonini, J. A. H. P. Sol, A. P. H. J. Schenning, S. Masiero, M. G. Debije, *Chem. – A Eur. J.* **2023**, *29*, 202300648.
[283] Y. S. Lui, W. T. Sow, L. P. Tan, Y. Wu, Y. Lai, H. Li, *Acta Biomater.* **2019**, *92*, 19.
[284] H. Shen, M. Li, W. Cui, R. Ran, *ACS Appl. Mater. Interfaces* **2024**, *16*, 62732.
[285] X. Wang, Y. He, Y. Liu, J. Leng, *Mater. Sci. Eng. R Reports* **2022**, *151*, 100702.
[286] M. Atif, A. Ghani, M. H. Ahmad, S. Z. Shah, M. Imran, N. Habib, *Polym. Adv. Technol.* **2024**, *35*, 6615.
[287] L. Zhao, R. Yu, Y. He, M. Zhang, F. Tian, L. Wang, Y. Zhao, W. Huang, *Addit. Manuf.* **2024**, *79*, 103904.
[288] E. Tekay, B. Aybakan, V. U. Aslan, T. Orhun, *Appl. Mater. Today* **2024**, *38*, 102199.
[289] J. Huang, L. Qiu, C. Ni, G. Chen, Q. Zhao, *Adv. Mater.* **2024**, *36*, 2408324.
[290] X. Wang, J. Zhang, L. Li, *Ind. Eng. Chem. Res.* **2025**, *64*, 10485.
[291] A. Concellón, Mainik, C. Vazquez-Martel, C. Álvarez-Solana, E. Blasco, *Angew. Chemie Int. Ed.* **2024**, *64*, 202421162.
[292] G. Wu, P. Bian, R. Xu, T. Wang, Z. Li, H. Mao, Y. Tai, C. Wang, Z. Ma, X. Hou, N. Carpentier, S. Dutta, S. Wuttke, M. Panahi-Sarmad, S. Van Vlierberghe, X. Xiao, *Chem. Eng. J.* **2024**, 158264.
[293] C. Liang, J. Liu, S. Lin, Y. Gao, X. Zou, W. Wang, F. Chen, N. Hu, Y. Li, Y.-F. Zhang, *ACS Appl. Mater. Interfaces* **2025**.
[294] R. B. da Cunha, L. B. Q. Brito, P. Agrawal, G. de Figueiredo Brito, T. J. A. de Mélo, *J. Manuf. Process.* **2024**, *119*, 596.
[295] C. Li, T. Wu, L. Zhang, H. Song, C. Tang, M. Wu, *Int. J. Adv. Manuf. Technol.* **2024**, *131*, 1241.
[296] J. Bang, S. H. Choi, K. R. Pyun, Y. Jung, S. Hong, D. Kim, Y. Lee, D. Won, S. Jeong, W. Shin, S. H. Ko, *Nat. Rev. Electr. Eng.* **2024**, *1*, 597.
[297] Q. Kong, Yu Tan, H. Zhang, T. Zhu, Y. Li, Y. Xing, X. Wang, *Adv. Sci.* **2024**, *11*, 2407596.

[298] Q. Zhang, J. Yang, Cao, J. Gong, Z. Tang, K. Zhou, H. Luo, X. Zhang, T. Wang, S. Chen, X. Pei, Q. Wang, Y. Zhang, *Macromol. Rapid Commun.* **2024**, *45*, 2400277.
[299] H. Yang, S. Li, Y. Wu, X. Bao, Z. Xiang, Y. Xie, L. Pan, J. Chen, Y. Liu, R.-W. Li, *Adv. Mater.* **2024**, *36*, 2311996.
[300] F. Guo, Y. Li, G. Ma, M. Zhang, J. Fu, C. Luo, L. Yuan, Y. Long, *ACS Appl. Mater. Interfaces* **2024**, *16*, 65779.
[301] A. Verma, D. K. Prasad, *Adv. Hum. Biol.* **2024**, *14*, 177.
[302] Y. Huang, W. Luo, W. Chen, X. Hu, G. Zhu, Y. Ma, X. Jiang, Q. Li, *Chem. Eng. J.* **2024**, *496*, 153789.
[303] H. Gu, T. Lv, Q. Zhang, D. Chi, Y. Zhang, Z. Cheng, Z. Xie, Y. Xu, D. Zhang, Y. Liu, *Chem. Eng. J.* **2024**, *491*, 152106.
[304] Bo Liu, H. Li, F. Meng, Z. Xu, L. Hao, Y. Yao, H. Zhu, C. Wang, J. Wu, S. Bian, W. W. Lu, W. Liu, H. Pan, X. Zhao, *Nat. Commun.* **2024**, *15*, 1587.
[305] S. S. L. Loo, K. Y. Tan, N. I Zahid, C. Y. Foo, Y. X. Neoh, K. Y. Chong, S. T. Tan, Y. S. L. Choo, *ACS Appl. Eng. Mater.* **2024**, *2*, 2569.
[306] M. J. Hossain, *Prog. Addit. Manuf.* **2025**, *10*, 775.
[307] A. Ding, F. Tang, E. Alsberg, *Chem. Rev.* **2025**, *125*, 3663.
[308] C. Abhishek, N. Raghukiran, *Forces Mech.* **2025**, *18*, 100304.
[309] Y. O. Waidi, *Macromol. Rapid Commun.* **2025**, *46*, 2401141.
[310] S. M. Esfarjani, A. Dadashi, M. Azadi, *Forces Mech.* **2022**, *7*, 100100.
[311] C. Yuan, T. Lu, T. J. Wang, *Forces Mech.* **2022**, *7*, 100081.
[312] G. Dixit, P. M. Pandey, *Int. J. Adv. Manuf. Technol.* **2025**, *136*, 3345.
[313] H. Zhang, S. Huang, Y. Zhang, Z. Qian, J. Sheng, J. Zhang, E. Agyenim-Boateng, M. Zhu, J. Zhou, *Chem. Eng. J.* **2025**, *513*, 162877.
[314] M. H. Yousuf, W. Abuzaid, M. Egilmez, *Adv. Eng. Mater.* **2025**, *27*, 2402423.
[315] K. Bouguermouh, M. Habibi, L. Laperrière, D. Monplaisir, Z. Li, Y. Abdin, *Polymer (Guildf)* **2025**, *333*, 128587.
[316] S. Jayalath, E. Trifoni, J. Epaarachchi, M. Herath, E. E. Gdoutos, B. Samarasekara, *Compos. Sci. Technol.* **2024**, *258*, 110870.
[317] J. Lu, G. Zhu, S. Wang, C. Wu, X. Qu, X. Dong, H. Pang, Y. Zhang, *Small* **2024**, *20*, 2401565.
[318] U. Umer, M. H. Abidi, Z. Almutairi, M. A. El-Meligy, *Results Eng.* **2024**, *24*, 102978.
[319] Y. Xie, H. Zhang, H. Hu, Z. He, *Chem. – A Eur. J.* **2024**, *30*, 202304160.
[320] A. Bigham, A. Zarepour, A. Khosravi, S. Iravani, A. Zarrabi, *Mater. Horiz.* **2024**, *11*, 6257.
[321] I. Hussain, K. Singh, B. Kalidasan, M. Ali, K.-J. Meng, M. K. Aslam, S. Pandiyarajan, S. Hussain, Rosaiah, S. Ali, H.-C. Chuang, K. Zhang, *Chem. Eng. J.* **2025**, *508*, 160856.
[322] J. Li, M. M. Naiini, S. Vaziri, M. C. Lemme, M. Östling, *Adv. Funct. Mater.* **2014**, *24*, 6524.
[323] J.-W. T. Seo, J. Zhu, V. K. Sangwan, E. B. Secor, S. G. Wallace, M. C. Hersam, *ACS Appl. Mater. Interfaces* **2019**, *11*, 5675.
[324] R. Sargeni, E. Dimaggio, F. Pieri, F. Fabbri, G. Pennelli, L. Colombo, G. Iannaccone, M. Macucci, G. Fiori, *Adv. Mater. Technol.* **2025**, *10*, 2400610.
[325] S. Guo, H. Cui, T. Agarwal, L. G. Zhang, *Small* **2024**, *20*, 2307750.
[326] P. Agarwal, V. Mathur, M. Kasturi, V. Srinivasan, R. N. Seetharam, K. S Vasanthan, *ACS Omega* **2024**, *9*, 37445.
[327] J. Wang, Y. Zhao, Y. Zhu, F. Wang, X. Wang, B. Wang, H. Xiao, Y. Duan, *Adv. Funct. Mater.* **2024**, *34*, 2409611.
[328] P. Srinivas, L. Jacob, M. Shebeeb C, H. Butt, I. Barsoum, R. K. Abu Al-Rub, W. Zaki, *Adv. Eng. Mater.* **2024**, *26*, 2301698.
[329] A. Kamyshny, S. Magdassi, *Isr. J. Chem.* **2025**, *65*, 202512002.
[330] P. Honari, D. Rahmatabadi, A. Bayati, E. Rassi, I. Ghasemi, M. Baniassadi, M. Bodaghi, M. Baghani, *Manuf. Lett.* **2025**, *43*, 33.
[331] S. Namathoti, S. R. Murthy Paladugu, A. K. Barick, P. S. R. Sreekanth, *Polymer (Guildf)*. **2024**, 127932.
[332] D. Rahmatabadi, K. Mirasadi, A. Bayati, M. Khajepour, I. Ghasemi, M. Baniassadi, K. Abrinia, M. Bodaghi, M. Baghani, *Appl. Mater. Today* **2024**, *40*, 102361.
[333] D. Liu, L. Zhu, J. Zhou, Y. Xie, X. Luo, S. A. Evsyukov, *Polymer (Guildf)*. **2024**, *313*, 127718.
[334] A. Pavone, G. Stano, G. Percoco, *3D Print. Addit. Manuf.* **2023**, *6*.
[335] Z. Ren, K. Ding, X. Zhou, T. Ji, H. Sun, X. Chi, Y. Wei, M. Xu, *Int. J. Biol. Macromol.* **2024**, *277*, 134207.
[336] M. Lalegani Dezaki, M. Bodaghi, *Macromol. Mater. Eng.* **2022**, *307*, 2200490.
[337] M. Daly, M. Chihi, C. Bouraoui, M. Tarfaoui, *J. Manuf. Process.* **2024**, *131*, 1770.
[338] G. L. Goh, G. D. Goh, V. P. Nguyen, W. Toh, S. Lee, X. Li, B. D. Sunil, J. Y. Lim, Z. Li, A. K. Sinha, W. Y. Yeong, D. Campolo, W. T. Chow, T. Y. Ng, B. S. Han, *Adv. Mater. Technol.* **2023**, *8*, 2301426.
[339] C. Lin, L. Liu, Y. Liu, J. Leng, *ACS Appl. Mater. Interfaces* **2021**, *13*, 12668.
[340] H. Choi, T. Park, G. Hwang, Y. Ko, D. Lee, T. Lee, J.-O. Park, D. Bang, *Robotics* **2023**, *12*, 150.
[341] Y. B. Kim, H. Song, S. Kim, H.-J. Chun, *Smart Mater. Struct.* **2024**, *33*, 105004.
[342] C. Tawk, A. Gillett, M. in het Panhuis, G. M. Spinks, G. Alici, *IEEE Trans. Robot.* **2019**, *35*, 1268.
[343] A. Ahangari, H. Doostmohammadi, M. Baniassadi, M. Bodaghi, M. Baghani, *Eur. Polym. J.* **2024**, *220*, 113495.
[344] J. D. Carrico, N. W. Traeden, M. Aureli, K. K. Leang, *Smart Mater. Struct.* **2015**, *24*, 125021.
[345] H. Doostmohammadi, M. Baniassadi, M. Bodaghi, M. Baghani, *Macromol. Mater. Eng.* **2024**, *309*, 2400090.
[346] H. Zhai, X. Li, S. Yu, J. Wang, L. Zhou, X. Xiong, J. Li, Y. Chang, T. Liu, X. Yu, B. Li, *Compos. Part A Appl. Sci. Manuf.* **2024**, *187*, 108443.
[347] R. Mutlu, C. Tawk, G. Alici, E. Sariyildiz, in *IECON 2017 –43rd Annual Conference of the IEEE Industrial Electronics Society*, IEEE, Beijing, China, **2017**, pp. 6235–6240.
[348] S. Mettes, J. Bates, K. W. Allen, Y. C. Mazumdar, in *2023 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, IEEE, Singapore, Singapore, **2023**, pp. 517–524.
[349] Z. Wang, Y. Zheng, L. Qiao, Y. Ma, H. Zeng, J. Liang, Q. Ye, K. Shen, B. Liu, L. Sun, Z. Fan, *Adv. Healthcare Mater.* **2024**, *13*, 2401093.
[350] Z. Chen, Z. Li, in *2024 IEEE 1st International Workshop on Future Intelligent Technologies for Young Researchers (FITYR)*, IEEE, Shanghai, China, **2024**, pp. 97–103.
[351] Z. Yu, X. Sun, Y. Zhu, E. Zhou, C. Cheng, J. Zhu, P. Yang, D. Zheng, Y. Zhang, M. Panahi-Sarmad, F. Jiang, *ACS Nano* **2024**, *18*, 28142.
[352] Y. Zhao, X. Lei, Z. Zeng, D. Guo, Y. Li, R. Ma, S. Shen, F. Liu, *ACS Appl. Mater. Interfaces* **2023**, *15*, 54743.
[353] M. Dehghan, M. Tahmasebipour, S. Ebrahimi, *Microelectron. Eng.* **2022**, *254*, 111695.
[354] X. Fang, K. Wei, R. Yang, *Soft Robot.* **2023**, *11*.
[355] Z. J. Patterson, D. K. Patel, S. Bergbreiter, L. Yao, C. Majidi, *Soft Robot.* **2022**, *10*, 292.
[356] P. Huang, H. Fu, M. W. M. Tan, Y. Jiang, P. S. Lee, *Adv. Mater. Technol.* **2024**, *9*, 2301642.
[357] J. Z. Gul, B.-S. Yang, Y. J. Yang, D. E. Chang, K. H. Choi, *Smart Mater. Struct.* **2016**, *25*, 115009.
[358] K. Ruenpanya, Mora, Karagiannidis, K. Bunyanuwat, S. Rimdusit, *Adv. Ind. Eng. Polym. Res.* **2024**.
[359] R. MacCurdy, R. Katzschmann, Y. Kim, D. Rus, in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, Stockholm, Sweden, **2016**, pp. 3878–3885.
[360] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, C. Charitidis, *Mater. Today* **2018**, *21*, 22.
[361] J. Xiao, G. Ji, Y. Zhang, G. Ma, V. Mechtcherine, J. Pan, Li Wang, T. Ding, Z. Duan, S. Du, *Cem. Concr. Compos.* **2021**, *122*, 104115.

[362] E. A. Monaco, T. Reed, T. J. Lynn, S. A. Rimini, A. A. Patel, S. E. Monaco, B. S. Patterson, *Cancer Cytopathol* **2024**, *132*, 75.
[363] R. Sedghi, K. Rashidi, M. Hojati, *Autom. Constr.* **2024**, *159*, 105255.
[364] S. Remke, G. Sant, T. Gädt, *ce/papers* **2023**, *6*, 818.
[365] G. D. Goh, K. K. Wong, N. Tan, H. L. Seet, M. L. S. Nai, *Virtual Phys. Prototyp.* **2024**, *19*, 2336160.
[366] L. Huang, D. Zhao, X. Yan, X. Liu, Q. Sun, H. Yang, X. Liu, H. Jia, *Adv. Electron. Mater.* **2024**, *11*, 2400474.
[367] J. Kim, S.-H. Jeong, B. C. Thibault, J. A. L. Soto, H. Tetsuka, S. V. Devaraj, E. Riestra, Y. Jang, J. W. Seo, R. A. C. Rodríguez, L. L. Huang, Y. Lee, I. Preda, S. Sonkusale, L. Fiondella, J. Seo, L. Pirrami, S. R. Shin, *Adv. Healthcare Mater.* **2024**, *14*, 2401735.
[368] M. Leschok, M. Kladeftira, Y.-F. Chan, B. Dillenburger, *3D Print. Addit. Manuf.* **2024**, *11*, 907.
[369] W.-H. Tsai, C.-K. Su, *Anal. Chem.* **2024**, *96*, 4469.
[370] W. Shi, S. Jang, M. A. Kuss, O. A. Alimi, B. Liu, J. Palik, L. Tan, M. A. Krishnan, Y. Jin, C. Yu, B. Duan, *ACS Nano* **2024**, *18*, 7580.
[371] L. Joharji, F. Alam, N. El-Atab, *ACS Omega* **2024**, *9*, 14638.
[372] S. Feng, X. Peng, J. Cui, R. Feng, Y. Sun, Y. Guo, Z. Lu, W. Gao, F. Liu, C. Liang, G. Hu, B. Zhang, *Adv. Funct. Mater.* **2024**, *34*, 2401431.
[373] M. Jurinovs, M. Veseta, A. Sabalina, P. E. S. Silva, A. Linarts, H. Baniasadi, J. Vapaavuori, S. Gaidukovs, *Small Sci.* **2025**, 2500104.
[374] E. Tekay, B. Aybakan, V. U. Aslan, *React. Funct. Polym.* **2025**, *209*, 106188.
[375] Y. Wang, W. Liang, W. Cai, J. Zhang, W. Guo, B. Qi, H. Zhang, H. Lu, Z. Ding, *Eng. Struct.* **2025**, *336*, 120459.
[376] M. Seong, K. Sun, S. Kim, H. Kwon, S.-W. Lee, S. C. Veerla, D. K. Kang, J. Kim, S. Kondaveeti, S. M. Tawfik, H. W. Park, H. E. Jeong, *Nat. Commun.* **2024**, *15*, 7929.
[377] J. Wang, G. Wang, H. Chen, Y. Liu, Wang, D. Yuan, X. Ma, X. Xu, Z. Cheng, B. Ji, M. Yang, J. Shuai, F. Ye, J. Wang, Y. Jiao, L. Liu, *Nat. Commun.* **2024**, *15*, 8853.
[378] H. R Nohooji, H. Voos, *Adv. Intell. Syst.* **2025**, 2400785.
[379] J. Zhu, A. Cherubini, C. Dune, D. Navarro-Alarcon, F. Alambeigi, D. Berenson, F. Ficuciello, K. Harada, J. Kober, X. Li, J. Pan, W. Yuan, M. Gienger, *IEEE Robot. Autom. Mag.* **2022**, *29*, 67.
[380] W. Xue, B. Jian, L. Jin, R. Wang, Q. Ge, *Adv. Mater. Technol.* **2025**, 00278.
[381] X. Li, B. Sun, D. Li, H. Jing, Y. Sun, M. Li, *Adv. Mater. Technol.* **2025**, 00611.
[382] H. Son, E. Byun, Y. J. Yoon, J. Nam, S. H. Song, C. Yoon, *ACS Macro Lett.* **2020**, *9*, 1766.
[383] C. Matta, C. Tawk, P. Rahme, *Smart Mater. Methods* **2025**, 1.
[384] K. Wei, C. Tang, H. Ma, X. Fang, R. Yang, *Biomater. Sci.* **2024**, *12*, 4301.
[385] Y. Lin, F.-Y. Fan, W.-C. Lin, J.-S. Lai, Y.-K. Shen, M. Ruslin, *Polym. Eng. Sci.* **2024**, *64*, 5761.
[386] S. H. Jeon, G. W. Hwang, J. Kim, D. Lim, Y. Son, T.-H. Yang, D. W. Kim, C. Pang, *InfoMat* **2024**, *7*, 12640.
[387] Y. Dewang, V. Sharma, V. K. Baliyan, T. Soundappan, Y. K. Singla, *Polymers* **2025**, *17*, 746.
[388] M. J. Thomas, S. Mohan, *J. Indian Inst. Sci.* **2024**, *104*, 645.
[389] P. Wu, T. Yu, M. Chen, N. Kang, M. El Mansori, *Adv. Funct. Mater.* **2024**, *34*, 2314854.
[390] J. An, J. E. M. Teoh, R. Suntornnond, C. K. Chua, *Engineering* **2015**, *1*, 261.
[391] T. Agarwal, S. Y. Hann, I. Chiesa, H. Cui, N. Celikkin, S. Micalizzi, A. Barbetta, M. Costantini, T. Esworthy, L. G. Zhang, C. De Maria, T. K. Maiti, *J. Mater. Chem. B* **2021**, *9*, 7608.
[392] I. Sahafnejad-Mohammadi, M. Karamimoghadam, A. Zolfagharian, M. Akrami, M. Bodaghi, *J. Brazilian Soc. Mech. Sci. Eng.* **2022**, *44*, 233.
[393] A. Sadraei, S. M. Naghib, *Polym. Rev.* **2024**, *65*, 1.
[394] J. Hussan K S, M. P. Subramaniam, M. KenzK T, P. Sreeram, S. Parvathi, S. PS, A. Pullanchiyodan, D. M. Mulhivill, P. Raghavan, *Results Eng.* **2024**, *21*, 101867.
[395] S. S. Sparks, A. G. Obando, Y. Li, S. Chen, S. Yao, K. Qiu, *IET Cyber-Systems Robot.* **2024**, *6*, 70001.
[396] S. Cao, S. Zhang, M. Liu, M. Heydaroglu, C. Wen, J. Sun, Y. Wang, M. Yu, X. Han, *ACS Appl. Polym. Mater.* **2024**, *6*, 13268.
[397] M. A. Ali, M. Rajabi, S. S. Sali, *Curr. Opin. Chem. Eng.* **2020**, *28*, 127.
[398] A. E. Eldeeb, S. Salah, N. A. Elkasabgy, *AAPS PharmSciTech* **2022**, *23*, 267.
[399] S. McGivern, H. Boutouil, G. Al-Kharusi, S. Little, N. J. Dunne, T. J. Levingstone, *Bioengineering* **2021**, *8*, 144.
[400] J. T. Toombs, I. K. Shan, H. K. Taylor, *Macromol. Rapid Commun.* **2023**, *44*, 2200872.
[401] L. Großmann, M. Kieckhöfer, W. Weitschies, J. Krause, *Eur. J. Pharm. Biopharm.* **2022**, *181*, 227.
[402] R. Guo, W. Qi, H. Liu, D. Li, G. Chen, Q. Li, Z. Zhou, *Chem. Eng. J.* **2024**, *485*, 149850.
[403] W. Huang, W. Chen, V. Singh, J. Zhang, Y. Wang, M. Alabdullatif, E. B. Gary, J. L. Helen, C. Hailes, M. K. Tiwari, *Addit. Manuf.* **2025**, *101*, 104699.
[404] X. Zhou, H. Liu, J. Zhang, L. Ren, Lu Zhang, Q. Liu, B. Li, C. Xu, L. Ren, *Thin-Walled Struct.* **2024**, *205*, 112609.
[405] D. Shen, M. Zhang, A. S. Mujumdar, J. Li, *Innov. Food Sci. Emerg. Technol.* **2025**, *100*, 103896.
[406] S. Cen, Z. Meng, *Trends Food Sci. Technol.* **2024**, *153*, 104729.
[407] Z. Guo, B. Yang, N. Liang, X. Huang, J. Shi, Z. Li, Paximada, Z. Xiaobo, *J. Food Eng.* **2025**, *386*, 112258.
[408] S. M. Naghib, S. N. Hosseini, A. Beigi, *Carbohydr. Polym. Technol. Appl.* **2024**, *8*, 100594.
[409] L. Zhang, W. Zhang, Q. Wang, S. Ma, X. Yan, *J. Bionic Eng.* **2025**, *22*, 238.
[410] C. M. Llanos, D. Saakes, M. Mehrpouya, *Eur. J. Mech. – A/Solids* **2025**, *112*, 105649.
[411] J. Qian, S. Kolagatla, A. Pacalovas, X. Zhang, L. Florea, A. L. Bradley, C. Delaney, *Adv. Funct. Mater.* **2023**, *33*, 2211735.
[412] M. Lay, M. G. Say, I. Engquist, *Adv. Mater. Technol.* **2023**, *8*, 2300652.
[413] X. Shen, A. Akbarzadeh, C. Shi, Z. Pang, Y. Jin, M. Ge, *J. Mater. Res. Technol.* **2021**, *13*, 1374.
[414] Z. Li, Z. Cao, Q. Zhao, S. Mei, Y. Zhang, W. Zhao, X. Li, X. Zhang, Z. Cui, Fu, X. Pang, M. Liu, *Chem. Eng. J.* **2024**, *485*, 149933.
[415] S. Narendhiran, S. Meher, S. Midya, S. Mishra, S. P. Prusti, M. Balachandran, A. K. Singh, Kumbhakar, *ACS Appl. Nano Mater.* **2024**, *7*, 21200.
[416] M. Mehrpouya, Z. Ding, W. M. Huang, in *Additive Manufacturing Materials and Technologies*, (Eds. M. Mehrpouya, M. B. T.-A. M. of S. M. M. Elahinia), Elsevier, Amsterdam, Netherlands, **2025**, pp. 53–84.
[417] T. Tang, M. Zhang, A. S. Mujumdar, X. Teng, *Food Res. Int.* **2022**, *158*, 111496.
[418] Z. Tang, G. Deng, Y. Sun, L. Tao, C. Wang, Z. Yang, P. Liu, Q. Wang, Y. Zhang, T. Wang, *Adv. Ind. Eng. Polym. Res.* **2024**, *8*, 226.
[419] Y. Cui, R. Jin, Y. Zhang, M. Yu, Y. Zhou, L.-Q. Wang, *Int. J. bioprinting* **2021**, *7*, 397.
[420] S. Zhuo, L. M. Geever, E. Halligan, B. S. Tie, C. Breheny, *Journal of Functional Biomaterials* **2022**, *13*, 262.
[421] V. C. Agbakoba, Hlangothi, J. Andrew, M. J. John, *Sustainability* **2022**, *14*, 12759.
[422] A. Ghalayaniesfahani, B. Oostenbrink, H. van Kasteren, I. Gibson, M. Mehrpouya, *Polymer (Guildf)* **2024**, *307*, 127252.
[423] Y. Zhou, F. Wang, Z. Yang, X. Hu, Y. Pan, Y. Lu, M. Jiang, *Ind. Crops Prod.* **2022**, *182*, 114831.
[424] A. Ghalayaniesfahani, B. Oostenbrink, H. van Kasteren, M. Mehrpouya, *Adv. Eng. Mater.* **2024**, *26*, 2401705.

[425] P.-C. Lai, Z.-F. Ren, S.-S. Yu, *ACS Appl. Polym. Mater.* **2022**, *4*, 9221.
[426] T. C. Cheung, S. Y. Choi, S. Jiang, *Addit. Manuf.* **2024**, *79*, 103909.
[427] Ș.-D. Sava, B. Pricop, R.-I. Comaneci, N. Cimpoe?u, M. Popa, N.-M. Lohan, L.-G. Bujoreanu, *Polymers* **2024**, *16*, 1965.
[428] H. Doostmohammadi, K. Kashmarizad, M. Baniassadi, M. Bodaghi, M. Baghani, *J. Mech. Behav. Biomed. Mater.* **2024**, *160*, 106719.
[429] A. Li, X.-G. Chen, L.-Y. Zhang, Y.-F. Zhang, *Materials* **2022**, *15*, 8838.
[430] S. Namathoti, R. S. PS, M. R. K. Vakkalagadda, *J. Polym. Res.* **2024**, *31*, 229.
[431] C. Cheng, H. Xie, Z.-y Xu, L. Li, M.-N. Jiang, L. Tang, K.-K. Yang, Y.-Z. Wang, *Chem. Eng. J.* **2020**, *396*, 125242.
[432] H. Kulkarni, J. Xi, A. Sallam, P. Lee, D. Safranski, R. Mirzaeifar, S. Shahab, *Addit. Manuf.* **2024**, *94*, 104465.
[433] F. S. Senatov, K. V. Niaza, M. Y. Zadorozhnyy, A. V. Maksimkin, S. D. Kaloshkin, Y. Z. Estrin, *J. Mech. Behav. Biomed. Mater.* **2016**, *57*, 139.
[434] L. Lin, J. Yan, S. Qiu, *Smart Mater. Struct.* **2024**, *33*, 105022.
[435] B. Goo, C.-H. Hong, K. Park, *Mater. Des.* **2020**, *188*, 108485.
[436] Z. Lei, Q. Wang, P. Wu, *Mater. Horiz.* **2017**, *4*, 694.
[437] L. Jiang, C. Long, S. Xiong, X. Wang, Y. Mo, J. Zeng, Z. Liu, C. Liu, Z. Chen, *Virtual Phys. Prototyp.* **2024**, *19*, 2406408.
[438] Y. Wang, J. Zhang, M. Li, M. Lei, Y. Wang, Q. Wei, *J. Polym. Res.* **2022**, *29*, 243.
[439] M. Song, X. Liu, H. Yue, S. Li, J. Guo, *Polymer (Guildf).* **2022**, *256*, 125190.
[440] Y. Yuts, R. McCabe, M. Krell, M. Bohley, J.-C. Leroux, *Int. J. Pharm.* **2024**, 125051.
[441] Z. Tang, Z. Yang, L. Tao, Y. Zhang, Y. Sun, Liu, X. Zhang, Q. Wang, T. Wang, *ACS Appl. Polym. Mater.* **2024**, *6*, 15313.
[442] C. Cao, D. Liu, L. Zhu, S. Gu, S. A. Evsyukov, X. Luo, *Polym. Eng. Sci.* **2025**, https://doi.org/10.1002/pen.70013.
[443] A. de Souza Leão Rodrigues, M. A. Chinelatto, A. C. Chinellato, Z. de Castro Silveira, *Prog. Addit. Manuf.* **2025**.
[444] S. Chen, X. Mao, Z. He, W. Lu, B. Wu, H. Zhuo, *Smart Mater. Struct.* **2024**, *33*, 085042.
[445] F. Wang, M. Jiang, Y. Pan, Y. Lu, W. Xu, Y. Zhou, *Polym. Test.* **2023**, *119*, 107934.
[446] X. Li, Y. Zhan, W. Li, Z. Huang, A. Amirfazli, *Adv. Eng. Mater.* **2024**, *26*, 2401415.
[447] Y. Wang, Y. Wang, M. Liu, Q. Wei, B. Du, *High Perform. Polym.* **2022**, *35*, 366.
[448] L. Ren, Z. Wang, L. Ren, Q. Liu, W. Li, Z. Song, B. Li, Q. Wu, X. Zhou, *Mater. Today Chem.* **2023**, *29*, 101470.
[449] X. Zuo, S. Wang, Y. Zhou, C. Wu, A. Huang, T. Wang, Y. Yang, *Chem. Eng. J.* **2022**, *447*, 137492.
[450] Y. Cao, Y. Wu, Y. Huang, H. Xiang, L. Zhang, *Chem. Eng. J.* **2024**, *498*, 155140.
[451] I. Choi, S. Jang, S. Jung, S. Woo, J. Kim, C. Bak, Y. Lee, S. Park, *Mater. Horiz.* **2023**, *10*, 3668.
[452] T. Gu, H.BiH. Sun, J. Tang, Z. Ren, X. Zhou, M. Xu, *Addit. Manuf.* **2023**, *70*, 103544.
[453] M. C. de Alencar Lira, V. A. de Sousa Filho, R. B. da Cunha, J. M. de Araújo, P. Agrawal, G. de Figueiredo Brito, T. J. A. de Mélo, *Polymer (Guildf).* **2025**, *319*, 128059.
[454] A.-A. Ene, T. G. Alexandru, D. Popescu, *Designs* **2024**, *8*, 56.
[455] M. Barbier, M. J. Le Guen, J. McDonald-Wharry, J. H. Bridson, K. L. Pickering, *3D Print. Addit. Manuf.* **2021**, *8*, 193.
[456] S. Kumar, N. Ojha, M. R. Ramesh, M. Doddamani, *Polym. Compos.* **2024**, *45*, 15460.
[457] M. Lalegani Dezaki, C. Branfoot, J. Baxendale, M. Bodaghi, *Macromol. Mater. Eng.* **2024**, *310*, 2400276.
[458] R. Yu, X. Yang, Y. Zhang, X. Zhao, X. Wu, T. Zhao, Y. Zhao, W. Huang, *ACS Appl. Mater. Interfaces* **2017**, *9*, 1820.
[459] S. Zeng, Y. Gao, H. Qiu, J. Xu, J. Tan, *Sci. Rep.* **2022**, *12*, 18874.
[460] A. N. Nikishina, B. Ch. Kholkhoev, K. N. Bardakova, Z. A. Matveev, Z. I. Kurdanova, K. T. Shakhmurzova, A. A. Zhansitov, S. Y. Khashirova, P. S. Timashev, V. F. Burdukovskii, *React. Funct. Polym.* **2024**, *202*, 106001.
[461] Y. Y. C. Choong, S. Maleksaeedi, H. Eng, J. Wei, P.-C. Su, *Mater. Des.* **2017**, *126*, 219.
[462] G. Aydin, T. Abdullah, O. Okay, *Eur. Polym. J.* **2024**, *223*, 113651.
[463] S. Mei, J. Wang, Z. Li, B. Ding, S. Li, X. Chen, W. Zhao, Y. Zhang, X. Zhang, Z. Cui, Fu, X. Pang, M. Liu, *J. Manuf. Process.* **2023**, *92*, 157.
[464] Y. Huang, S. Löschke, Y. Gan, G. Proust, *J. Manuf. Mater. Process.* **2024**, *8*, 77.
[465] X. Zhou, C. Tian, J. Zhang, L. Ren, L. Ren, *Int. J. Mech. Sci.* **2025**, *288*, 110038.
[466] P. Cao, J. Yang, J. Gong, L. Tao, T. Wang, J. Ju, Y. Zhou, Q. Wang, Y. Zhang, *J. Appl. Polym. Sci.* **2023**, *140*, 53241.
[467] M. Barletta, A. Gisario, M. Mehrpouya, *J. Manuf. Process.* **2021**, *61*, 473.
[468] L. Cecchini, S. Mariani, M. Ronzan, A. Mondini, N. M. Pugno, B. Mazzolai, *Adv. Sci.* **2023**, *10*, 2205146.
[469] A. B. Baker, S. R. G. Bates, T. M. Llewellyn-Jones, L. P. B. Valori, M. P. M. Dicker, R. S. Trask, *Mater. Des.* **2019**, *163*, 107544.
[470] H. M. Pan, J. Sarkar, A. Goto, *ACS Appl. Polym. Mater.* **2022**, *4*, 8876.
[471] J. Wang, Y. Zhang, J. Zheng, H. Guo, Y. Qiu, X. Wang, L. Liu, H. Yu, *Addit. Manuf.* **2024**, *84*, 104122.
[472] H. Ikram, A. Al Rashid, M. Koç, *Compos. Part C Open Access* **2022**, *9*, 100331.
[473] L. Ren, B. Li, Q. Liu, L. Ren, Z. Song, X. Zhou, P. Gao, *Frontiers in Materials* **2021**, *8*, 134.
[474] X. Wan, Y. He, Y. Liu, J. Leng, *Addit. Manuf.* **2022**, *53*, 102689.
[475] T. Hupfeld, S. Salamon, J. Landers, A. Sommereyns, C. Doñate-Buendía, J. Schmidt, H. Wende, M. Schmidt, S. Barcikowski, B. Gökce, *J. Mater. Chem. C* **2020**, *8*, 12204.
[476] D. Ravichandran, R. J. Ahmed, R. Banerjee, M. Ilami, H. Marvi, G. Miquelard-Garnier, Y. Golan, K. Song, *J. Mater. Chem. C* **2022**, *10*, 13762.
[477] H. Liu, F. Wang, W. Wu, X. Dong, L. Sang, *Compos. Part B Eng.* **2023**, *248*, 110382.
[478] H. Wu, O. Wang, Y. Tian, M. Wang, B. Su, C. Yan, K. Zhou, Y. Shi, *ACS Appl. Mater. Interfaces* **2021**, *13*, 12679.
[479] M. Moradi, M. Lalegani Dezaki, E. Kheyri, S. A. Rasouli, M. Aghaee Attar, M. Bodaghi, *J. Magn. Magn. Mater.* **2023**, *568*, 170425.
[480] M. Tyagi, G. M. Spinks, E. W. H. Jager, *Soft Robot.* **2020**, *8*, 19.
[481] S. Mousavi, D. Howard, F. Zhang, J. Leng, C. H. Wang, *ACS Appl. Mater. Interfaces* **2020**, *12*, 15631.
[482] Y. Li, X. Yang, J. Li, Q. Liu, B. Li, K. Wang, *J. Bionic Eng.* **2024**, *21*, 2302.
[483] M. Y. Razzaq, J. Gonzalez-Gutierrez, M. Farhan, R. Das, D. Ruch, S. Westermann, D. F. Schmidt, *Polymers* **2023**, *15*, 832.
[484] X. Dong, F. Zhang, L. Wang, Y. Liu, J. Leng, *Compos. Part A Appl. Sci. Manuf.* **2022**, *157*, 106925.
[485] Y. Wang, N. Alizadeh, M. Barde, M. L. Auad, B. S. Beckingham, *ACS Appl. Polym. Mater.* **2022**, *4*, 971.
[486] N. Wang, X. Xiao, T. Liu, C. Zhang, M. Gu, X. Qi, *Adv. Mater. Technol.* **2025**, *10*, 2401345.
[487] M. Zarek, M. Layani, I. Cooperstein, E. Sachyani, D. Cohn, S. Magdassi, *Adv. Mater.* **2016**, *28*, 4449.
[488] H. Bi, G. Ye, H. Sun, Z. Ren, T. Gu, M. Xu, *Addit. Manuf.* **2022**, *49*, 102487.
[489] Y. He, R. Yu, X. Li, M. Zhang, Y. Zhang, X. Yang, X. Zhao, W. Huang, *ACS Appl. Mater. Interfaces* **2021**, *13*, 36286.
[490] T. Makki, S. H. Vattathurvalappil, R. Theravalappil, A. Nazir, A. Alhajeri, M. A. Azeem, E. Mahdi, A. C. Ummer, U. Ali, *Compos. Part C Open Access* **2024**, *14*, 100472.

[491] J. Su, W. L. Ng, J. An, W. Y. Yeong, C. K. Chua, S. L. Sing, *Virtual Phys. Prototyp.* **2024**, *19*, 2438899.
[492] F. S. Shahar, M. T. Sultan, R. Grzejda, A. Łukaszewicz, Z. Oksiuta, R. R. Krishnamoorthy, *Materials* **2024**, *17*, 6045.
[493] R. Agrawal, A. Kumar, M. K. A. Mohammed, S. Singh, *J. Zhejiang Univ. A* **2023**, *24*, 1027.
[494] H. Shokrani, A. Shokrani, F. Seidi, M. Mashayekhi, S. Kar, D. Nedeljkovic, T. Kuang, M. R. Saeb, M. Mozafari, *Bioeng. Transl. Med.* **2023**, *8*, 10503.
[495] T. Hwang, D. Tsogbayar, Vanessa, H. H. Choi, H. S. Lee, *J. Mater. Chem. C* **2024**, *12*, 15310.
[496] M. Alonso-González, M. Felix, A. Romero, C. Sergi, I. Bavasso, F. Sarasini, *Resour. Conserv. Recycl.* **2025**, *212*, 107990.
[497] P. D. C. Costa, D. C. S. Costa, T. R. Correia, V. M. Gaspar, J. F. Mano, *Adv. Mater. Technol.* **2021**, *6*, 2100168.
[498] T. Cordonnier, J. Sohier, Rosset, P. Layrolle, *Adv. Eng. Mater.* **2011**, *13*, B135.
[499] A. Mecheter, F. Tarlochan, *Sustainability* **2023**, *15*, 12319.
[500] A. S. Tiwari, S. Yang, *Polymers* **2023**, *15*, 1290.
[501] B. Arsuffi, T. Magrini, M. Champeau, G. Siqueira, S. Titotto, *Sustain. Mater. Technol.* **2025**, *44*, 01346.
[502] A. M. Rahman, T. T. Rahman, Z. Pei, C. O. Ufodike, J. Lee, A. Elwany, *Bioengineering* **2023**, *10*, 845.
[503] Y. S. Jung, J. Park, S. Lee, E. J. Shin, *Fash. Text.* **2025**, *12*, 3.
[504] C. Lu, Y. Shen, X. Wang, S. Xu, J. Wang, Q. Yong, F. Chu, *Int. J. Biol. Macromol.* **2023**, *226*, 1468.
[505] N. Boonnao, Luengrojanakul, R. Gholami, C.-H. Ahn, Karagiannidis, S. Rimdusit, *Appl. Mater. Today* **2025**, *44*, 102774.
[506] P. Agrawal, P. de Andrade Lima, R. B. da Cunha, S. N. Cavalcanti, V. A. de Sousa Filho, R. L. P. Bonfim, G. de Figueiredo Brito, C. T. C. Cunha, T. J. A. de Mélo, *Polym. Eng. Sci.* **2024**, *64*, 6037.
[507] H. Tao, H. Shijun, H. Yuanchao, L. Zhiwei, J. Tiancheng, L. Wei, M. Xintong, *J. Appl. Polym. Sci.* **2025**, 57297.
[508] J. Zhang, S. Zhao, M. Zhu, Y. Zhu, Y. Zhang, Z. Liu, C. Zhang, *J. Mater. Chem. B* **2014**, *2*, 7583.
[509] N. D. A. Kusmono, M. W. W. Herianto, *Results Eng.* **2023**, *17*, 100842.
[510] Q. Ji, X. V. Wang, L. Wang, L. Feng, *Sci. Rep.* **2022**, *12*, 7566.
[511] S. H. Ladakhan, R. B. Sreesha, S. M Adinarayanappa, *Smart Mater. Struct.* **2024**, *33*, 105037.
[512] B. B. Samal, S. K. Varshney, C. S. Kumar, *J. Mech. Sci. Technol.* **2024**, *38*, 4313.
[513] F. Zhang, N. Wen, L. Wang, Y. Bai, J. Leng, *Int. J. Smart Nano Mater.* **2021**, *26*, 1.
[514] S. Figalla, V. Jašek, J. Fučík, Menčík, R. Přikryl, *Biomacromolecules* **2024**, *25*, 6645.
[515] R. De Santis, U. D'Amora, T. Russo, A. Ronca, A. Gloria, L. Ambrosio, *J. Mater. Sci. Mater. Med.* **2015**, *26*, 250.
[516] J. Wang, T. Mu, Y. Xia, B. Jiang, C. Wang, *Appl. Mater. Today* **2025**, *42*, 102604.
[517] I. Ud Din, S. S. Kulkarni, K. A. Khan, *Polym. Test.* **2025**, *143*, 108708.
[518] C. Wang, X. P. Tan, S. B. Tor, C. S. Lim, *Addit. Manuf.* **2020**, *36*, 101538.
[519] S. Inayathullah, R. Buddala, *Results Eng.* **2025**, *25*, 103676.
[520] D. R. Gunasegaram, A. S. Barnard, M. J. Matthews, B. H. Jared, A. M. Andreaco, K. Bartsch, A. B. Murphy, *Addit. Manuf.* **2024**, *81*, 104013.
[521] A. H. Ridlo, Kusmono, M. A. Muflikhun, R. A. Putra, W. Thongking, A. Wiranata, *J. Appl. Polym. Sci.* **2025**, 57435.
[522] M. Parsazadeh, S. Sharma, N. Dahotre, *Prog. Mater. Sci.* **2023**, *135*, 101102.
[523] P. Mieszczanek, P. Corke, C. Mehanian, D. Dalton, D. W. Hutmacher, *Commun. Eng.* **2024**, *3*, 158.
[524] W. L. Ng, G. L. Goh, G. D. Goh, J. S. J. Ten, W. Y. Yeong, *Adv. Mater.* **2024**, *36*, 2310006.
[525] X. Zhang, D. Chu, X. Zhao, C. Gao, L. Lu, Y. He, W. Bai, *Appl. Mater. Today* **2024**, *39*, 102306.
[526] T. Nasrin, F. Pourkamali-Anaraki, A. M. Peterson, *J. Polym. Sci.* **2024**, *62*, 2639.
[527] C. M. Hamel, D. J. Roach, K. N. Long, F. Demoly, M. L. Dunn, H. J. Qi, *Smart Mater. Struct.* **2019**, *28*, 065005.
[528] M. Salman, S. Schmauder, *Comput. Mater. Sci.* **2024**, *232*, 112658.
[529] I. Malashin, I. Masich, V. Tynchenko, A. Gantimurov, V. Nelyub, A. Borodulin, D. Martysyuk, A. Galinovsky, *Polymers* **2024**, *16*, 3125.
[530] O. Ejeromedoghene, M. Kumi, E. Akor, Z. Zhang, *Adv. Colloid Interface Sci.* **2025**, *336*, 103360.
[531] L. Jin, X. Zhai, K. Wang, K. Zhang, D. Wu, A. Nazir, J. Jiang, W.-H. Liao, *Mater. Des.* **2024**, *244*, 113086.
[532] Y. Ma, Z. Tian, B. Wang, Y. Zhao, Y. Nie, R. D. Wildman, H. Li, Y. He, *Mater. Des.* **2024**, *241*, 112978.
[533] J.-W. Su, D. Li, Y. Xie, T. Zhou, W. Gao, H. Deng, M. Xin, J. Lin, *Smart Mater. Struct.* **2021**, *30*, 015028.
[534] Y. A. Alli, H. Anuar, M. R. Manshor, C. E. Okafor, A. F. Kamarulzaman, N. Akçakale, F. N. Mohd Nazeri, M. Bodaghi, J. Suhr, N. A. Mohd Nasir, *Hybrid Adv.* **2024**, *6*, 100242.
[535] G. D. Goh, S. L. Sing, W. Y. Yeong, *Artif. Intell. Rev.* **2021**, *54*, 63.
[536] T. S. Tamir, G. Xiong, Q. Fang, Y. Yang, Z. Shen, M. Zhou, J. Jiang, *Int. J. Comput. Integr. Manuf.* **2023**, *36*, 1362.
[537] Y.-H. Chiu, H. Yu-Ting, C. Mao-Chuan, X. Yi-Xian, Y. Yu-Chen, J.-Y. Juang, *Virtual Phys. Prototyp.* **2025**, *20*, 2507099.
[538] P. Castro, G. Pathinettampadian, S. Nandagopal, M. K. Subramaniyan, *Int. J. Adv. Manuf. Technol.* **2024**, *135*, 5323.
[539] L. Tan, T. Huang, J. Liu, Q. Li, X. Wu, *Comput. Ind. Eng.* **2023**, *176*, 108887.
[540] S. Garfo, M. A. Muktadir, S. Yi, *J. Mechatronics Robot.* **2020**, *4*, 74.
[541] A. F. Bonatti, *IJB* **2022**, *8*, 620.
[542] U. Delli, S. Chang, *Procedia Manuf.* **2018**, *26*, 865.
[543] B. Satyanarayana, J. Sreedevi, B. T. D. S. Varshini, *Prog. Addit. Manuf.* **2024**, *10*, 3893.
[544] N. Hooda, J. S. Chohan, R. Gupta, R. Kumar, *ISA Trans.* **2021**, *116*, 121.
[545] M. Ogunsanya, J. Isichei, S. K. Parupelli, S. Desai, Y. Cai, *Procedia Manuf.* **2021**, *53*, 427.
[546] M. Chen, M. Gao, L. Bai, H. Zheng, H. J. Qi, K. Zhou, *Adv. Mater.* **2022**, *35*, 2209566.
[547] S. Miao, N. Castro, M. Nowicki, L. Xia, H. Cui, X. Zhou, W. Zhu, S.-J. Lee, K. Sarkar, G. Vozzi, Y. Tabata, J. Fisher, L. G. Zhang, *Mater. Today* **2017**, *20*, 577.
[548] A. López-Díaz, A. S. Vázquez, E. Vázquez, *ACS Nano* **2024**, *18*, 20817.
[549] Z. M. Png, C.-G. Wang, J. C. C. Yeo, J. J. C. Lee, N. E. Surat'man, Y. L. Tan, H. Liu, Wang, B. H. Tan, J. W. Xu, X. J. Loh, Q. Zhu, *Mol. Syst. Des. Eng.* **2023**, *8*, 1097.
[550] Q. Zhang, Y. Zhang, Y. Wan, W. Carvalho, L. Hu, M. J. Serpe, *Prog. Polym. Sci.* **2021**, *116*, 101386.
[551] N. Li, L. Liu, Y. Liu, J. Leng, *Adv. Funct. Mater.* **2024**, *34*, 2406789.
[552] P. Rastogi, B. Kandasubramanian, *Chem. Eng. J.* **2019**, *366*, 264.
[553] Y. Zheng, Y. Du, L. Chen, W. Mao, Y. Pu, S. Wang, D. Wang, *Biomater. Sci.* **2024**, *12*, 2033.
[554] Y. Deng, B. Yang, F. Zhang, Y. Liu, J. Sun, S. Zhang, Y. Zhao, H. Yuan, J. Leng, *Biomaterials* **2022**, *291*, 121886.
[555] C. Li, C. Feng, L. Zhang, L. Zhang, L. Wang, *Polym. Eng. Sci.* **2024**, *65*, 431.
[556] H. Gao, J. An, C. K. Chua, D. Bourell, C.-N. Kuo, D. T. H. Tan, *Mater. Today* **2023**, *69*, 107.
[557] S. Huo, L. Sheng, B. Su, W. Xue, Li Wang, H. Xu, X. He, *Adv. Mater.* **2024**, *36*, 2310396.
[558] J. Fei, Y. Rong, L. Zhu, H. Li, X. Zhang, Y. Lu, J. An, Q. Bao, X. Huang, *Macromol. Rapid Commun.* **2023**, *44*, 2300211.

[559] X. Kong, M. Dong, M. Du, J. Qian, J. Yin, Q. Zheng, Z. L. Wu, *Chem Bio Eng.* **2024**, *4*, 312.
[560] S. Yin, D. R. Yao, Yu Song, W. Heng, X. Ma, H. Han, W. Gao, *Chem. Rev.* **2024**, *124*, 11585.
[561] M. Bodaghi, L. Wang, F. Zhang, Y. Liu, J. Leng, R. Xing, M. D. Dickey, S. Vanaei, M. Elahinia, S. V. Hoa, D. Zhang, K. Winands, T. Gries, S. Zaman, H. Soleimanzadeh, T. Barsi Palmic, J. Slavic, Y. Tadesse, Q. Ji, C. Zhao, L. Feng, K. Ahmed, Md. N. Islam Shiblee, L. Zeenat, F. Pati, L. Ionov, A. Chinnakorn, W. Nuansing, A. M. Sousa, J. Henriques, et al., *Smart Mater. Struct.* **2024**, *33*, 113501.
[562] J.-Y. Lee, J. An, C. K. Chua, *Appl. Mater. Today* **2017**, *7*, 120.
[563] E. Pei, G. H. Loh, *Prog. Addit. Manuf.* **2018**, *3*, 95.
[564] Y. Ji, C. Luan, X. Yao, J. Fu, Y. He, *Adv. Intell. Syst.* **2021**, *3*, 2000271.
[565] T.-G. La, L. H. Le, *Adv. Mater. Technol.* **2022**, *7*, 2100798.
[566] H. Deshpande, H. Takahashi, J. Kim, *ACM Trans. Comput. Interact.* **2024**, *31*, 1.
[567] S. Ali, I. Deiab, S. Pervaiz, *Int. J. Adv. Manuf. Technol.* **2024**, *135*, 5085.
[568] S. Palanisamy, G. Karuppiah, Kumar, S. Dharmalingam, S. Mubarak, C. Santulli, N. Ayrilmis, S. Karumuri, *Adv. Polym. Technol.* **2024**, *2024*, 3480281.
[569] J. K. Lu, W. Wang, J. Goh, A. B. Maier, *Heliyon* **2024**, *10*, 33488.
[570] Y. Sun, Y.-Z. Li, M. Yuan, *Nano Energy* **2023**, *115*, 108715.
[571] Y. Chen, F. Fang, N. Zhang, *npj 2D Mater. Appl.* **2024**, *8*, 17.
[572] L. Zhang, J. Qin, Das, S. Wang, T. Bai, F. Zhou, M. Wu, Z.-S. Wu, *Adv. Mater.* **2024**, *36*, 2313930.
[573] Y. Liu, Y. Zhu, *Additive Manufacturing: Materials, Functionalities and Applications* (Ed.: K. Zhou), Springer International Publishing, Cham **2023**, pp. 1–49.
[574] T. Zang, S. Fu, J. Cheng, C. Zhang, X. Lu, J. Hu, H. Xia, Y. Zhao, *Chem Bio Eng.* **2024**, *1*, 488.
[575] C. D. Wick, A. J. Peters, G. Li, *J. Polym. Sci.* **2024**, *63*, 9.
[576] A. Enayati-Gerdroodbar, A. Khayati, A. Zolfagharian, M. Salami-Kalajahi, M. Bodaghi, *Smart Mater. Methods* **2024**, *1*, 251.
[577] Z.-Z. Nie, M. Wang, H. Yang, *Commun. Chem.* **2024**, *7*, 58.
[578] Y. Zhao, M. Hua, Y. Yan, S. Wu, Y. Alsaid, X. He, *Annu. Rev. Control. Robot. Auton. Syst.* **2022**, *5*, 515.
[579] M. Aronne, M. Polano, V. Bertana, S. Ferrero, F. Frascella, L. Scaltrito, S. L. Marasso, *J. Manuf. Mater. Process.* **2024**, *8*, 164.
[580] Raman, S. L, J.-H. Dirks, *Sci. Rep.* **2024**, *14*, 22024.
[581] S. S., A. P. R. G., G. Bajaj, A. E. John, S. Chandran, V. V. Kumar, S. Ramakrishna, *J. Mater. Sci. Mater. Med.* **2023**, *34*, 62.
[582] S. Kumar, T. Gopi, N. Harikeerthana, M. K. Gupta, V. Gaur, G. M. Krolczyk, C. Wu, *J. Intell. Manuf.* **2023**, *34*, 21.
[583] A. Hamrani, A. Agarwal, A. Allouhi, D. McDaniel, *J. Intell. Manuf.* **2024**, *35*, 2407.
[584] J. Qin, F. Hu, Y. Liu, P. Witherell, C. C. L. Wang, D. W. Rosen, T. W. Simpson, Y. Lu, Q. Tang, *Addit. Manuf.* **2022**, *52*, 102691.
[585] M. Hamidpour, S. V. Hoa, *Compos. Part C Open Access* **2024**, *15*, 100522.
[586] S. Vatanparast, A. Boschetto, L. Bottini, P. Gaudenzi, *Appl. Sci.* **2023**, *13*, 7744.
[587] A. C. Pereira, V. V. Nayak, G. Coelho, L. Witek, *Polymers* **2024**, *16*, 2686.
[588] X. Xin, C. Lin, X. Wang, F. Liu, L. Dong, L. Liu, Y. Liu, J. Leng, *Mater. Futur.* **2025**, *4*, 012402.
[589] L. Valenzuela Sandoval, M. Han, L. Li, *3D Print. Addit. Manuf.* **2024**.

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