International Journal of Precision Engineering and Manufacturing-Green Technology (2023) 10:1661–1710
https://doi.org/10.1007/s40684-023-00533-4
Online ISSN 2198-0810
Print ISSN 2288-6206

REVIEW PAPER

# A Review of Recent Manufacturing Technologies for Sustainable Soft Actuators

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Received: 6 April 2023 / Revised: 16 June 2023 / Accepted: 21 June 2023 / Published online: 13 July 2023

## Abstract

Soft actuators have brought significant advancements to robotics, allowing robots to perform a diverse range of tasks across various domains. However, the increased use of soft actuators has resulted in negative environmental impacts, including material consumption, waste generation, and energy consumption. To address these challenges, research is increasingly focused on developing sustainable soft actuators (SSAs) that can provide high performance while minimizing environmental harm. This review article aims to explore the development and manufacturing of SSAs and their potential to reduce material waste and energy consumption promoting sustainability. The article examines various categories of soft actuators, such as multi-responsive ones, shape-locking variants, and biological water-responsive models, as well as their implementation through multi-material printing and, 3D and 4D printing techniques. The article also highlights the potential applications of these SSAs, including manufacturing, human–machine interaction, locomotion, and manipulation. Furthermore, the review explores various methods for reducing energy consumption and material waste in soft actuators, such as using recycled materials and eco-friendly manufacturing processes for a circular economy. Finally, the study provides a comprehensive analysis of SSAs and their potential to steer the evolution of robotics towards a more sustainable future and a circular economy.

**Keywords** Smart materials · Soft actuators · Sustainable actuators · 4D Printing · Sustainability · Energy consumption

## 1 Introduction

The current state of the world, impacted by climate change and widespread waste production, highlights the importance of considering the environmental impact of technological advancements. Consumer products, once they reach the end of their lifespan, are often discarded due to the difficulty in recycling their various materials and designs, which are produced inexpensively [1–3]. The use of rare and toxic materials, which can harm the environment if not properly disposed of, adds to the concern. The emergence of technology with a self-contained life cycle, such as easily recyclable objects, materials that are affordable and renewable, and temporary or biodegradable systems, provides new possibilities in a variety of industries, including healthcare, environmental monitoring, security, and intelligence [4–6].

Current advancements in robotics are often influenced by the diversity found in nature. This includes a focus on safe interaction between humans and machines, swarm robotics, and autonomous operation without a tether [7, 8]. Scientists from various fields are working to create soft and lightweight robots that mimic the fluid movements and energy efficiency of animals [9, 10]. The complexity of nature is a source of inspiration for these developments. Soft robots are drawing considerable attention due to their advantageous qualities. They can deform and maintain their mechanical strength, adapt to their surroundings without endangering humans, and manufacture more cost-effective than their rigid counterparts [11, 12]. However, the use of soft robots in our daily lives will bring up environmental worries like energy or power consumption and material waste. To solve this, we can make these robots in a way that is better for the environment, like nature does.

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This paper is an invited paper (Invited Review).

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Soft robots face unique challenges due to the close relationship between their sensing and actuation devices and their overall function [13]. To overcome these difficulties, the development of soft actuators is crucial. These actuators should be able to respond to various stimuli, show large deformations, and still maintain their mechanical resilience [14]. These actuators have a lot of promise to be used in areas like sensors [15], artificial muscles [16], microrobots [17], and micro-manipulation [18]. The advancements are the result of extensive research into soft actuators for various industries aimed at addressing the growing demand for energy and material consumption of soft actuators in mobile devices. The future challenge for autonomous soft robots lies in combining various fields to achieve better performance and sustainability. Collaboration between experts from various disciplines, including material science, chemistry, engineering, biology, computer science, and robotics, will be necessary to successfully integrate components such as actuators, sensors, computing, and power through only one robot.

There are many insightful reviews available on various areas of soft technology, such as soft robots [19], electronic skins [20], wearable devices [21], rehabilitation exoskeletons [22], healthcare systems [23], and textile exosuits [24]. Despite the existence of literature related to soft actuators, there is a lack of research works on sustainable soft actuators (SSAs) and fabrication techniques that are explicitly tailored for low or zero power consumption, with minimal material waste. This review emphasizes the design principles and manufacturing approaches that enable the creation of soft actuators that are eco-friendly, consume less power, and produce minimal waste. The article places particular emphasis on SSAs and fabrication methods, beginning with an examination of sustainability and different approaches for reducing the environmental impact of technology. The authors then shift their focus to soft and lightweight multi-responsive and shape-locking soft actuators, which require minimal power to activate or none to maintain their position. The paper outlines the suitability of each actuator through specific examples and assesses the future growth potential of the soft actuators discussed. Notably, the evaluation of biological soft actuators stands out because of their ability to be activated by water or humidity, offering a sustainable option worth considering. Additionally, the article explores the potential of multi-material printing for soft actuators, as this technology minimizes waste production.

### 1.1 Why Sustainable Actuators?

Soft actuators have gained significant utilization in various industries and research disciplines in the last few decades, prompting researchers to focus extensively on this field [25–28]. The remarkable capabilities exhibited by these actuators have sparked considerable interest across different domains of study [29–31]. The visualization in Fig. 1a highlights the most frequently utilized keywords associated with soft actuators since 2010, providing valuable insights into the prominent areas of exploration using the visualization tool named VOSviewer. Additionally, Fig. 1b from Web of Science data presents a comprehensive overview of the percentage distribution of soft actuator development across different sections, emphasizing the diverse applications being pursued in response to specific requirements. The data elucidates that multiple fields have been actively working on the advancement of soft actuators, tailoring their designs to suit needs. This underscores the versatility and adaptability of soft actuators as a technology.

Furthermore, an intriguing trend has emerged since 2010, as evidenced by a substantial surge in the number of research endeavours focused on soft actuators (see Fig. 1c). This exponential growth attests to the escalating interest and recognition of the immense potential held by soft actuators in advancing numerous scientific and technological domains. The expanding body of research signifies the increasing significance placed on harnessing the capabilities of soft actuators to address a wide range of challenges and pave the way for innovative solutions in various fields.

Moreover, soft actuators are devices that are used to produce motion or force through the deformation of a soft material [32–34]. However, developed actuators consume energy to be activated or required a constant power source to hold them in the required position. Meanwhile, they require high electrical voltage like dielectric actuators to be activated [35, 36]. Hence, it is vital to reduce energy consumption for long-term tasks or develop actuators with less activation power. SSAs are those that are designed and developed to reduce their environmental impact and promote sustainability.

One of the key considerations in SSAs is the selection of materials and reduce material consumption. The materials used in these devices can significantly impact their sustainability. Sustainable materials can be used to reduce the device's environmental impact. In addition to material selection, energy efficiency is another important factor to consider when designing SSAs [37, 38]. Soft actuators can be designed to be energy-efficient, consuming minimal energy to produce motion or force. This can be achieved by optimizing the design of the actuator and using energy-efficient control systems. Also, multi-responsive soft actuators are an alternative option to reduce power consumption due to the multi-triggering ways to activate them [39].

Another approach to achieving SSAs is to design them to be biodegradable. Soft actuators can be made from materials that are designed to decompose naturally at the end of their lifespan [40, 41]. This can help reduce the

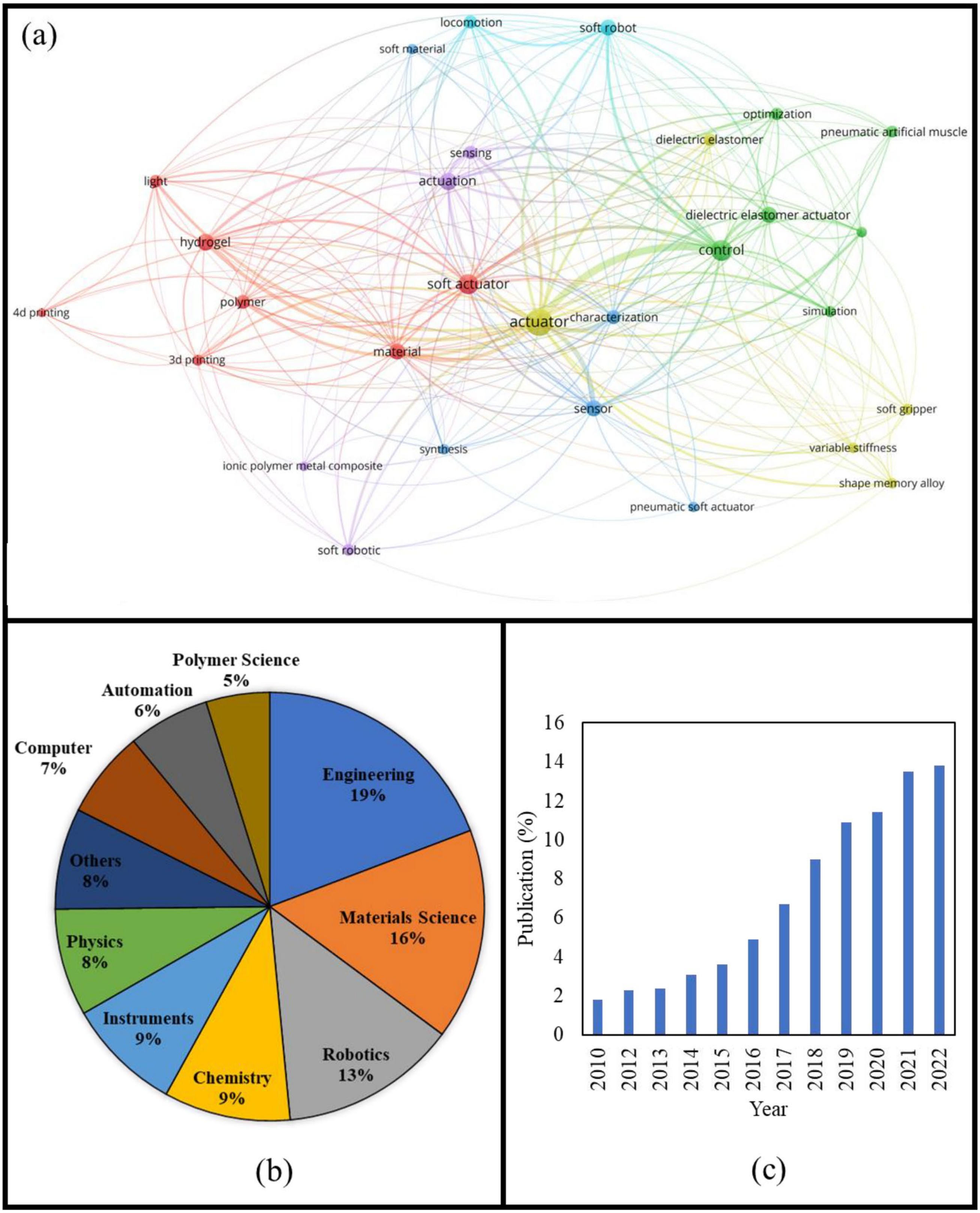


**Fig. 1** **a** The frequently utilized keywords associated with soft actuators. **b** The progress made in developing soft actuators across various research domains. **c** The distribution of soft actuator publications as a percentage over time

amount of waste generated by the device and promote sustainability. Manufacturing processes are also a key consideration when designing SSAs. The manufacturing processes used to produce soft actuators can impact their sustainability. Processes that use minimal energy or produce minimal waste can be employed to reduce the environmental impact of the device [42, 43]. Finally, the end-of-life management of the device can also impact its sustainability. Designing SSAs with easy disassembly and recyclability in mind can promote a circular economy and reduce waste.

While there have been advancements in developing SSAs using various methods and techniques, there are still challenges that need to be addressed and understood [44]. Researchers should find a balance between performance and sustainability when selecting materials for soft actuators. Also, energy efficiency is another critical factor in achieving SSAs. Soft actuators typically consume a considerable amount of energy to operate and designing energy-efficient soft actuators is crucial to reducing their environmental impact. This can be achieved by optimizing their design and using energy-efficient control systems [45, 46].

Moreover, durability is another challenge that must be addressed when designing SSAs. Soft actuators are often made from soft materials that can be prone to wear and tear, limiting their lifespan. Designing SSAs that can last longer and withstand repeated use is critical. This can be achieved by selecting durable materials and optimizing the design of the device to reduce stress on the materials. Designing soft actuators that can be easily disassembled, recycled, or disposed of in an environmentally friendly way is crucial for achieving sustainability [47, 48]. This requires a holistic approach that considers the entire lifecycle of the device. Meanwhile, there is currently no standardized framework for designing SSAs, making it challenging to compare different designs and assess their environmental impact. Developing a standardized framework for SSA design can help accelerate their development and adoption.

These are just a few challenges of developing SSAs. Eliminating these drawbacks will lead to advance soft actuators which are green and sustainable for a circular economy. The development of SSAs presents several significant challenges that need to be addressed to create more environmentally friendly devices. Addressing these challenges requires a multidisciplinary approach and collaboration between various stakeholders, including researchers, policymakers, and industry experts. By overcoming these challenges and eliminating the drawbacks, it is possible to develop advanced soft actuators that are more green, sustainable, and suitable for a range of applications in a circular economy. Achieving these goals would benefit the environment and improve the performance, reliability, and lifespan of soft actuators, making them a more viable option for a wide range of industries and applications. Therefore, it is crucial to continue research and development in this field to create more sustainable and efficient soft actuators in the future. In this review, we will investigate low-energy consumption, multi-responsive soft actuators, biological actuators, and manufacturing techniques of soft actuators to reduce material consumption as part of a circular economy.

## 1.2 Overview of Soft Actuators

Soft actuators are a type of flexible device that has been designed to mimic the motion and functionality of biological systems such as muscles, tendons, and skin [49, 50]. Unlike traditional rigid actuators, soft actuators are made of soft and flexible materials that enable them to deform and adapt to different shapes, environments, and applications [51]. The manufacturing methods for soft actuators can vary depending on the type of actuator and the materials used. There are general steps in all actuators from design to testing via different manufacturing techniques. The processes can be divided into different categories, including 3D printing [52], 4D printing [53, 54], casting and moulding [55], textile processing [56], electrospinning [57], laser cutting [58], origami/kirigami folding [59], and electrowetting [60]. Each manufacturing technology has a unique ability to produce soft actuators accordingly. The combination of soft materials, flexible design, and innovative control strategies allow soft actuators to offer new functionalities, such as the ability to adapt to different shapes and environments, improved safety, and increased comfort and human–machine interaction [61]. The field of soft actuators is continuously growing, and new developments in materials science, electronics, and control engineering are leading to the creation of more sophisticated and capable devices.

Sustainability in soft actuators encompasses various aspects, strategies, and solutions, including the use of renewable resources, recycling, and biodegradability [62]. However, the focus is to create SSAs that consume low power and material. SSAs are robotic devices that are designed to have a minimal impact on the environment. They aim to reduce energy consumption and material waste while ensuring long-term performance and reliability. To achieve this, SSAs often use environmentally friendly materials and low power-consuming technologies. By designing soft actuators with sustainability in mind, it is possible to create devices that can operate efficiently and effectively while reducing their environmental footprint.

Soft actuators are often made of materials that are less rigid than traditional actuators, making them safer to use around humans and other living creatures. Additionally, their flexible design makes them less likely to cause damage if they encounter other objects. Also, soft actuators

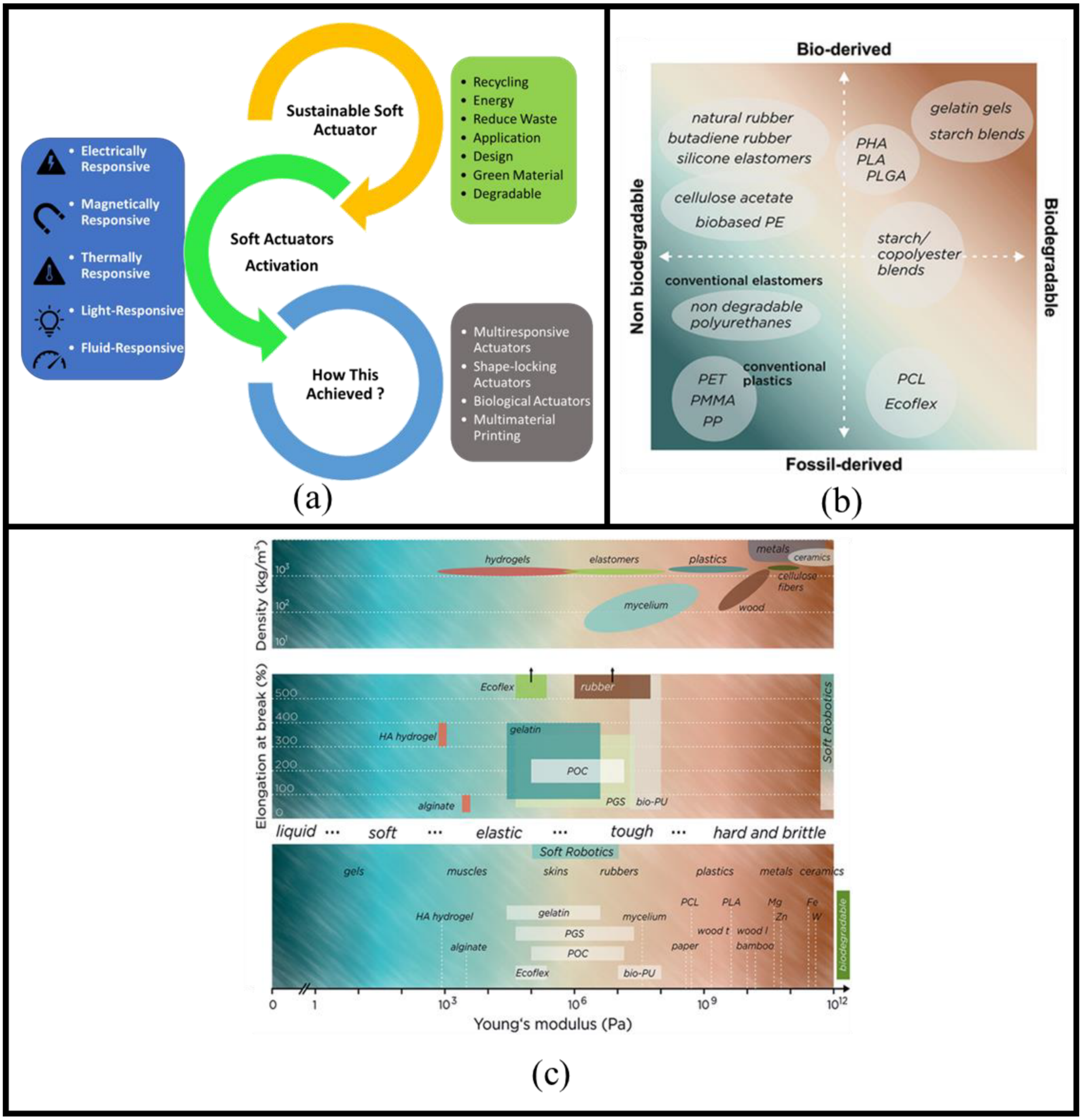


**Fig. 2** **a** SSAs with various types of soft actuators based on stimulation. **b** Elastomers and plastics are classified into four distinct sectors based on their origin, whether they are derived from fossil or bio-based sources, and their degradability, either biodegradable or non-biodegradable [100]. **c** The physical characteristics of biomaterials and standard materials are compared in terms of their mechanical properties [100]

typically use less energy than traditional rigid actuators and can be powered by a variety of energy sources, including electricity [63], pneumatic pressure [64], light [65], pH [66], humidity [67], magnetic field [68], thermal energy [69], and a combination of these. There are different ways to activate soft actuators as shown in Fig. 2a. The use of materials that are responsive to different stimuli is a promising way in the creation of soft actuators. Soft actuators and devices often utilize soft materials that are made through low-temperature fabrication processes, making the production process easier and more cost-effective. The viscoelastic properties of these materials allow them to absorb energy from impacts and smooth out any discontinuous movements or forces by dampening oscillations [70].

The materials utilized in producing soft actuators have a significant impact on their effectiveness and capabilities. There is a broad spectrum of materials that can be utilized to create soft actuators. The choice of materials depends on the specific requirements of the application, such as the type of movement or deformation desired, the energy source used, and the environment in which the actuator will operate. By utilizing these materials, it becomes possible to produce soft actuators that exhibit remarkable flexibility, strength, and the ability to generate motion and deformation with minimal energy consumption, all without requiring an actuator or motor. Materials for soft actuators are thermoplastics [71], elastomers [72], shape memory alloys (SMAs) [73], shape memory polymers (SMPs) [74], hydrogels [75], electroactive polymers (EAPs) [76], liquid metals [77], piezoelectric materials [78], magnetic materials [79], carbon nanotubes (CNTs) [80, 81], graphene [82], polyvinyl alcohol (PVA) [83], magnetic fluids [84], and electrospun nanofibers [85]. The classification of biodegradable and biomaterials and their mechanical properties used in SSAs are shown in Fig. 2b, c , respectively.

In recent times, with a growing emphasis on sustainability, scientists and engineers have dedicated their attention to creating SSAs that not only exhibit efficient performance but also mitigate their environmental footprint. The capacity of these actuators to replicate natural motions and deformations holds significant value in applications that necessitate meticulous and accurate movements. Nevertheless, given the urgent environmental challenges faced by the world, it becomes crucial to incorporate sustainability into the design and production of soft actuators, guaranteeing that these technological advancements adhere to eco-friendly principles [86]. The operational principles of SSAs encompass a wide range of innovative approaches. This mechanism facilitates seamless and uninterrupted movement, rendering it well-suited for applications that require meticulous control. To enhance the sustainability of soft actuators, various strategies can be implemented throughout their lifespan. Material selection stands out as a crucial factor. Choosing eco-friendly materials like biodegradable or recyclable polymers and elastomers helps decrease the environmental footprint and supports the principles of a circular economy [87]. Through the adoption of sustainable materials, the negative effects associated with the disposal and end-of-life stages of soft actuators can be minimized. The types of SSAs are briefly discussed as follows:

- *Pneumatic and hydraulic soft actuators*: A prevalent principle involves the utilization of pneumatic or hydraulic actuation, where the application of air or fluid pressure induces the deformation of the flexible material. These soft actuators are composed of pliable materials like elastomers or pneumatic chambers that undergo expansion or contraction when subjected to pressure [88]. Using environmentally friendly fluids and the optimization of actuator design, pneumatic and hydraulic soft actuators can achieve actuation that is both energy-efficient and sustainable. These actuators are applied in fields such as robotics, prosthetics, and haptic interfaces, where there is a need for precise and compliant movements.
- *Shape memory soft actuators*: Shape memory soft actuators integrate substances that possess shape memory properties, such as SMAs or SMPs [89, 90]. These materials can undergo reversible deformations when exposed to temperature fluctuations, enabling the actuators to demonstrate programmable and adaptable movements. By incorporating sustainable shape memory materials and reducing energy consumption during thermal actuation, these actuators present eco-conscious options for various applications, including morphing structures, adaptive textiles, and biomedical devices [89, 91].
- *Electroactive soft actuators*: SSAs based on electroactive principles utilize electroactive polymers, which demonstrate substantial deformations when subjected to electrical stimuli. Examples of EAPs utilized in soft actuators include ionic polymer-metal composites, dielectric elastomers, and conductive polymers [92]. These actuators offer numerous benefits, including excellent deformability, low power consumption, and lightweight construction. To further promote sustainability, eco-friendly and biocompatible EAP materials can be employed, and energy-efficient control strategies can be adopted.
- *Magnetic soft actuators*: Magnetic soft actuators employ magnetism to achieve precise control over movements and deformations. They incorporate magnetic particles or materials into a flexible matrix and utilize external magnetic fields to induce shape changes and alter properties [93]. These actuators excel in non-contact actuation, precise positioning, and the generation of significant forces and displacements, making them ideal for applications in soft robotics, biomedical devices, and haptic interfaces. Using sustainable and recyclable materials, as well as optimized actuator designs, magnetic soft actuators promote eco-friendly actuation and circular economy while maintaining exceptional controllability [94].
- *Light-responsive soft actuator*: A sustainable light-responsive soft actuator is designed to achieve controlled

movements and deformations using light as a stimulus. These actuators incorporate light-sensitive materials, such as photoresponsive polymers or liquid crystal elastomers, which undergo reversible changes in response to specific light wavelengths [95]. Offering advantages such as precise actuation, tunable responsiveness, and wireless control, they find applications in fields such as soft robotics, smart textiles, and responsive structures [96]. To enhance sustainability, these actuators utilize eco-friendly and recyclable materials while minimizing power consumption using energy-efficient light sources, contributing to a greener and more efficient future.

- *Humidity-responsive soft actuator*: A sustainable humidity-responsive soft actuator is designed to achieve controlled movements and deformations by responding to changes in humidity levels [97]. These actuators incorporate humidity-sensitive materials, such as hydrogels or hygroscopic polymers, which undergo reversible changes in shapes or mechanical properties in response to humidity or pH variations [98]. Offering advantages such as sensitivity to small humidity changes, rapid response times, and the ability to achieve complex motions, they find applications in environmental monitoring, energy harvesting, and bio-inspired systems [99]. To enhance sustainability, these actuators utilize eco-friendly and biodegradable materials while optimizing energy efficiency, aligning with eco-conscious principles and contributing to a greener future.

These are some of the most used materials and techniques in the manufacture of soft actuators. These materials and techniques can be combined to produce soft composite actuators. The choice of materials will depend on the specific requirements of the application, such as the type of movement or deformation desired, the energy source used, the environment in which the actuator will operate, and the responses to the external stimuli.

## 2 Manufacturing Technologies

SSAs can be produced using a range of methods, including subtractive, forming, and additive manufacturing (AM). These techniques involve processes such as cutting, moulding, spinning, lithography, and 3D/4D printing, among others. Each technique's suitability is determined by the characteristics of the material. In the subsequent section, we will offer an overview outline of these fundamental techniques.

### 2.1 Moulding

Moulding is an economical technique that falls under the category of forming manufacturing methods [101]. It enables the production of several thousand parts using a single mould insert. There are five categories of moulding techniques. Since its heating and cooling cycles are short, one of the major processes is injection moulding, which is mostly used for large-scale manufacturing. The second is reaction injection moulding, which uses heat or ultraviolet (UV) light to activate polymer solidification [102]. The third process, hot embossing, entails inserting a film into a mould and creating a residual layer over time. This method is ideal for laboratory settings, as it results in lower stress levels in the polymer and has the potential for higher aspect ratios. Injection-compressed moulding, the fourth step, combines the stamping and injection moulding processes. Finally, the creation of patterns with large aspect ratios is frequently done using the popular thermoforming process. Moulding, on the other hand, is commonly employed in creating soft actuators based on pneumatic networks [103, 104]. For the construction of arrays, moulding has several advantages, including quick manufacturing, uniform surface coverage, customizable pillar diameter size, and adjustable pillar spacing. It does, however, have several limits, notably when mixing various materials and building complex constructions. It is great for materials with long solidification durations, including poly(dimethylsiloxane) (PDMS), and is more suitable for mass production than prototyping [105].

### 2.2 Cutting

Cutting is a mechanical process used in subtractive manufacturing, usually with blades or lasers. However, laser cutting is a more sophisticated form of cutting that has several benefits, such as greater precision, resolution, and no wear and tear [106]. To obtain the finest cut with the highest degree of precision, several variables must be tuned [107]. Laser cutting can be used to cut and engrave a wide range of polymers and metals. This method can be used in making origami and kirigami smart structures or actuators [108]. This shows that manufacturing using equipment enables better control over designs and raises the standard of fabrication in general. However, cutting, like other subtractive manufacturing techniques, is unable to combine a variety of materials.

### 2.3 Spinning

Spinning is a method of forming manufacturing that alters the shape of material without adding or removing it [109]. However, not all materials are capable of being formed into fibres. The fundamental condition for fibre creation is that the solidification process must proceed more quickly than the material's rate of relaxation. This prevents stretched liquid objects from reverting to a more energetically advantageous spherical form due to the surface tension force. Based on the process used to harden fibres after spinning, fibre-spinning methods are divided into four categories: wet, dry, melt, and gel spinning. The diameter range for wet spinning is roughly between 250 and 500 µm, and the fibres are solidified in a coagulation bath [110]. In contrast, to melt spinning, which uses extrusion to solidify a molten polymer in the air, dry spinning uses airflow to dry and solidify fibres. Gel spinning includes extending the partially dried gel to produce fibres after chilling and drying the extruded gel solution with other solvents [111]. Microfluidics is another fibre fabrication method that is a derivative of wet spinning and produces fibres in the micro range. However, the mechanical stability of the fibres obtained using this method is a current issue.

Electrospinning is a type of fibre-spinning method that falls under the category of dry and melt spinning [112]. It involves using an electrical field to draw fibres from a solution or melt, resulting in small-diameter fibres ranging from several nanometers to micrometres in size and with a high surface area. Touch spinning, which starts with the initial contact between the polymer and wire and forms a fluid connection that lengthens once the collector turns and the solvent evaporates, is another technique for creating fibres that are smaller than nanometers [113]. In addition, the fibres produced through spinning are drawn and have strongly oriented polymer chains aligned with the direction of the stretching, leading to increase strength and hardness compared to materials formed through other methods. Multicomponent fibres can be produced by spinning multiple polymers simultaneously. These fibres can exhibit bending and curling behaviour due to their asymmetric composition [114]. One illustration of such a fibre is the Janus fibre, which is composed of two substances with various softening points and is capable of changing shape when one of the polymers experiences a change in property. These fibres can be created using melt spinning and have potential applications in the creation of self-walking structures and multi-responsive soft actuators [115].

## 2.4 Lithography

Based on the type of irradiation, there are many lithography techniques, including photolithography, electron beam lithography, and ion beam lithography [116, 117]. Accordingly, this technique may be utilised to create multi-responsive soft actuators. In photolithography, the desired geometric pattern is created on the surface by exposing a photosensitive polymer to light through a photomask. Depending on the light's wavelength and the optics employed, the resolution can reach hundreds of nanometers. By utilising electrons or ions to irradiate an electron- or ion-sensitive material, electron and ion beam lithography may produce objects with better resolution (30–50 nm) without the need of a photomask. Self-folding tubes and intricate three-layer structures with specialised geometries for cell adhesion have been made using photolithography, which is suited for producing few-layer films [118, 119]. This approach can create multilayer structures using various polymers, but it takes a lot of time and expensive equipment.

In photolithography, materials that have been both cross-linked and fixed or removed without a half-tone are frequently utilised. By projecting structured illumination onto dry polymer films that may be photo-cross-linked using a digital mirror device system, 2D photolithography enables the production of shape-changing structures [120, 121]. The time can be varied to create lateral gradients of swelling properties, which enable different shape transformations. Photosensitive compounds, such as photoresists or active polymers, are required for photolithography. It is recommended to employ photo-cross-linkable active polymers since it eliminates the need for photoresists and simplifies the fabrication process.

## 2.5 3D/4D Printing

3D printing is a new and innovative technology that has allowed for the creation of multi-material and highly customized devices, including soft actuators with exceptional spatial resolution and design flexibility [122–124]. This innovation has created new opportunities for soft actuators and has the potential to fundamentally alter how we produce smart SSAs [125, 126]. Compared to conventional production techniques, which are often used in the industry, it is more affordable and quicker [127, 128]. A range of soft actuators necessitates dynamic changes in shape, which are not feasible with traditional 3D printing technologies. 4D printing has been developed to fulfil this demand by adding the fourth dimension of time to 3D space [129–131].

External energy sources like UV radiation, heat, pH, or other stimuli are the main initiators of the form change of dynamic products. 4D printing has reversibility in addition to one-way change as a feature. To create complex and reversible 4D-printed structures, it is essential to utilise the right stimulus-responsive materials that can be activated by both internal and external inputs [132]. Light, an electric field, sound waves, and magnetic fields are examples of external stimuli, whereas pH and humidity are examples of interior stimuli. Smart materials are useful in a variety of applications because of their ability to respond to stimuli and take on an infinite number of shapes [133]. For the creation of macro- and micro-scale soft robots for diverse technical applications, 4D printing technology has recently gained widespread usage [134–136].

Smart materials and 3D printing technologies are used in the upcoming technology of 4D printing to produce soft actuators [137]. The same 3D printing techniques such as fused deposition modelling (FDM) [138], direct ink writing (DIW) [139], inkjet printing (IJP) [140], stereolithography (SLA) [141], selective laser sintering (SLS) [142], digital light processing (DLP) [143], selective laser melting (SLM) [144], sound printing [145], and direct laser writing (DLW) [146] have been used for 3D/4D printing, but not all of them are suitable for creating soft actuators.

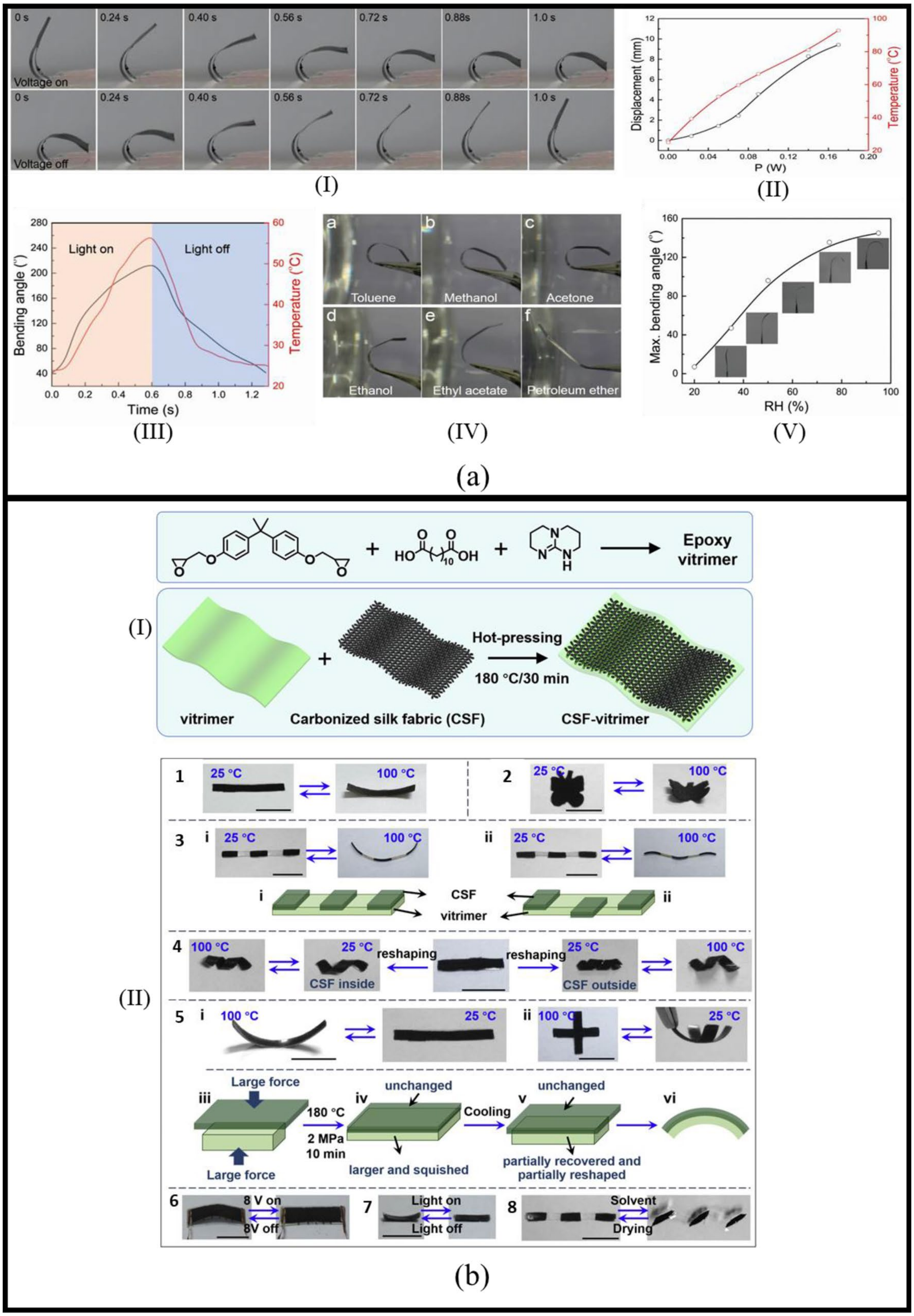
With the use of a beam of laser energy and a UV light source, SLA and DLP rely on light-based technology to begin the photo-polymerization of photo-sensitive materials [147]. Because of their great printing resolution and quick speed, they are ideally suited for manufacturing soft actuators [148]. SLA produces incredibly precise printed components by cross-linking photosensitive materials via photochemical processing [149], whereas DLP generates patterns using an optical mirror, guaranteeing outstanding printability. [150]. These techniques have lesser resolution than lithography techniques, however projection micro-SLA, a modified form of SLA, is excellent for creating multi-material structures, such as actuators, flowers, and grippers, because it has a high-resolution capability [151]. This method uses a projector to start photopolymerization using a virtual photomask, creating complex soft actuators with several materials and scales. [152].

Out of all the available methods, the most used one is FDM due to its feasibility. This technique involves extruding a material onto a substrate which then hardens. The nozzle is moved in the X and Y axes by a motor, while the printed layer is built up in the Z-axis by moving the nozzle upwards. This process is repeated until the final structure is completed. The 3D printer liquefier is the main element utilised in this kind of printing. The extruder on the printer consists of two parts: a cold end and a hot end. A stepper motor controls the cold end's feed rate as it extracts the material from the spool using either gear- or roller-based torque. The feedstock is then forced into the hot end, which has a heating chamber and a nozzle, by the cold end. The feedstock is melted in the liquefier, which is a component of the heating chamber. The thin plastic bead that results from pushing this liquid through the tiny nozzle sticks to the surface it is printed on. Depending on the material being printed, the nozzle's diameter is normally between 0.3 mm and 1.0 mm, and the heating technique is chosen accordingly. FDM is frequently utilised in 4D printing because it is affordable and simple to maintain [153]. Currently, research is being conducted to improve its effectiveness and compatibility with new materials. FDM is also capable of easily fabricating self-coiling and self-folding metamaterials [154]. The technology has also been updated to enable the printing of new materials [155, 156].

The IJP technique, also known as material jetting, creates 3D structures by directly extruding ink materials onto the surface using small nozzles [157]. The chemical composition of the inks, such as surface tension must satisfy specific requirements [158]. This method is excellent for developing microfluidic systems, flexible electronics, optoelectronic components, and microrobots [159]. A range of materials can be deposited using the IJP technique since it can also handle less viscous materials [160]. Insoluble nanoparticles like metal oxides and ceramics, as well as organic materials, can also be printed. The method is well-liked in the field of microfabrication since it is very accurate and affordable [161]. Droplets of photopolymer ink are directly sprayed during the polyjet printing process, where they solidify on a printer bed. This process is commonly utilised to create intelligent materials [162]. Currently, 4D-printed objects that respond to heat are produced using polyjet printing [163]. Printing various materials at once using numerous printheads is one benefit of this technique [164].

Like FDM, the DIW printing technique creates 3D structures under high pressure using a wide range of viscoelastic ink ingredients [165]. To print using the DIW method, a viscoelastic ink is extruded via a tiny nozzle and applied layer by layer. This technique is highly regarded for its capacity to finely control the inks and print structures at the meso- and microscales. Printing speed and nozzle size are two factors that affect printing resolution and accuracy. Its capability to create multi-material structures in a single step decreases total production time, energy, cost, and waste while maintaining material qualities. This is one of DIW's main benefits [166, 167]. DIW also has the potential to be used for 4D printing, which permits the creation of smart materials that can change form in response to environmental factors. DIW is a highly adaptable production method since the three-axis platform, computer, and dispenser are all interchangeable and inexpensively priced. Recent years have seen the development of DIW as a dependable method for producing a range of soft actuators and smart devices [168].

Additionally, two-photon polymerization, also known as DLW, is widely utilised at the microscale to produce extremely precise and finely detailed 3D-printed robots [169]. Multiphoton DLW is a high-resolution AM technique that utilizes a pulsed femtosecond laser to fabricate 3D photonic devices with submicron voxel resolution [170, 171]. The process involves a multiphoton polymerization process in which the laser initiates a chemical reaction in the photoresist. DLW has been used to create a range of optical components and other related elements for beam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(II)
Bending angle (°)
Temperature (°C)
Light on
Light off
Time (s)
(III)
Toluene
Methanol
Acetone
Ethanol
Ethyl acetate
Petroleum ether
(IV)
Max. bending angle (°)
RH (%)
(V)
(a)
Epoxy vitrimer
HO
OH
10
vitrimer
Carbonized silk fabric (CSF)
Hot-pressing
180 °C/30 min
CSF-vitrimer
(I)
25 °C
100 °C
CSF
vitrimer
reshaping
CSF inside
CSF outside
Large force
180 °C
2 MPa
10 min
unchanged
larger and squished
Cooling
partially recovered and partially reshaped
8 V on
8V off
Light on
Light off
Solvent
Drying
(II)
(b)

◂**Fig. 3** **a**. (I) A square wave voltage (0–10 V) at a frequency of 0.5 Hz was applied to the IPS actuator. (II) The IPS actuator's displacement and temperature change are measured while varying the power density. (III) The IPS actuator's maximum temperature and bending angle change over time when exposed to NIR radiation at 130 mW/cm$^2$. (IV) The IPS actuator when exposed to various types of volatile organic vapours. (V) The link between relative humidity (RH) and the IPS actuator's bending angle [188]. **b**. (I) The depiction of the method for creating a composite of CSF and vitrimer through hot-pressing. (II) Various examples of the responsive behaviour of the soft actuators. 1. The CSF-vitrimer actuator's forming and unbending motion brought on by heat. 2. A butterfly-shaped actuator with reversible heating and cooling actuation. 3. Actuators with various CSF patterns that were hot-pressed onto the vitrimer surface produced various actuation modes. 4. Modification of the CSF-vitrimer actuator's form. 5. CSF-vitrimer actuators that are straight at high temperatures but bend at normal temperatures, as well as a diagram of how to prepare such actuators. 6. Electricity-driven, reversible CSF-vitrimer actuator actuation. 7. The CSF-vitrimer actuator is reversibly activated by infrared light with an intensity of 0.56 W/cm$^2$. 8. Tetrahydrofuran-triggered reversible CSF-vitrimer actuator actuation (Scale bar of 1 cm for all images.) [195]

shaping, imaging, and photonic integration [172, 173]. Despite its widespread accessibility, DLW is limited by the single refractive index of the photoresist, which restricts the fabrication of microscale optics with more complex shapes and structures. Additionally, the DLW process cannot be used to create free-standing elements, which limits the formation of compound lenses and intricate waveguiding photonic networks. Femtosecond pulsed laser technology is utilized to create sub-micrometre resolution structures in liquid crystal elastomer (LCE), hydrogels, and other composites [174, 175].

## 3 Multi-Responsive Soft Actuator

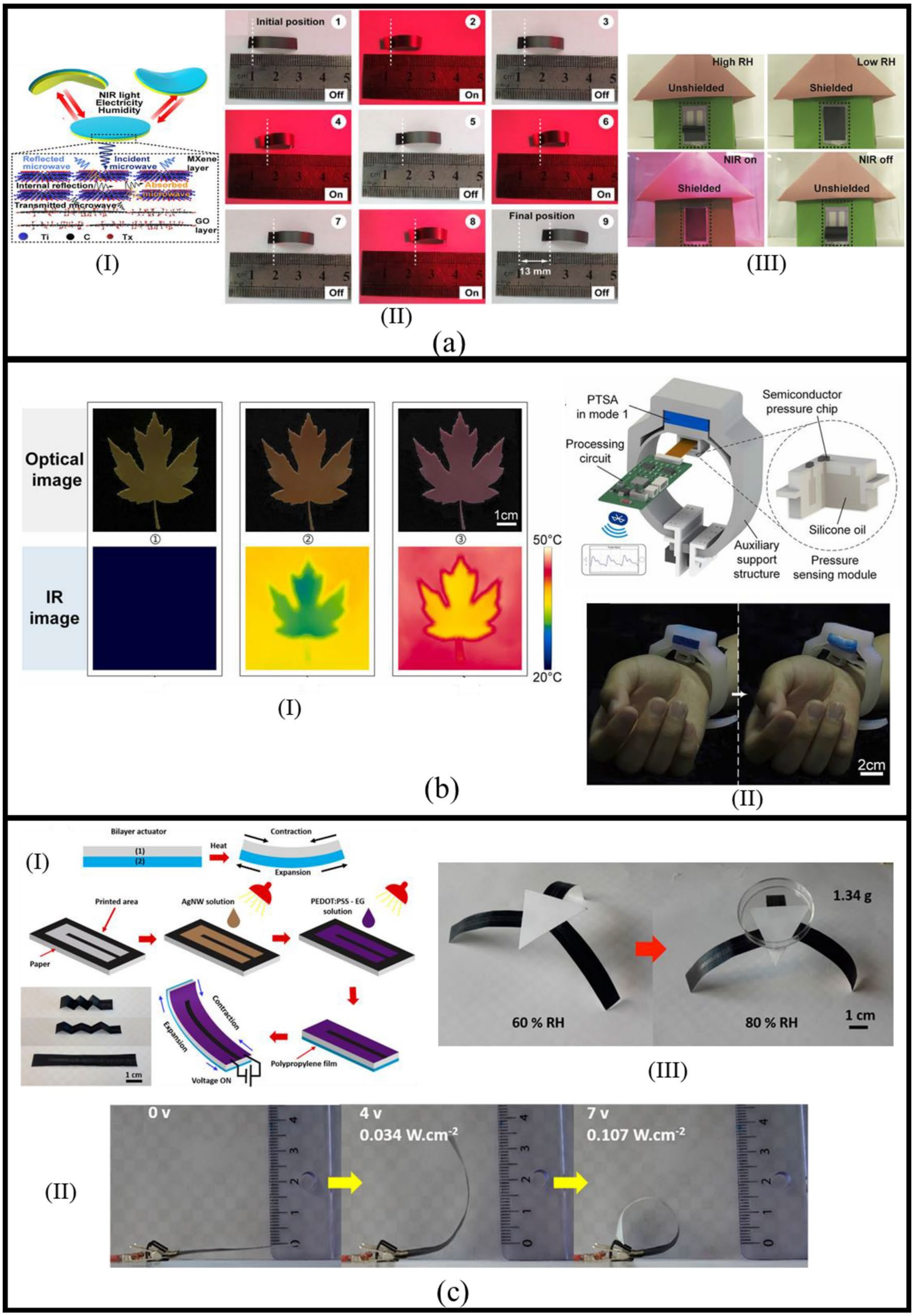
Soft actuators represent an exciting new technology with the capacity to transform multiple industries, ranging from healthcare to robotics. One of the most notable breakthroughs in the field of SSAs is the creation of multi-responsive versions, which present numerous benefits compared to mono-responsive types [176–178]. The improved functionality of multi-responsive soft actuators is a crucial advantage. In contrast to mono-responsive actuators, which can only react to one stimulus, multi-responsive ones can detect and respond to a wide range of stimuli [179]. This versatility provides them with a more diverse range of capabilities than mono-responsive actuators, which allows them to undertake more complex tasks.

Multi-responsive soft actuators possess a greater degree of adaptability compared to mono-responsive actuators. Their ability to respond to multiple stimuli means they can adjust to changes in their surroundings, allowing them to function effectively in a broader range of environments. This adaptability is particularly advantageous in fields such as soft robotics, where the robots must operate in unpredictable or harsh conditions. Multi-responsive soft actuators also offer enhanced efficiency when compared to their mono-responsive counterparts. The ability to respond specifically to stimuli present in their surroundings enables them to minimize energy consumption and optimize their performance. This feature is especially beneficial in fields where energy efficiency is a top priority, environmental monitoring [180].

These advantages encompass enhanced functionality, improved control, greater adaptability, and increased efficiency. As a result, multi-responsive soft actuators are anticipated to make a significant impact on numerous industries in the future, transforming their capabilities and revolutionizing their operations. The recent focus of research has been on developing multi-responsive actuators with a wide range of manufacturing techniques that can function in a variety of settings. There are several different manufacturing techniques and smart materials available for creating multi-responsive soft actuators as mentioned in the previous section [181–183]. These actuators are a great choice for usage in SSAs since they may alter their size, shape, or other characteristics in response to varied inputs. As the field of multi-responsive soft actuators continues to advance, there are constantly evolving and expanding techniques available that offer exciting possibilities for developing soft actuators that are more versatile, efficient, and affordable. In this section, we will explore the development of multi-responsive actuators utilizing various techniques. The primary focus will be on evaluating their sustainability and behaviour when subjected to different stimuli.

### 3.1 Carbon-Based Actuators

Carbon materials like graphite, carbon spheres, CNTs, graphene, and their derivatives are considered vital functional components for multi-responsive soft actuators [184]. This is because of their distinct characteristics such as high electrical conductivity, intrinsic mechanical flexibility, and high chemical and thermal stability [185]. As a result, these materials present a viable option for several applications, particularly in the advancement of mechanical sensing and actuation. The creation of carbon-based actuators that possess both conductive and photo/electrothermal or moisture-responsive properties can provide a useful platform for mechanical sensing and actuation development [186, 187]. Furthermore, by controlling the coupling of the functional components and their interfacial structures, multiple functions can be synergized while ensuring structural stability. Thus, the research should explore effective integration methods, principles of


NIR light
Electricity
Humidity
Reflected microwave
Incident microwave
MXene layer
Internal reflection
Absorbed microwave
Transmitted microwave
GO layer
Ti
C
Tx
(I)
Initial position
1
2
3
4
5
6
7
8
9
Final position
13 mm
Off
On
Off
On
Off
On
Off
On
Off
(II)
High RH
Low RH
Unshielded
Shielded
NIR on
NIR off
Shielded
Unshielded
(III)
(a)
Optical image
IR image
①
②
③
1cm
50°C
20°C
(I)
PTSA in mode 1
Processing circuit
Semiconductor pressure chip
Silicone oil
Auxiliary support structure
Pressure sensing module
2cm
(II)
(b)
(I)
Bilayer actuator
(1)
(2)
Heat
Contraction
Expansion
Printed area
Paper
AgNW solution
PEDOT:PSS - EG solution
Polypropylene film
Contraction
Expansion
Voltage ON
1 cm
60 % RH
80 % RH
1.34 g
1 cm
(III)
(II)
0 v
4 v
0.034 W.cm$^{-2}$
7 v
0.107 W.cm$^{-2}$
(c)

◂**Fig. 4** **a**. (I) A visual representation of the GO/MXene Janus film actuator. (II) The walking motion of a soft robot is powered by NIR light. (III) The operational concept of an intelligent EMI shielding curtain is based on its ability to be regulated by changes in moisture levels and NIR [205]. **b**. (I) The thermochromic strain limiting layer undergoes alterations in both temperature and colour when exposed to heat. The first and second sets of images depict the layer's visible and infrared representations. (II) The structure and components of the wearable wristband are designed for sensing blood pressure [210]. **c**. (I) The diagram, fabrication, and optical images of bilayer multi-responsive soft actuators. (II) The response of an actuator under different levels of voltage and electric power. (III) Three actuator legs that are 4.5 cm long work cooperatively and are activated by a humidity-induced trigger [211]

functional component combination, and applications for these materials.

For example, Li et al. [188] used ink/PET/super-aligned carbon nanotube (IPS) to create a novel multi-responsive actuator that can react to four different stimuli such as electricity, near-infrared (NIR) light, humidity, and organic vapours (see Fig. 3a). Super-aligned carbon nanotube sheets and a PET film with an ink coating were employed as the actuator. When subjected to electrical stimulation, the actuator demonstrated quick and reversible actuation with a significant displacement-to-length ratio of 0.79. The actuator bent dramatically, reaching a considerable bending angle of 212° in 0.55 s at a speed of 646°/s when exposed to NIR light. The actuator also reacted swiftly to moisture and organic vapours, dramatically bending in less than 0.1 s when exposed to various organic solvents and instantly reverting to its original shape after removal. At a reasonably high on/off frequency of up to 17.5 Hz, the actuator might be utilised as a smart electrical control frequency switch. Also, Zhang et al. [189] created a new technique for embedding CNT onto a photo-crosslinked poly (-caprolactone) (cPCL) film using hot pressing, which allowed them to produce a soft actuator that was sensitive to several stimuli. The mechanical and thermal stability of the cPCL films were enhanced by the addition of CNT to its surface. The final multi-responsive actuator maintained its heat actuation while exhibiting good electric actuation. Furthermore, the actuator demonstrated a larger recovery force and a faster rate of recovery compared to cPCL films with just one CNT-embedded surface. It should be emphasised that reversible SMPs can lose some of their inherent actuation capability when CNT is added, therefore finding a means to include CNT without doing so is still a difficult task. Ji et al. [190] developed a soft actuator with a dual-response and self-sensing feature using a 2D metallic molybdenum disulfide ($MoS_2$). Due to the good electrical property and network structure of CNTs, the great photothermal property of 1 T phase $MoS_2$, the hygroscopic expansion of paper, and the thermal expansion of polyimide, this actuator responds to external voltage and light stimulation and generates quick and massive bending deformation. The $MoS_2$-CNT composite film's piezoresistive ability was used to detect real-time bending deformation using the actuator's dual function as a flexible strain sensor. The $MoS_2$-based actuator has been utilised to create wearable intelligent gloves that automatically close to prevent light irradiation as well as a flexible mechanical gripper that can handle delicate items with uneven forms. Additionally, the sensing capability of the $MoS_2$-based actuator is combined to provide a gripper with an integrated sensing function. This type of actuator enhances efficiency across diverse environments and can be activated through various stimuli, ultimately minimizing material consumption in manufacturing production [191].

The environmental issues and worries about traditional plastics' non-renewability in today's world have caused a considerable focus on the development of recyclable plastics. The possibility for vitrimeric materials to possess strength, durability, and chemical resistance comparable to those of conventional thermosets while simultaneously being recyclable at the end of their useful lives has lately attracted attention [192]. This is because vitrimers have dynamic covalent crosslinks in their chemical structure, which provide stability while still being reprocessable. The new uses for vitrimers include their various shape memory capabilities, malleability, and ability to process in orthogonal directions [193, 194]. Another novel multi-responsive soft actuator is developed by Yang et al. [195]. They developed a novel SSA that was made by hot-pressing carbonized silk fabrics (CSF) into the surface of vitrimers (see Fig. 3b). The resultant thermosetting soft actuator could effectively and frequently self-heal in the presence of five stimuli, including electromagnetic waves, heat, solvent, light, and electricity, and could also react to four stimuli at once. Due to the characteristics of the vitrimer, the actuator was also durable, sustainable, recyclable, and reprocessable. This makes it a flexible and adaptable instrument for usage in a range of environmental situations. Also, Chen et al. [196] used vitrimers with exchangeable disulfide links to develop an actuator that could be reconfigured, welded, patterned, and transformed using kirigami techniques to create intricate 3D geometries. The actuator may be frequently modified for different purposes, offering a less expensive option for the preparation of new materials. These actuators are an economical and ecologically beneficial option since they work in conjunction with humidity and sunlight without extra energy input. Vitrimeric materials are categorized as polymers that can maintain their mechanical properties even after multiple processing and shaping cycles. These materials are currently considered for SSA due to their exceptional qualities that surpass traditional materials, including high durability, toughness, and recyclability [197–199]. Vitrimeric materials are well-suited for soft actuators accompanied by carbon materials because they can be effortlessly moulded into complex designs and can withstand frequent mechanical deformation without deteriorating. The potential for vitrimeric materials in SSAs appears to be promising, and further research in this area could lead to the emergence of innovative and sustainable technologies.

### 3.2 MXene-Based Actuators

MXene-based multi-responsive actuators are emerging materials that have promising potential in the realm of SSAs [185, 200]. These 2D materials are made of transition metal carbides, nitrides, and carbonitrides, which are particularly attractive for soft actuators because they have excellent electrical conductivity, mechanical strength, and surface area [201]. They may be functionalized with various compounds that can react to various stimuli, including temperature, humidity, and light, thanks to their distinctive surface chemistry [202]. In comparison to conventional actuators, MXene-based actuators have benefits including simplicity of manufacture, quick reaction times, and low operating voltages [201]. Additionally, they can be integrated with other sensors and actuators to create complex robotic systems. The MXene component also provides good thermal management performance, making the sandwich film suitable for thermal treatment of the body and thermal imaging [203]. Applications of these materials include soft robotics, microelectromechanical systems, and biomedical devices [204]. Li et al. [205] developed a flexible, electrically conductive, and multi-responsive graphene oxide (GO)/MXene Janus film using a scalable sequential vacuum filtering method. A film that could respond to humidity, light, and electricity as well as offer superior electromagnetic interference (EMI) shielding capability was created because of the hydrophilic qualities of GO and MXene. The film is appropriate for application as a smart switch and soft walking robot because it can be bent to a significant degree over a wide range of RH and exhibits quick and sensitive actuation reactions to NIR light and electricity (see Fig. 4a). The film's EMI shielding effectiveness increased to 40 dB at just 1.5 µm thickness because of the extremely conducting MXene coating. They used the Janus material to create an intelligent EMI shielding curtain and a stimulus-responsive EMI shielding system as a proof-of-concept, demonstrating the film's ability to modify signal transmission in response to stimuli to meet shielding needs in intelligent electronics and devices [206].

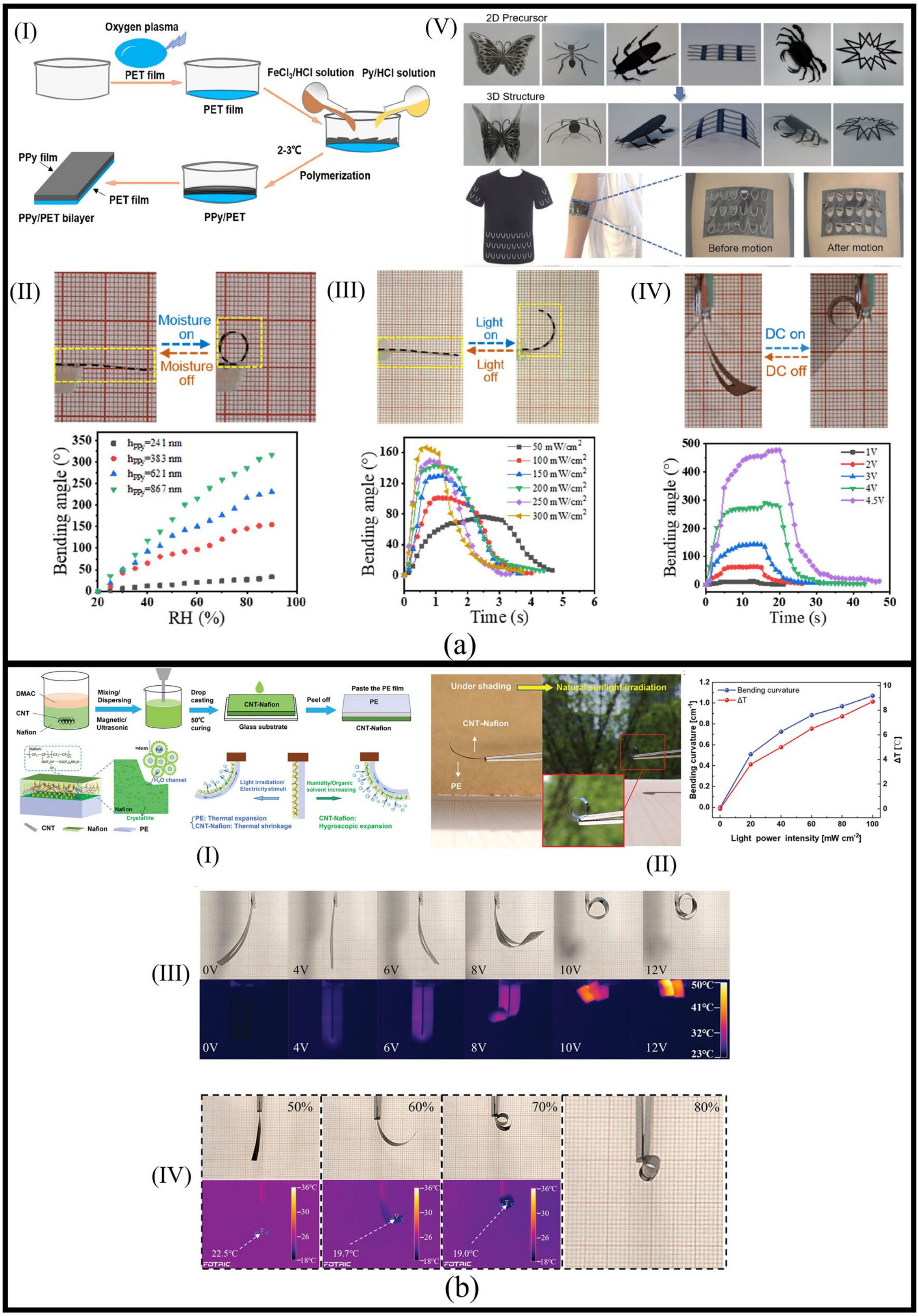
In another study, Liu et al. [207] created a bilayer actuator by casting MXene solution on low-density polyethylene (LDPE) film, which reacts to electric voltage, heat, and light. With 1.5 V electric voltage, the actuator could travel a significant offset distance of 20 mm. The temperature and curvature that corresponded were 32.7 °C and 0.079 $mm^{-1}$, respectively. The actuator was bionic and could detect temperature variations as well as grab items like how natural flytraps do. The actuator also can walk at a pace of up to 16.52 mm/second. The soft actuator's adaptable characteristics, which may be activated by a variety of stimuli in a variety of situations and circumstances, make it very sustainable. For soft robotics, flexible actuators with high mechanical strength and multiple responsivenesses are crucial. Tang et al. [208] have created a novel $Ti_3C_2T_x$ MXene-based actuator with a straightforward design and little power consumption. The biaxially oriented polypropylene layer and the bacterial cellulose layer's hygroexpansion and thermal expansion were the driving forces behind the actuator's dual-mechanism synergistic effect. Contrary to traditional actuators that employed a single actuation, this design offers an architecture that is more conducive to reversible actuation performance under electrical and NIR light stimuli. Compared to other single-mechanism soft actuators that have been described, the actuator achieved the largest bending angle (around 400°) at the lowest 4 V voltage. Being able to be driven by NIR light at a distance of 2 m, it also exhibits exceptional long-distance photoresponsiveness. Also, AgNWs/$Ti_3C_2T_x$ MXene thermal actuators that could react to various stimuli, such as electricity, NIR light, and UV light, were successfully constructed by Chen et al. [209]. The excellent photothermal properties of $Ti_3C_2T_x$ MXene, the great conductivity of AgNWs, the significant difference in coefficient of thermal expansion between MXene/AgNW layer and LLDPE layer, the synergistic effect of plasmonic properties between AgNWs and $Ti_3C_2T_x$ MXene, and the high coefficient of thermal expansion of MXene/AgNW layer all contribute to the high effectiveness of the thermal actuator. At an operating of 2 V, the actuator could roll up for 2200° and bend 360° when exposed to NIR light with a quick response time of 0.4 s. UV radiation might also cause it to flex 360 degrees in 1.2 s. Additionally, by using fluorescent material, the thermal actuator may emit light when bent under UV light.

### 3.3 Bilayer Actuators

Bilayer smart materials can be used to create SSAs that are multi-responsive. Devices that may convert several types of energy into mechanical motion include bilayer multi-responsive soft actuators [212]. These gadgets have a bilayer construction, consisting of two responsive layers, that can react to different stimuli, such as electrical, thermal, and chemical ones. These devices are versatile and adaptable to various applications and environments. The bilayer structure can be composed of a variety of materials like hydrogels, polymers, and composites and consists of two layers with distinct properties, such as different thermal expansion coefficients [80, 191, 213]. The bilayer structure experiences differential expansion or contraction between the two layers in response to a stimulus, leading to bending or curling and producing mechanical motion. For example, Zhong et al. [210] introduced liquid vapour phase transitions to programmable thermochromic soft actuators (PTSAs). PTSAs were programmable thermochromic soft actuators that were susceptible to drastic volume fluctuations because of implanted low boiling point fluid that undergoes reversible liquid-to-vapour phase transitions. Additionally, they were capable of changing colour thanks to thermochromic microcapsules that were implanted (see Fig. 4b) [214]. Three alternative modes for starting shape and deformation type might be simply programmed into these actuators' "two-dimensional" design. Multiple stimuli might cause PTSAs to react. They were appropriate for use in a variety of applications, including wearable devices, because of their suitable operating temperature and stretchability. Also, Amjadi et al. [211] created a brand-new kind of bilayer actuator that could be programmed to bend and change form by leveraging the significant thermal expansion of heated polypropylene film and the significant water-soluble shrinkage of copy paper (see Fig. 4c). These bending actuators could function at low input electric power per unit area (0.14 W cm$^2$), low input voltages (8 V), and low-temperature fluctuations (35 °C). With strong actuation and reversible behaviour, they could change shape with curvature radii up to 1.07 cm$^{-1}$ and a bending angle of 360°. In addition, they could also be triggered by light or dampness. This work uses a soft gripper and a light paper wing for aerial robotics to show the adaptability of these paper actuators.

Moreover, Wang et al. [212] discussed the creation of a high-performance bilayer actuator made of a substrate made of polyethylene glycol terephthalate and a polypyrrole (PPy) layer. Due to the bilayer's synergistic deformations brought on by their significant thermal expansion mismatch as well as the coupling effect of PPy's hygroscopicity, photothermal effect, and conductivity, the actuator displayed exceptional humidity, light, electricity, and thermal responses in addition to a significant deformation as shown in Fig. 5a. The group was successful in achieving a variety of reversible complicated deformations between 2 and 3D configurations by utilising the actuator's multi-responsive properties and laser-engraved geometries. Additionally, they demonstrated the actuator's potential uses in temperature-gradient-driven rapid rolling, light-induced crawling, and smart clothing with humidity control. Soft functional materials that mimic the adaptable motions of living things are becoming more popular due to the possibility of making artificial gadgets and robots that behave realistically. Chang et al. [215] created a perfluoro-sulfonic acid ionomer-based bilayer actuator that could react to a variety of stimuli (see Fig. 5b). The actuator's high-performance actuation was made possible by combining CNT's complete conversion characteristics, stress-mismatching structure, high negative coefficient of thermal expansion, and enormous anisotropic thermal expansion of PE polymer. The actuator also had a structural feedback loop built in, which enabled intelligent systems like self-sustaining mobility in the sunlight, self-sustaining oscillation and solar-electric production, and bionic floral responsiveness to environmental change. These various actuation techniques have exciting prospects for the creation of bio-hybrid soft robotic systems that can coexist peacefully with their surroundings.

Xing et al. [216] built a tri-layer shape memory soft actuator that could actuate and sense strains through reversible electric/moisture stimulation using a compact sandwich structure. A middle composite layer made of silver nanoparticles (AgNPs) connected a hygroscopically deformable layer of PVA to a high-performance, flexible SMP layer. The PVAAgNPs flexible (PAF) SMP composite recovered quickly at an ultralow voltage (2 V) thanks to the electrothermal AgNP layer, which also had a high strain-sensing sensitivity (1.56 Gauge Factor) and a rapid reaction to deformation (110 m/s). The low-power PAF actuator was able to efficiently load and unload target items without the need for extra cooling procedures and to identify their presence and weights in real time because of a new mix of PVA, flexible SMP, and AgNPs. These findings revealed that the soft PAF actuator was well suited for SSAs and biomimetic applications, notably in automated packaging production lines for food, pharmaceutical, logistics, and other sectors. These actuators are the kind of machines that can transform different kinds of energy into mechanical motion. They are equipped with a structural feedback loop, which is a process that provides information about the output of a system and uses it to adjust their behaviour. This structural feedback loop enables the actuator to adapt to changes in its environment and perform intelligent functions. One such function is the ability to achieve self-sustainable locomotion using sunlight as its power source. This is particularly useful in fields such as robotics and autonomous vehicles where energy efficiency and sustainability are crucial factors [217]. Additionally, the actuators can generate mechanical oscillations and convert them into electrical energy, enabling them to be used as a self-sustaining power source for devices such as wearable technology and remote sensors. The actuators may also adapt to changes in their surroundings in a fashion that resembles the behaviour of plants, which is known as bionic floristic responses. For example, it can change its shape or orientation in response to changes in light, temperature, or humidity [218]. This feature has the potential to be applied in architecture to develop adaptive building materials that improve energy efficiency and comfort.


(I)
Oxygen plasma
PET film
PET film
FeCl$_3$/HCl solution
Py/HCl solution
2-3℃
Polymerization
PPy film
PET film
PPy/PET bilayer
PPy/PET
(V)
2D Precursor
3D Structure
Before motion
After motion
(II)
Moisture on
Moisture off
(III)
Light on
Light off
(IV)
DC on
DC off
Bending angle (°)
RH (%)
$h_{PPy}$=241 nm
$h_{PPy}$=383 nm
$h_{PPy}$=621 nm
$h_{PPy}$=867 nm
Bending angle (°)
Time (s)
50 mW/cm$^2$
100 mW/cm$^2$
150 mW/cm$^2$
200 mW/cm$^2$
250 mW/cm$^2$
300 mW/cm$^2$
Bending angle (°)
Time (s)
1V
2V
3V
4V
4.5V
(a)
DMAC
CNT
Nafion
Mixing/ Dispersing
Magnetic/ Ultrasonic
Drop casting
50℃ curing
CNT-Nafion
Glass substrate
Peel off
Paste the PE film
PE
CNT-Nafion
H$_2$O channel
Crystallite
CNT
Nafion
PE
Light irradiation/ Electricity stimuli
Humidity/Organic solvent increasing
PE: Thermal expansion
CNT-Nafion: Thermal shrinkage
CNT-Nafion: Hygroscopic expansion
(I)
Under shading
Natural sunlight irradiation
CNT–Nafion
PE
Bending curvature
ΔT
Bending curvature [cm$^{-1}$]
ΔT [℃]
Light power intensity [mW cm$^{-2}$]
(II)
(III)
0V
4V
6V
8V
10V
12V
50°C
41°C
32°C
23°C
(IV)
50%
60%
70%
80%
22.5°C
19.7°C
19.0°C
36°C
30
26
18°C
FOTRIC
(b)

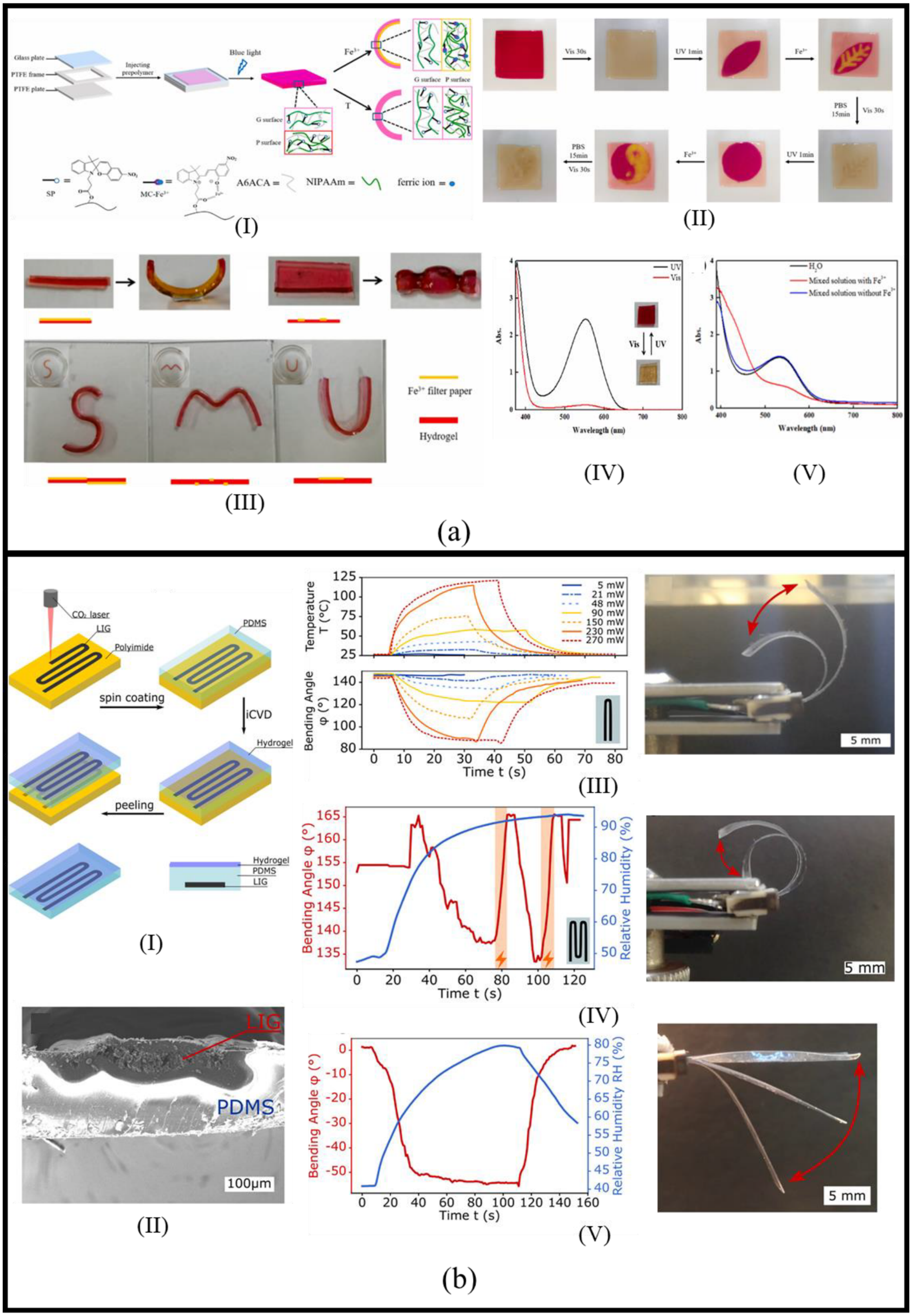
◂**Fig. 5** **a**. (I) PPy/PET bilayer fabrication schematic illustration. (II) Responses of the PPy/PET bilayer actuators to the applied RH for different PPy layer thicknesses, as well as a relationship between the actuator's bending angle and the applied RH. (III) The link between the bending angle and the applied illumination at various NIR light intensities is seen in optical pictures of the actuator. (IV) When the 4.5 V DC is switched ON/OFF, the electrical behaviour of the Au-coated PPy/PET bilayer actuator changes, as does the impact of the loaded DC voltage on the bending angle. (V) A sort of smart clothing that responds to variations in humidity and the translation of complicated 2D configurations into 3D ones using the right stimuli [212]. **b**. (I) Diagrams showing the manufacturing method and actuator setup of the proposed CNT-Nafion/PE bilayer actuator. (II) Natural curling induced by sunlight and temperature and bending curvature change in response to the light power density after 10 s of exposure (ΔT: elevated temperature). (III) Photographs of the actuation in the infrared and optical range at various voltages. (IV) Images of the humidity-driven curling in optical and infrared light at various RH levels [215]

## 3.4 Hydrogel-Based Actuators

Hydrogels are polymer networks that can absorb water and exhibit unique properties such as high-water content and softness [219]. These properties make hydrogels useful for many applications, including drug delivery, tissue engineering, and soft robotics [220, 221]. In addition, hydrogels can have multi-responsive behaviour, which means they can react to a variety of stimuli, including pH, temperature, and ionic strength variations [222]. This multi-responsive behaviour allows for the design of hydrogel actuators that can undergo various types of mechanical deformation. By selecting specific polymers, cross-linkers, and stimuli, researchers can develop advanced hydrogels that exhibit even more complex behaviour, leading to new materials and devices that can address complex challenges in various fields [213, 223]. For example, Xiao et al. [224] created a hydrogel that is flexible and colourful and reacted to various stimuli. The N-isopropylacrylamide (NIPAAm), acryl-6-aminocaproic acid (A6ACA), and spiropyran (SP) derivatives employed to make the hydrogel gave it the ability to deform under the influence of temperature, ferric ion ($Fe^{3+}$), and chromatic phenomena (see Fig. 6a). When exposed to UV light, the hydrogel displayed the merocyanine UV absorption peak at 540 nm, which vanished in the presence of $Fe^{3+}$ due to its selective chromatic response. The hydrogel was programmed to deform in the presence of $Fe^{3+}$ using the ionoprinting technique. Due to its anisotropic structure, the hydrogel also displayed reversible bending deformation brought on by temperature. The hydrogel displayed programmable, spatiotemporal, and sophisticated deformation behaviours as well as colour changes when subjected to temperature and $Fe^{3+}$.

As illustrated in Fig. 6b, Dallinger et al. [225] created a technique for changing polymers into conductive 3D carbon constructs with pores using a readily accessible $CO_2$ laser engraving technology. This process, known as laser-induced graphene (LIG), has several uses in energy, actuation, and sensing. To achieve multi-responsive actuation in a humid environment, the work focuses on the coupling of LIG with a smart hydrogel named poly(N-vinylcaprolactam)-pNVCL. Initiated chemical vapour (iCVD) deposition was used to deposit a thin layer of pNVCL hydrogel over a matrix of PDMS with embedded LIG tracks to form the actuator. The ability of smart hydrogels like pNVCL to reverse their phase transition from a swelled to a collapsed state in response to various external stimuli including temperature, pH, and magnetic/electric fields is one of its special characteristics. Despite the actuator matrix being 500 times thicker than the active hydrogel layer, which is just 300 nm thick, Joule heating was able to cause a reversible bending of nearly 30° in a humid environment. Before fine-tuning the characteristics of the multi-responsive PDMS/LIG/pNVCL actuator, they also produced single-responsive variants of the actuator to examine thermoresponsive and humidity-responsive qualities. The piezoresistive PMDS/LIG composite's change in resistance was used to track the actuator's bending angle as it also displayed self-sensing capabilities. The researchers built an octopus-shaped demonstrator with four independently movable limbs to demonstrate the processing methods and material combinations.

For the in-situ polymerization of anisotropic hydrogels consisting of highly ordered lamellar networks crosslinked by metal nanostructure assemblies, Qin et al. [226] created a universal method. Amazing anisotropic mechanical, optical, de-swelling, and swelling behaviours were displayed by these hydrogels [227]. Due to the dynamic thiolate-metal interaction, the composites also exhibit quick and effective self-healing capability under NIR irradiation and low pH circumstances. Anisotropic features in the hydrogels allowed for regulated solvent-responsive mechanical actuation. By using healing-induced assembly, the integrated device could deliver more complex and intricate actuation forms, demonstrating its potential as an excellent SSAs for applications such as smart robots. The multi-responsive hydrogels could be also self-healable and responsive to changes in pH or water content, allowing for controlled changes in volume, shape, and transparency [228]. These actuators have potential applications as smart switches and shape memory materials, actuated by various environmental stimuli [229, 230]. These actuators are advantageous in safeguarding equipment in severe environments without consuming excessive energy. It is designed to endure harsh conditions that could otherwise impair its functionality, such as high temperatures and corrosive substances. Its sturdiness and resilience make it preferable to conventional actuators, which might not withstand extreme environments. This capability to withstand adverse conditions can increase the dependability and lifespan of equipment that requires reliable performance in harsh conditions. Additionally, the actuator's


Glass plate
PTFE frame
PTFE plate
Injecting prepolymer
Blue light
Fe³⁺
T
G surface
P surface
SP
MC-Fe³⁺
A6ACA =
NIPAAm =
ferric ion =
(I)
Vis 30s
UV 1min
Fe³⁺
PBS 15min
Vis 30s
(II)
Fe³⁺ filter paper
Hydrogel
(III)
UV
Vis
Abs.
Wavelength (nm)
(IV)
H₂O
Mixed solution with Fe³⁺
Mixed solution without Fe³⁺
(V)
(a)
CO₂ laser
LIG
Polyimide
PDMS
spin coating
iCVD
Hydrogel
peeling
(I)
LIG
PDMS
100μm
(II)
Temperature T (°C)
5 mW
21 mW
48 mW
90 mW
150 mW
230 mW
270 mW
Bending Angle φ (°)
Time t (s)
(III)
Relative Humidity (%)
(IV)
Relative Humidity RH (%)
(V)
5 mm
(b)

◂**Fig. 6** **a**. (I) A hydrogel actuator with malleable and colour-changing characteristics is schematically illustrated. (II) Chromatic deformation behaviours are triggered by dual stimuli of light and $Fe^{3+}$. (III) Hydrogel deformation behaviour triggered by $Fe^{3+}$. (IV) The hydrogel's UV absorption spectrum under UV and white light. (V) The hydrogel's UV spectrum after being submerged in various solutions [224]. **b**. (I) Diagram showing the cross-section of the fabrication process for multi-responsive actuators. (II) A cross-section of LIG-LO implanted in PDMS is seen in the scanning electron microscope picture. (III) PDMS/LIG actuators' thermoresponsive response with localised Joule heating. Plot displaying the temperature and corresponding bending angle as a function of time for a PDMS/LIG actuator subjected to Joule heating at various levels of applied electrical power starting from the OFF state, with superimposed images demonstrating actuation at t = 0 and 35 s for an applied electrical power of P = 230 mW. (IV) A multi-responsive PDMS/LIG/pNVCL actuator's bending angle and RH are shown over time; orange regions denote the ON state for applied current with a power of P 30 mW. A superimposed picture demonstrates actuation at RH 100% with = 135° under Joule heating and = 165° without Joule heating. (V) A humidity responsive PDMS/pNVCL actuator's bending angle and RH are shown over time, with superimposed pictures demonstrating the actuator's bending at t = 0, 25, and 80 s, respectively, corresponding to RH = 40%, 55%, and 80% [225]

low energy consumption means that it has a minor impact on the overall energy consumption of the system [231]. This feature enhances the sustainability and energy efficiency of the operation, making it an appealing choice for applications where energy consumption is a concern.

## 4 Shape-Locking Soft Actuators

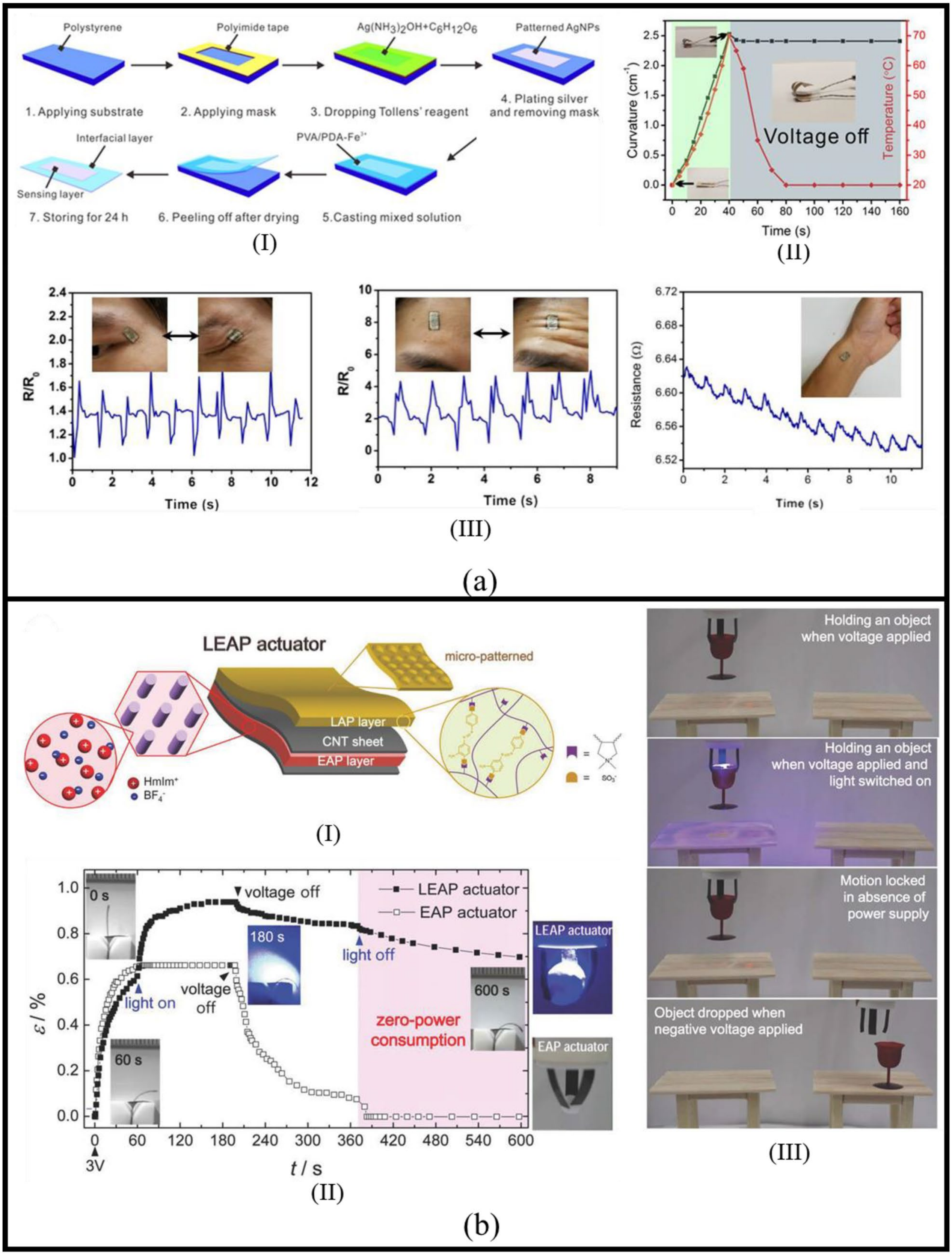
Soft actuators that can safely and effectively interact with the environment rely on programmable shape morphing. While some materials can transform from 2D sheets into 3D shapes when exposed to certain stimuli, these solutions cannot often maintain their shape without power, are restricted to predetermined configurations, or do not have enough mechanical stiffness to manipulate common objects. Shape locking is one of the advanced features of soft actuators that can be effective in reducing energy consumption. Shape locking is a technique used in soft actuators where the shape of a soft actuator is fixed using an external mechanism [232]. This allows the actuator to maintain its shape without consuming additional energy, which reduces its overall energy consumption. Additionally, by maintaining a specific shape, shape locking can increase the efficiency of the actuator, as it reduces the amount of energy required to perform a specific task. However, it is important to note that while shape locking can be effective in reducing energy consumption, it is not always the best solution for every application. There is a variety of manufacturing techniques to develop actuators with shape locking. In this section, we will look at recent developments in soft actuators with the shape-locking feature.

### 4.1 Electro-Based Soft Actuators

Fast reaction, precise control, and programmable deformation are just a few advantages that electro-responsive soft actuators and their derivatives have, making them ideal for cutting-edge applications [233]. The physical, chemical, and mechanical features of smart materials, such as their excellent transport movement, robustness, and transparency, have influenced their recent acceptance in the design of these kinds of actuators [234, 235]. Electrodes, electro-responsive materials, and deformable substrates or materials that are connected make up the simple design of electro-responsive soft actuators [236]. This section focuses on electro-responsive actuators that possess the ability to lock their shape in the required position. As an example, Chen et al. [237] used in situ dopamine polymerization along PVA macromolecular chains and the inclusion of ionic coordination between polymer molecular chains (PVA and polydopamine chains) and metal ions ($Fe^{3+}$) to develop an adhesive and modulus tailorable interface (see Fig. 7a). To boost water tolerance and absorption, which is necessary for adjusting the adhesion and modulus of the interface, the $Fe^{3+}$ cations encouraged coordination. The resultant interface was used to create a soft, ultra-thin, skin-compliant sensor that is also self-adhesive and multi-responsive with a configurable modulus for locking actuator modes and lowering power consumption. To gain a deeper understanding of the sensing ability of the on-skin sensor, the researchers measured and graphed the resistance change of the sensor when subjected to strain. This study presents a novel approach to addressing interface-related challenges in sensing and actuating.

Also, Kim et al. [238] unveiled a brand-new kind of double-layered actuator based on light- and EAP (LEAP). The LEAP actuators have a 250% increase in displacement over standard EAP actuators and can support items that are three times heavier. The LEAP actuators also have a special self-locking capability that allows the bending action to be maintained for several tens of minutes without power. These self-locking LEAP actuators can hold an item for 15 min at a 3 V working voltage and have a significant, reversible bending strain of over 2.0% (see Fig. 7b). Researchers created a multifunctional artificial muscle based on a concentric tube/rod built of polydopamine-coated LCE and low-melting-point alloy, inspired by the linked behaviour of muscles, bones, and nerves in animals [239]. This suggested artificial muscle exhibits programmable bending angle, position, and direction, deformation locking for supporting large items, and real-time angle variation monitoring.

Moreover, Aksoy et al. [240] introduced soft electromagnetic actuators that were integrated with SMP films,


Polystyrene
Polyimide tape
Ag(NH3)2OH+C6H12O6
Patterned AgNPs
1. Applying substrate
2. Applying mask
3. Dropping Tollens' reagent
4. Plating silver and removing mask
Interfacial layer
Sensing layer
PVA/PDA-Fe3+
7. Storing for 24 h
6. Peeling off after drying
5. Casting mixed solution
(I)
Curvature (cm-1)
Temperature (°C)
Voltage off
Time (s)
(II)
R/R0
Time (s)
R/R0
Time (s)
Resistance (Ω)
Time (s)
(III)
(a)
LEAP actuator
micro-patterned
LAP layer
CNT sheet
EAP layer
HmIm+
BF4-
SO3-
(I)
LEAP actuator
EAP actuator
voltage off
light on
voltage off
light off
0 s
60 s
180 s
600 s
zero-power consumption
LEAP actuator
EAP actuator
ε / %
t / s
3V
(II)
Holding an object when voltage applied
Holding an object when voltage applied and light switched on
Motion locked in absence of power supply
Object dropped when negative voltage applied
(III)
(b)

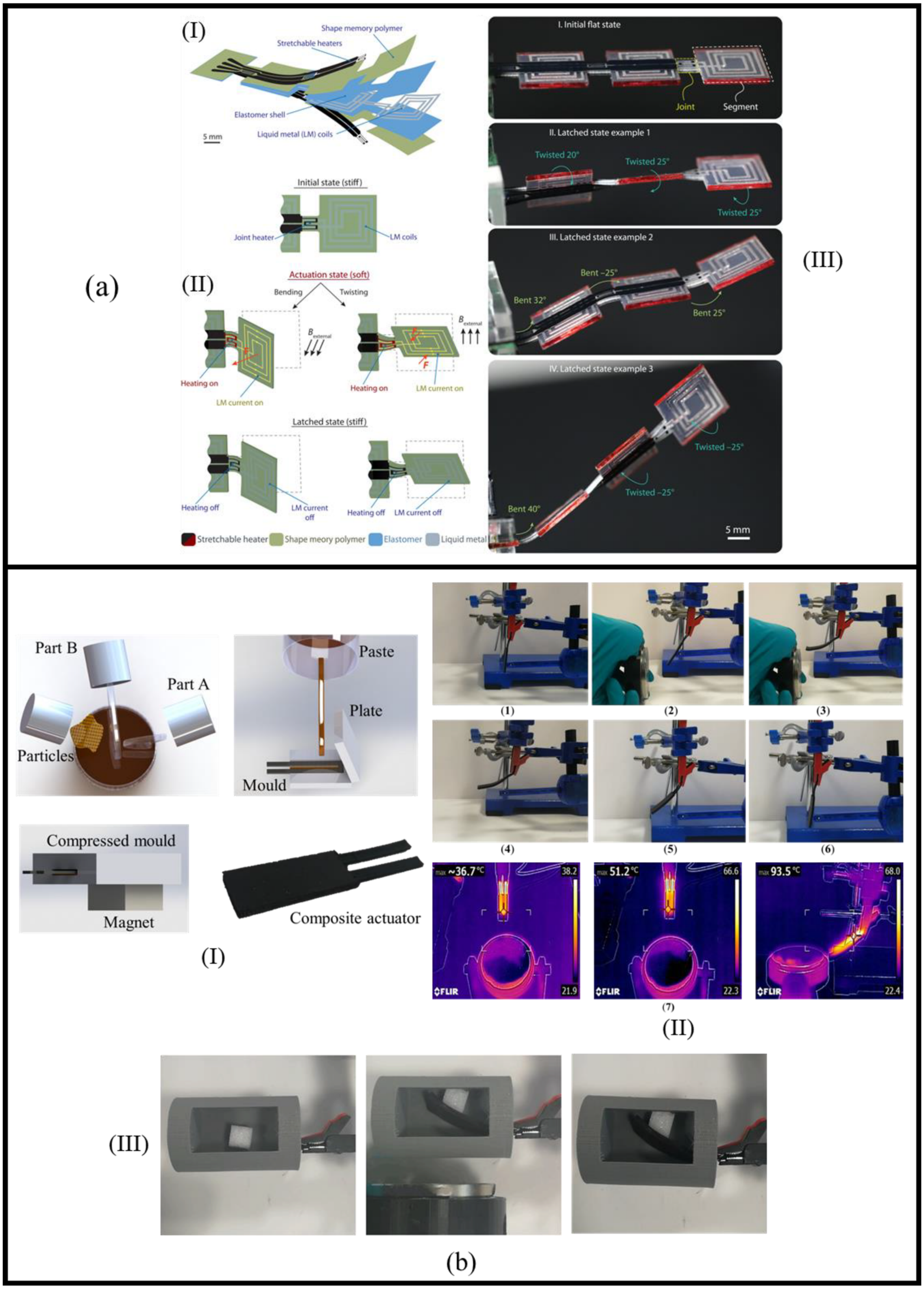
◂**Fig. 7** **a**. (I) On-skin sensor design, production, and performance. (II) Temperature change during voltage on/off (red) and matching curvature (black) as a function of time. The photos of the actuator were taken in the insets when the voltage is on/off. (III) Monitoring in real time of different movements (on the canthus, forehead, and wrist) using a sample scale of 1.0 cm 2.0 cm [237]. **b**. (I) The combination of EAP and LAP layers in the LEAP actuator manufacture process. (II) The comparison between the time-dependent bending strain of the LEAP actuator and the EAP actuator at a voltage of 3 V and light irradiation ($\lambda = 455$ nm). The LEAP actuator is visible in the inset photos at specific periods. Photos in the right panel attest to the LEAP actuator's ability to support objects that are three times heavier than those that would require the EAP actuator. (III) Images showing the LEAP actuator moving in the holding, locking, and descending positions in response to voltage and light stimulation [238]

enabling them to deform and latch into a wide range of configurations (see Fig. 8a). The component was made up of liquid metal coils that were sandwiched between two SMP sheets and an elastomer cover. The SMP's rigidity was greatly decreased by heating it. When a magnetic field was present and current was flowing through a liquid metal coil, the device experienced substantial bending or twisting. Once the SMP was cooled, the shape was locked in, and the device could bear a load. Despite starting as a flat device, complex shapes could be achieved through this process. Also, Lalegani Dezaki et al. [241] provided details of an innovative idea for advanced bi-stable magnetorheological composite actuators (see Fig. 8b). A lightweight, bi-stable composite actuator with customizable magnetic patterns was possible because of the use of magnetorheological elastomer composites and 4D printing of conductive SMPs. The actuator was propelled by Joule heating and magnetic fields, and it might be left in the actuated position for a long time without any stimulation. The actuator had the potential used in mechanical and biological systems and had a lifting capacity of 200 g.

## 4.2 Pneumatic-Based Actuators

The use of pneumatic actuation is still the primary technology in soft robotics because it is lightweight, has a quick response time, and is easy to implement [242]. Pneumatic systems are cost-effective because they may be built using low-cost parts like solenoids and diaphragm pumps. These robots are composed of fibre-reinforced actuators and soft pneumatic actuators (SPAs), which comprise pneumatic networks [243]. SPAs are very flexible, safe, and capable of significant deformations. They also have strong power-to-weight ratios and are inexpensive to produce [244, 245]. Positive or negative pressures can be used to activate SPAs, and vacuum actuators are best for situations with limited volumes [246]. Based on their properties, SPAs display several sorts of movements [247–249]. Applications for SPAs include minimally invasive surgery, rehabilitation, helping the elderly, interacting with people and other robots, and handling delicate materials [250–252]. However, SPAs and robots still face challenges and limitations in terms of continuous input power to hold them in a required position. There have been developments in SPAs to make them variable stiffness and lock their shape in the required position. For example, Li et al. [253] introduced a small soft gripper that uses a variable stiffness module made of polylactic acid (PLA) and a retractable mechanism to achieve a soft-rigid hybrid action. By using the variable stiffness module, the gripper could increase its stiffness by 18 times without losing its flexibility. The variable stiffness module was divided into three regions that can be activated separately to create varying levels of flexibility, while a water-cooling system reduces the cooling time. The retractable mechanism allowed the gripper to adjust its layout, expand its workspace, and perform manipulations by opening and closing its fingers. The soft fingers, combined with the ability to adjust stiffness, can maintain their shape and grip objects with a high load, without the need for repeated heating and cooling. As illustrated in Fig. 9a, Pal et al. [254] provided a simple method for quickly producing prestressed soft actuators (PSAs) that used elastic energy storage to increase the capabilities of soft robots. PSAs were produced by pouring a silicone elastomer into moulds created by a SLA 3D printer, followed by curing in an oven at 60 °C for 45 min. The elastomer was stretched and affixed to an inextensible blend of polyester and cellulose paper soaked in a liquid prepolymer. The entire assembly was then cured to create different PSAs. The pneumatic channel of the PSAs was connected to a polyethylene tubing using a cannula, and the PSAs were actuated by pneumatic means using a regulated compressed air supply. The prestressed elastomeric layer of PSAs contains elastic energy that can be used to build grippers that can perch upside down at 116° angles and hold up to 100 times their weight without the need for any external power. Both the final shape of the PSA and its actuation sequence may be set by adjusting the direction and strength of the force utilised to prestress the elastomeric layer. Additionally, the short recovery time (of around 50 ms), made possible by the release of elastic energy held in PSAs, greatly increases the actuation rates of soft pneumatic actuators, especially following motions requiring severe deformations. The development of bistable soft robotic systems that leverage elastic energy stored in the PSAs as a source of power amplification for quick movements is another benefit of strategically prestressing PSAs. Employing these methods has proven to be extremely advantageous in terms of reducing the overall energy consumption required for tasks that span extended periods [100].

Moreover, jamming has advantages over fluidic actuation in terms of maximum stiffness and versatility, making it a popular mechanism in SPAs [255]. It allows for

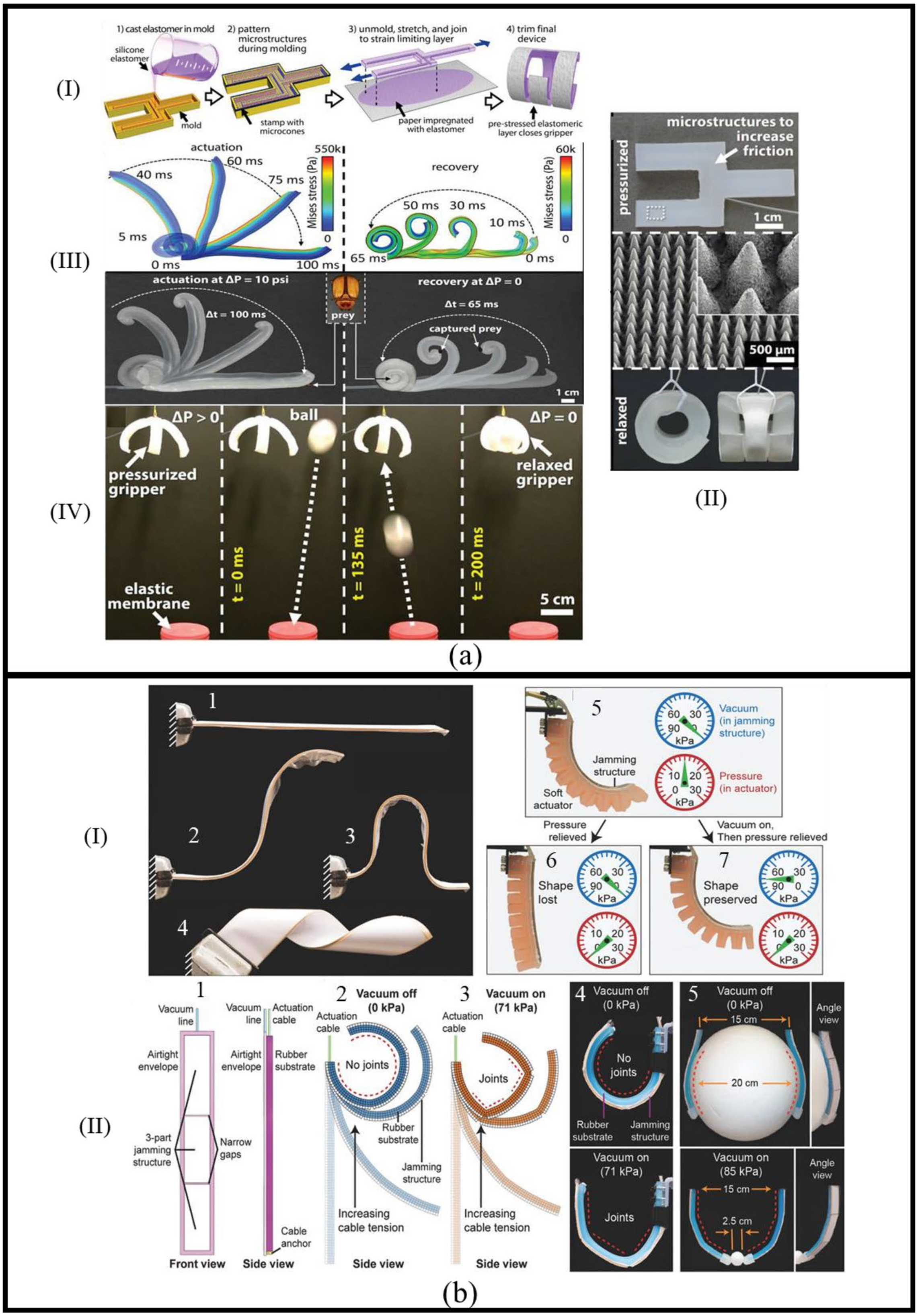


the creation of systems that have high stiffness variation while minimizing volume changes. This technique also assists in shape locking and reducing power consumption. Narang et al. [256] demonstrated how the nonlinear laminar jamming phenomena may link the ideas of soft robotics with traditional rigid robotics. The authors generated

◂**Fig. 8** **a**. (I) The actuator is depicted schematically as being made up of three-square segments connected by three small joints. The segments are composed of liquid metal coils encased in a silicone shell and have a coating of an SMP covering both the top and bottom surfaces. The joints contain stretchable heaters on both sides in addition to having the same internal construction as the segments. (II) By passing electricity through one or more coils, the device is electromagnetically activated, producing a bending or twisting force depending on the direction of the external magnetic field. Due to the SMP's high rigidity and lack of heater current, the hinges do not distort when they are cold. The SMP stiffness decreases by two orders of magnitude and the Lorentz force permits bending or twisting when the hinges are heated above the SMP's glass transition temperature. When the heating current is turned off, the form is locked in place, enabling the coil current to be disconnected. (III) The pictures show several latched states that were attained by a series of bend-and-latch and twist-and-latch procedures. To achieve a variety of distinctive configurations, the sequence and kind of joint deformation can be changed [240]. **b**. (I) A diagram illustrating the various stages involve in creating and implementing the proposed actuator. (II) A composite actuator is tested in a vertical position. The actuator is heated through Joule heating and a magnet is brought close to it. The actuator is attracted to the magnet, reaching its maximum temperature and bending angle. After the permanent magnet is removed, the actuator remains in its position. The actuator is heated once more using Joule heating, and it takes 18 s for it to assume its previous form. Throughout the actuator's energization and attraction phases, heat dispersion is seen. (III) In the closed system of construction, switching on a hook-like actuator [241]

extremely accurate finite element models (FEMs) of multilayer laminar jamming structures as well as a model for two-layer jamming structures that considers all stages of deformation. Shape-locking and changeable kinematics, two novel properties of laminar jamming that the authors exhibited, showed how this phenomenon may allow soft machines to act like conventional rigid robots reversibly (see Fig. 9b). To demonstrate how jamming might improve the performance of real-world soft robotic systems, the authors also constructed a simple grasper that is capable of performing both pinch grasps and wrap grasps. Also, Crowley et al. [257] built a gripper with adjustable stiffness using a technique called positive pressure layer jamming. Utilizing specialised additive printing, the gripper was constructed from two materials: a soft airtight actuation bellow and a somewhat rigid backbone. It was discovered that positive pressure layer jamming technology had a larger performance potential than traditional vacuum layer jamming because it could apply higher pressure, resulting in a 1.6 × higher payload capacity. This technology was created to modify the stiffness of the gripper. Using the positive layer jamming technique, experimental tests revealed that the soft gripper was able to modify its stiffness by 25 × factor.

Moreover, Lalegani Dezaki et al. [258] presented a brand-new design for FDM 4D printed SMP meta-structures on meta-laminar jamming (MLJ) actuators (see Fig. 10). Through hot and cold programming, negative air pressure, and both soft and harsh robot behaviour, these SSAs might act. Since they don't require constant negative air pressure to excite the actuator, MLJ actuators offer an advantage over traditional jamming actuators. Three-point bending and compression tests were used to assess the mechanical characteristics of the SMP meta-structures, which were 4D printed in a variety of forms. Using hot air programming, the shape memory effects (SMEs) and shape recovery of the meta-structures and MLJ actuators were examined. Better performance was shown by MLJ actuators with auxetic meta-structure cores in terms of contraction and bending with 100% shape recovery after stimulation. These environmentally friendly MLJ actuators were capable of lifting loads to 200 g in weight and can grip items of a variety of sizes and forms. MLJ actuators found valuable SSAs as grippers in long-term tasks where they could securely hold objects without requiring continuous energy consumption. These actuators were designed to maintain their gripping force over extended periods, making them suitable for scenarios that demand sustained holding capabilities. By utilizing their unique mechanical properties, MLJ actuators offered an energy-efficient solution for gripping tasks, reducing overall power consumption and contributing to longer operation times. Their ability to maintain a firm grip without constant energy input made them ideal for applications that prioritize energy efficiency and long-term stability. For wearable applications, Liu et al. [259] created a reconfigurable self-sensing pneumatic artificial muscle (RSPAM). By converting the soft actuator's expansion into contraction by fabric winding, the RSPAM was a modular multi-chamber soft actuator with a high contraction ratio that avoided compressing human tissue. The RSPAM has locking capability based on positive pressure jamming and self-sensing of contraction stroke based on liquid metal. The actuator's modular construction allows for configuration changes according to the application by varying the actuator quantity and fabric length. The actuator unit may also move independently on the fabric, giving the muscle the capacity to self-adjust. At 3 bar air pressure, the RSPAM was able to provide a driving force and contraction ratio of 70.14 N and 71%, respectively. Through square-wave tracking studies with closed-loop control, the displacement self-sensing capability was confirmed. Additionally, a preliminary evaluation of the RSPAM's capacity to help elbow movement revealed that it can minimise 53.05% of muscle fatigue. By utilizing this approach, individuals and organizations can effectively minimize the amount of energy required to complete a given task over a prolonged period. This reduction in energy usage not only leads to cost savings but also contributes to sustainability efforts by reducing carbon footprint and conserving natural resources. Furthermore, this method can also extend the lifespan of machinery and equipment by mitigating the wear and tear that occurs due to prolonged usage. Consequently,


(I)
1) cast elastomer in mold
silicone elastomer
mold
2) pattern microstructures during molding
stamp with microcones
3) unmold, stretch, and join to strain limiting layer
paper impregnated with elastomer
4) trim final device
pre-stressed elastomeric layer closes gripper
(III)
actuation
0 ms
5 ms
40 ms
60 ms
75 ms
100 ms
550k
Mises stress (Pa)
0
recovery
50 ms
30 ms
10 ms
65 ms
0 ms
60k
Mises stress (Pa)
0
actuation at ΔP = 10 psi
Δt = 100 ms
prey
recovery at ΔP = 0
Δt = 65 ms
captured prey
1 cm
(IV)
ΔP > 0
pressurized gripper
elastic membrane
ball
t = 0 ms
t = 135 ms
t = 200 ms
ΔP = 0
relaxed gripper
5 cm
(II)
pressurized
microstructures to increase friction
1 cm
500 µm
relaxed
(a)
(I)
1
2
3
4
5
Vacuum (in jamming structure)
60
30
90
0
kPa
Jamming structure
Soft actuator
Pressure (in actuator)
10
20
0
30
kPa
Pressure relieved
Vacuum on, Then pressure relieved
6
Shape lost
7
Shape preserved
(II)
1
Vacuum line
Airtight envelope
3-part jamming structure
Narrow gaps
Front view
Vacuum line
Actuation cable
Airtight envelope
Rubber substrate
Cable anchor
Side view
2
Vacuum off (0 kPa)
Actuation cable
No joints
Rubber substrate
Jamming structure
Increasing cable tension
Side view
3
Vacuum on (71 kPa)
Actuation cable
Joints
Increasing cable tension
Side view
4
Vacuum off (0 kPa)
No joints
Rubber substrate
Jamming structure
Vacuum on (71 kPa)
Joints
5
Vacuum off (0 kPa)
15 cm
20 cm
Angle view
Vacuum on (85 kPa)
15 cm
2.5 cm
Angle view
(b)

◂**Fig. 9** **a**. (I) A diagram showing how PSAs are made can be summarized as follows: First, a mould is used to cast and cure a layer of silicone elastomer that contains a network of air-filled channels. Then, a stamp with a textured surface is used to create cone-shaped structures on the elastomer layer's gripping surface. A paper sheet that has been impregnated with elastomer is coupled with the stretched elastomer layer to form the PSA's strain-limiting layer. The pre-stretched elastomer finally contracts when the PSA is detached from the paper, causing the silicone-paper bilayer composite to curl. (II) When there is external pressure, the resultant PSA opens; otherwise, it is closed. The conical microstructures found on the PSA's gripping surface are shown in the inset of the picture. (III) After a 100 ms burst of pressurised air is given to the PSA's pneumatic channel at a pressure of 10 psi, FEM simulations show how the PSA gets activated (extended) and recovers. The PSA's elongation and subsequent recovery in response to the pressure are seen in the image. (IV) Snapshots depict the PSA catching a ball that is moving at approximately $\approx 10\ \mathrm{m\ s}^{-1}$ [254]. **b**. (I) The shape-locking ability of a composite structure made up of a 20-layer jamming structure and a pneumatic soft actuator is shown in this image. Panels 1–4 depict the deformation of the jamming structure into different forms, which are subsequently maintained by adding a vacuum. The jamming structure is shown in panel 5 attached to the soft actuator, which is pressurised to produce the necessary bending angle. In panel 6, the composite structure instantly recovers to its undistracted condition when the actuator is depressurized, and no vacuum is delivered to the jamming structure. However, in panel 7, the system maintains its form with excellent fidelity when a vacuum pressure of 85 kPa is supplied to the jamming structure before depressurizing the actuator. This is shown by a quantity R2 of 0.9835 between the arc of the ventral surface in panel 5 and the same arc in panel 7. (II) A variable kinematics system's FEM and experimental validation are shown in this picture. The system's schematic is shown in panel 1. With hoover on, the maximum-to-mean curvature ratio rose by a factor of 6.65, statistically proving the existence of joints. Panels 2 and 3 depict FEM of varied kinematics behaviour with increasing cable loads. The experimental verification of the variable kinematics system is shown in panel 4. A two-fingered grasper is shown in panel 5; each finger has a variable kinematics system and a rounded fingertip. When no suction was applied to the fingertips, the grasper could conduct a secure wrap grasp on a huge ball and withstand disturbance. The grasper could maintain a secure pinch grip on a ball with a diameter of one-eighth when hoover was applied [256]

implementing this approach not only reduces energy consumption but also decreases the frequency of required maintenance, thereby saving on repair costs and minimizing downtime [260].

## 4.3 Shape Memory Alloy-Based Actuators

SMAs are considered smart materials because of their ability to undergo electrothermal actuation with high durability. Additionally, SMA actuators have many advantages, such as low voltage requirements, biocompatibility, compact size, and quiet operation, which make them suitable for various applications [261, 262]. SMAs are a type of heat-activated smart material that utilizes the SME [263]. This implies that a high current is necessary to quickly move the actuator and create complex structures or robots. The nickel-titanium alloy (NiTi) is commonly used in SMA actuator design because of its excellent strain properties, which can reach up to 7% [264, 265]. Our study will centre around examining soft actuators that employ SMAs to achieve a particular phase-locking capability. These soft actuators are engineered to react to different stimuli and adapt to environmental changes. SMAs provide these actuators with the ability to change shape, which is valuable in numerous applications. With the ability to lock into a specific phase, these actuators can maintain a predetermined form or position, thus enhancing their accuracy and dependability. For example, Gong et al. [266] presented a solution to the challenges faced by SMA actuators, which were flexible and lightweight but had lower force density and consume excessive energy. A locking system that can mechanically maintain an actuator's contracted condition without requiring constant current was suggested as the fix. To prevent the actuator from extending in the other direction while locked, the locking mechanism was built using a ratchet structure and pawl. A bistable retractable mechanism was also used to transition between the locking and unlocking states with a single one-way actuation. This solution has the potential to overcome the limitations of SMA actuators and improve their performance in robotics applications. Additionally, since wearable robots run on batteries, it's critical to increase the effectiveness of their actuation mechanism to increase their operating time. Recently, soft wearable robots that employ fabric-type soft actuators have attracted a lot of attention. (FSAs). These actuators are soft, flexible, and light, but they need a steady stream of energy to stay actuated and support any burdens they could be carrying, like an item. Park et al. [267] created a locking-unlocking mechanism (LUM) that can maintain the FSA's contraction condition without requiring a continuous energy supply to decrease the energy consumption needed for holding motions in FSAs. The LUM, which included a ratchet-pawl mechanism, pawl rotating actuators (PRA) with SMA springs, and a wire encoder, was fastened to the top of the FSA. The wire encoder monitors the length of the FSA contraction, and the PRA enabled the pawl to lock and unlock the ratchet. The length of the FSA might be adjusted to a certain displacement using the LUM's displacement controller. The LUM allowed FSAs to sustain loads and retain their contraction condition without having to continuously use energy. With a projected improvement of at least two times, this can greatly increase the operation time of soft wearable robots employing FSAs.

Wang et al. [268] developed a brand-new class of composite actuators that made advantage of SMA to maintain a variety of configurations without requiring constant energy input. Fusible alloy (FA) material, Ni-chrome (Ni–Cr) wires, and SMA wires were incorporated into a smart soft composite (SSC) framework to create the actuators (see Fig. 11a). Continuous deformation was possible thanks to the SMA-based SSC structures' gentle morphing capabilities. By

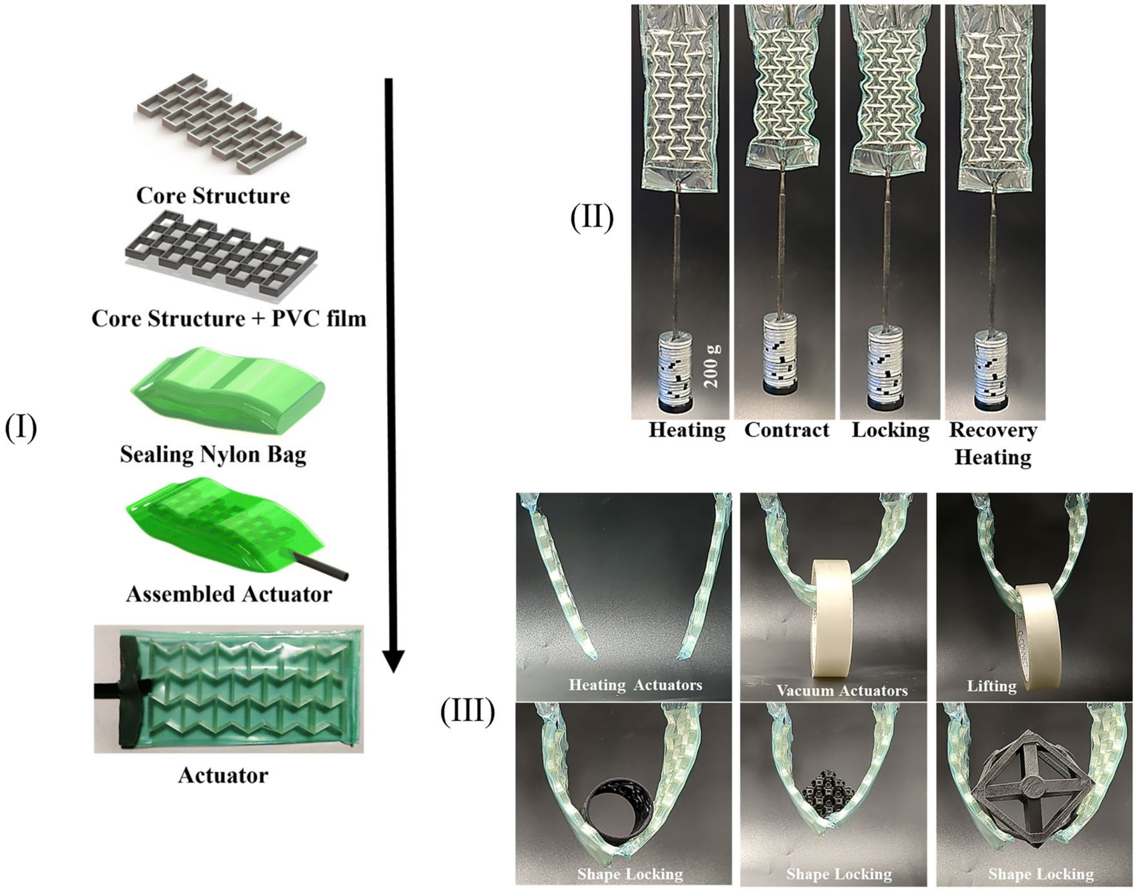


**Fig. 10** (I) Fabrication procedure of MLJ actuator. (II) The procedures for form-locking without power, shape recovery of actuators, and lifting weights using negative air pressure, each with a flowchart outlining the various phases. (III) The low level of force required to grasp and raise items of various weights [258]

melting the FA structures using NieCr wires, the actuator's stiffness was managed. The actuator's stiffness in low- and high-stiffness states for various applied currents and heating times of the FA structure is measured in this paper, which also provides data on the actuator's design and manufacturing process. The findings demonstrated that the actuator's maximum rigidity was more than eight times greater than its minimum stiffness. Using actuators with one or two segments, the actuator's capacity to retain its form was examined, and the findings were compared to a numerical model. Also, Akbari et al. [269] created soft composite actuators with form recovery and preservation capabilities (see Fig. 11b). The resistive and SMA wires were inserted in the actuators, together with flexible elastomeric and stiff SMP layers. These materials were utilised to print the hinges for the bending actuators, and the embedded wires were then employed to use Joule heating to modify the temperature and bending stiffness of the hinges. They utilised a nonlinear FEM to forecast the deformation of the actuators and looked at how changing the thickness of the SMP layer affected shape retention and recovery. Without the aid of any outside mechanical force, the resultant actuators are capable of significant bending deformations, can maintain their bent shape, and can regain their original shape. This technology is promising for producing soft composite actuators having adjustable rigidity since it does not require complicated manufacturing procedures.

Moreover, Patel et al. [270] created SMA-based actuators utilising two 3D-printed frames with integrated SMA coils and a pre-stretched membrane. The actuator can swiftly switch between two oppositely curved states and produce a force of 0.3 N by inducing a snap-through instability after 0.2 s of electrical activation with an input power of 21.1 ± 0.32 W. Through 580 cycles of cyclical testing, the consistency and dependability of the actuator response are confirmed. The soft bistable actuator's quick response time and small size make it ideal for use as an artificial muscle in shape-reconfigurable soft robots that can move in a variety of ways using SMA power. Three soft robots are developed to illustrate this, including a reconfigurable amphibious robot that can walk on land and swim in the water, a multimodal crawler that can crawl and leap, and a rolling robot inspired by caterpillars that can crawl and roll. An extremely compact and dynamic bistable soft actuator was also created by Huang et al. [271] to enable multimodal soft robot movement (see Fig. 11c). The actuator was made of thermally pre-stretched electrical rubber, and they investigated how actuation affected tip force, bending, and temperature. The thermal elastomer actuator comprises a U-shaped SMA wire between layers of strained and unstretched thermal elastomer. With 3.7 V lithium-polymer batteries, this design creates an actuator that weighs 3.7 g, produces a force of 0.2 N, bends with a change in curvature of 60 m in 0.15 s, and can be operated at a frequency exceeding 0.3 Hz. Accordingly, several models and combinations were created utilising this method.

Actuators, which are crucial for enabling movement in soft robots, may be created from materials that can change form in reaction to outside stimuli. The actuator may be retained in a bent position with the help of a pre-stretched elastomer, which results in a decrease in the energy needed to maintain that position. This is important in soft robotics, as these robots are often powered by batteries with limited capacity and reducing energy usage can extend their operational time. Meanwhile, to achieve energy savings, shape-locking features can also be added to secure the target position. This means that energy input is only required to initially bend the actuator, and no further energy is needed to maintain the bent position. Using the pre-stretched technique and shape-locking features can significantly reduce energy consumption in soft robotics, which is particularly useful in portable or battery-powered devices where energy usage is a concern. Overall, this simple yet effective technique can provide a way to improve the efficiency of soft robotic systems [272].

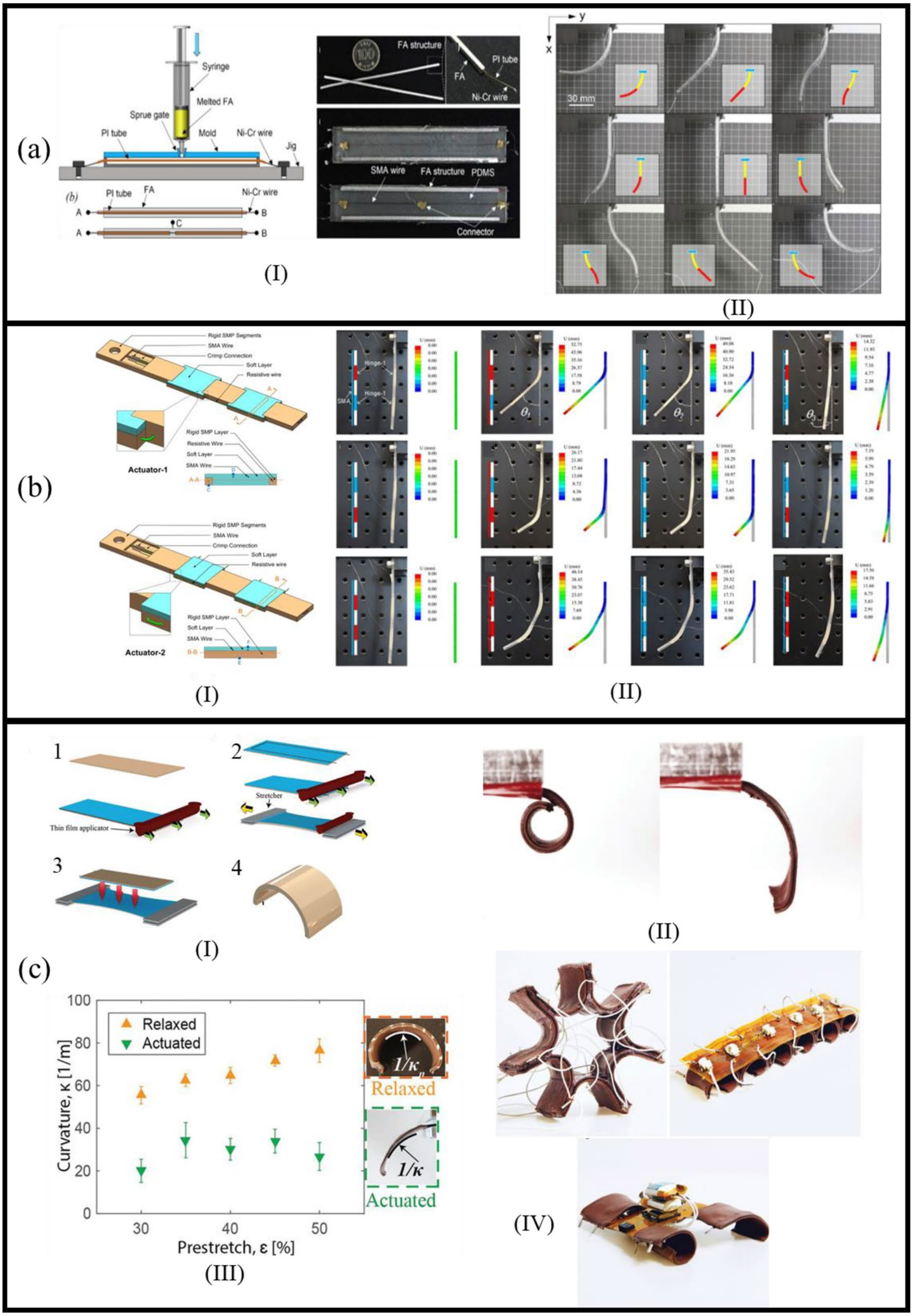
## 5 Biological Water-Responsive-Based Actuators

A potential class of stimuli-responsive materials known as biological water-responsive (WR) materials can alter in volume in response to changes in humidity in the environment brought on by the adsorption or desorption of water molecules [273]. As a result of this characteristic, they can utilize evaporation and humidity gradients to perform a diverse range of tasks. The development of humidity energy using WR materials is essential in addressing global energy challenges, promoting sustainable development, and reducing environmental concerns like greenhouse gas emissions. Water evaporation caused by solar radiation is a common and abundant resource on Earth's surface [274, 275]. Throughout countless years of evolution, nature has created a vast array of unique biological materials that exhibit moisture-responsive behaviour. Plants, for instance, have evolved the ability to exploit fluctuations in daily humidity levels to disperse and bury their seeds for reproduction [276–279].

Through its WR characteristics, which cause the contraction or expansion of plant fibres in a specified direction, resulting in the bending of the plant tissue, some plants can disperse their seeds and expand their species [280, 281]. Moreover, various arrangements of cellulose in the plant tissue can cause different movements [282, 283]. Actuators of this kind can function as energy harvesters or operate with low energy consumption over extended periods [284]. For these seeds to migrate across the soil surface and locate an ideal germination location, the spiral awns must tighten and release. For example, Kay et al. [285] mostly concentrated on single-stage reversible motions using shape-changing actuators, offering no guidance for attaining controlled multistage locomotion (see Fig. 12a). They developed a methodology for developing a flexible, self-propelling, and programmable robot (Hygrobot) capable of locomotion using cyclic moisture introduction and removal. The Hygrobot utilized several multi-layer mechanisms that operated in a synchronized manner with moisture changes to generate locomotion. This approach has the potential to advance research in hygroscopic self-propelled mechanisms and promote further investigations into developing more complex kinematic mechanisms requiring articulated and multi-stage actuation for direct use in architecture or robotics.

A rising number of applications, including architecture, soft robotics, and medicine, are interested in developing flexible and hinge-free compliant systems based on plant motions [286–289]. For the creation of motile technical systems using biomimetic methods, Poppinga et al. [290] explored the principles behind plant motions and offered a succinct overview of them (see Fig. 12b). These bio-inspired compliant techniques included snap-through elastic instability actuation, modular aperture designs, edge growth-driven actuation, bending scale-like structures with functional bilayer setups, and origami-like curved-folding kinematic amplification. Pinecone architecture served as inspiration for the development of new structures employing 4D printing technology that are capable of multiphase movement sequences and compliant systems that respond to inputs. Although many adaptive systems that move without the usage of any operational energy have been inspired by plants, these systems are often developed and made in the shape of streamlined bilayers.

The asymmetrical distribution of movable plant structures has been imitated and Cheng et al. [291] proposed approaches for printing bio-inspired structures with compounding processes on the mesoscale utilising extrusion-based 3D printing. The technique is illustrated in Fig. 13a by applying the idea of a twining plant (Dioscorea bulbifera) to a self-tightening splint.


(a)
Syringe
Melted FA
Sprue gate
PI tube
Mold
Ni-Cr wire
Jig
(b)
PI tube
FA
Ni-Cr wire
A
B
C
FA structure
PI tube
FA
Ni-Cr wire
SMA wire
FA structure
PDMS
Connector
(I)
y
x
30 mm
(II)
(b)
Rigid SMP Segments
SMA Wire
Crimp Connection
Soft Layer
Resistive wire
Rigid SMP Layer
Resistive Wire
Soft Layer
SMA Wire
Actuator-1
A-A
Actuator-2
B-B
(I)
Hinge-1
SMA
U (mm)
$\theta_1$
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$\theta_3$
(II)
(c)
1
2
3
4
Thin film applicator
Stretcher
(I)
(II)
100
80
60
40
20
0
30
40
50
Relaxed
Actuated
Curvature, κ [1/m]
Prestretch, ε [%]
$1/\kappa_n$
$1/\kappa$
Relaxed
Actuated
(III)
(IV)

◂**Fig. 11** **a**. (I) The actuator's fabrication method is shown, along with examples of the built FA structure and shape-retention actuator. (II) The two-segment actuator is available in nine different configurations [268]. **b**. (I) Two main designs of composite actuators with two hinges, resistive wires put in the SMP segments of each hinge, and SMA wire inserted along the length of the actuator. (II) Results of actuator experiments and computations. The SMP segments of each hinge are heated by resistive wires, changing from a glassy state (blue) at normal temperature to a rubbery one (red) at high temperature. The SMA wire's actuated (blue) and unactuated (red) states are depicted by the colour of the inset. The coloured outlines show the displacement of the actuator in various setups [269]. **c**. (I) Fabrication procedure of soft actuator. (II) Images of the actuator in both its unactuated (on the left) and actuated (on the right) states (right). (III) Based on the quantity of pre-stretch applied to the top layer of thermally conducting elastomer tape, the actuator's curvature changes when it is relaxed (κn) and when it is triggered (κ). Additionally, the picture insets depict an optical image of the actuator in both a relaxed state (represented by an orange box) and an active state (shown in a green box). (IV) Several soft robotic testbeds, including a quadruped, robot inspired by caterpillars, and a rolling robot, employed extremely dynamic actuators [271] (color figure online)

D. bulbifera exhibits a squeezing force on its support to offer stability against gravity by the tensioning of its stem helix. In a wrist-forearm splint without external stimuli, the function of self-tightening is prototyped after the squeezing pressures of these bio-inspired motion mechanisms are assessed. By drawing inspiration from the multi-phase motion found in hygroscopic plant structures, Tahouni et al. [292] proposed a method for physically controlling the timing and sequence of shape change in 4D-printed hygromorphic structures. They were able to control the motion's timeline by adjusting the layers' porosity, water permeability, and thickness. The authors showed numerous prototypes, including a self-locking mechanism with a multi-step self-shaping and locking function and an aperture with overlapping pieces that finished their movement sequentially to avoid collision. These techniques, however, are not restricted to 3D or 4D printing processes. Recently, Luo et al. [293] created and produced self-drilling seed carriers using wood veneer, drawing inspiration from Erodium seeds (see Fig. 13b). Due to their hygromorphic bending or coiling actuators, these carriers exhibit great stiffness (4.9 GPa when dry and 1.3 GPa when wet) and enormous bending curvatures (1,854 $m^{-1}$). The carriers can transport payloads of varied sizes and substances, including biofertilizers and plant seeds as large as those of whitebark pine, and have an 80% drilling success rate on flat terrain because of their advantageous resting position. To inform the design and optimisation of the carriers, the researchers analysed experimental data and numerical simulations. This device has applications in energy harvesting, soft robotics, and sustainable structures and has the potential to increase the efficacy of aerial seeding.

The actuation capabilities and material qualities of materials are fundamentally at odds with one another, despite major research efforts to enhance the properties of WR materials and boost their actuation capabilities. This is because most materials have soft properties, and the softer the material, the more quickly the actuator can react, but the less weight it can support. On the other hand, if the material' s stiffness is increased, the reaction time shortens and soft actuators lose flexibility and safety. Therefore, one of the biggest challenges in the development of WR materials is striking a compromise between mechanical characteristics and actuation capabilities [294]. It is necessary to integrate WR-based smart actuators with sensors, controllers, and other mechanisms to complete tasks since they may function as either an actuator or detectors [295–297]. For this reason, actuators must be compatible with other functionalities. However, compatibility is hindered by material properties, energy supply, and working environment. Actuators are unable to support heavy loads because of their small size and soft material. Since they only need a little amount of deformation to complete jobs in particular application settings, they are frequently utilised as sensors, such as clever switches and smart drawstrings. Wet-sensitive actuators that are integrated with other devices must also have their energy needs addressed because they operate on humidity gradients rather than a power source. Since these actuators operate in humid conditions, integrated devices must be treated for anticorrosion, water tightness, and insulation to guarantee stable functioning after being installed.

## 6 Multi-Material Printing of Soft Actuators

The use of multi-material AM (MMAM) can decrease the time required for production and does not add any extra cost when manufacturing complex-shaped parts [298]. It also aids in reducing material waste and consumption [299, 300]. However, only a limited number of 3D printers available commercially can produce soft actuators using multiple materials. The efficiency of soft actuators may be increased, and there is room for study into ways to lower manufacturing and material costs in multi-material printing systems. It's important to find a balance between part quality and manufacturing efficiency like production rate. Using several materials or different compositions of the same material, MMAM may increase the usefulness and complexity of 3D/4D printed components [301]. As a result, unique, valuable SSAs with enhanced characteristics can be produced. MMAM may modify a component's characteristics for a variety of scales and uses [299, 302–304]. While elastomers and hydrogels are the least researched multi-materials in MMAM, they provide printing challenges owing to partial melting, problems with material feeding, buckling, high viscosity, and limited gelling temperature ranges [305]. Recent research, however, has demonstrated that a variety of soft materials that are

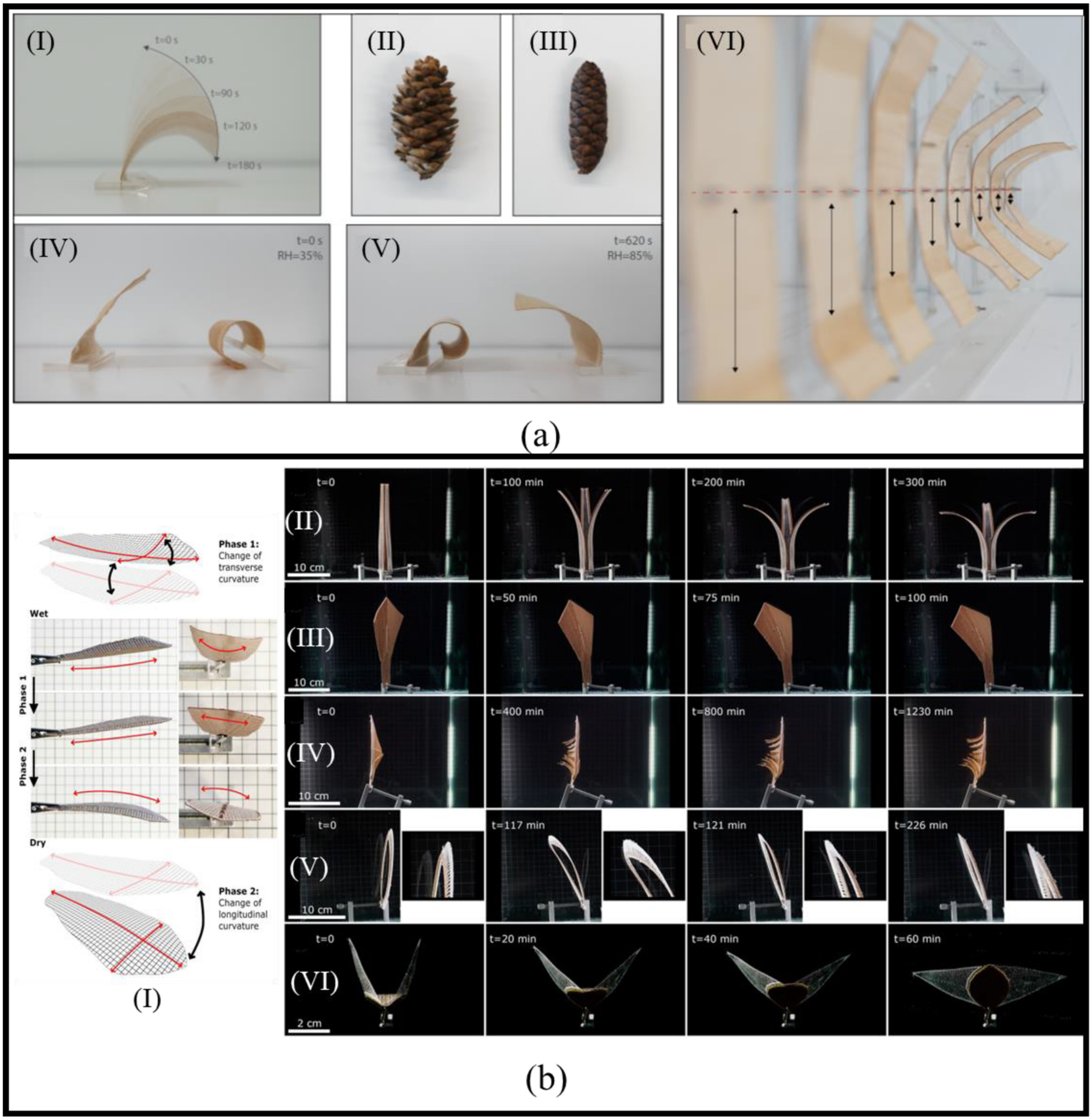


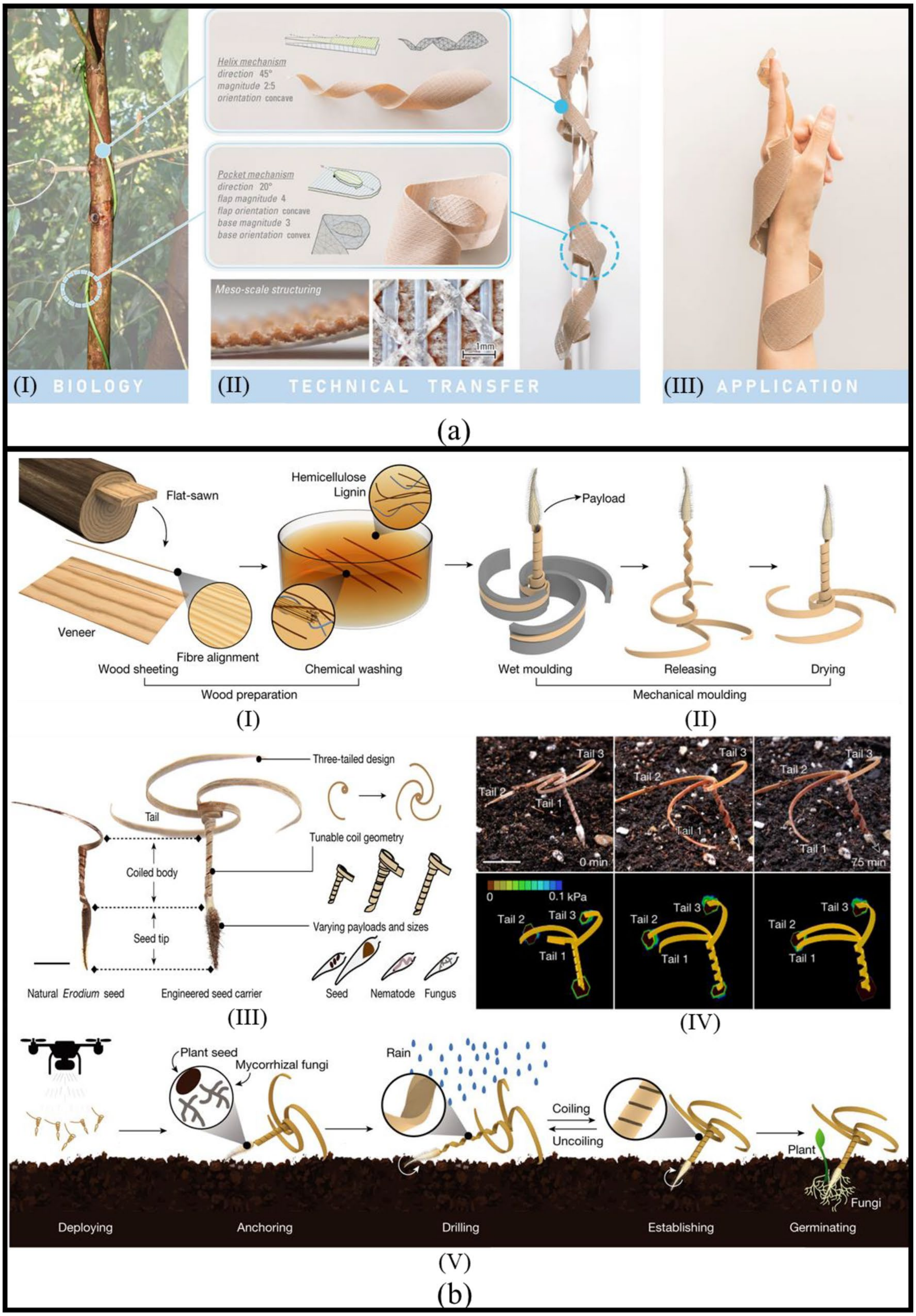
**Fig. 12** **a**. (I) Temporal evolution of hygroscopic bending in a bilayer of wood veneer and fibreglass, induced by variations in air humidity over time. (II) and (III) Hygroscopic bending in a pinecone scale triggered by an increase in air humidity over 25 min, from 10 to 85% relative humidity. (IV) and (V) Effect of active layer moisture level on bending direction: (Left) samples in both IV and V were fabricated at RH = 35%, while (right) samples in both IV and V were fabricated at RH = 85%. (VI) Effect of moisture introduction on targeted stamping location and bending degree at t = 45 min and RH = 85% [285]. **b**. (I) A synthetic seed scale created using 4D printing and modelled after the seed scale of the Bhutan pine (P. wallichiana) moves in two directions biaxially as it dries. The scale's transverse curvature changes during Phase 1, and then it bends lengthwise during Phase 2 as a result of a change in its longitudinal curvature. (II) Lily structure undergoes bending deformation via edge actuation. (III) A big pinecone seed size structure was found to have bi-directional bending deformation. (IV) Hygroscopic characteristics are used in a modular aperture construction with separately actuated sub-structures. (V) A flat, ring-like flytrap structure's snap-through behaviour with larger inlets exhibits curvature inversion between t = 117 min and t = 121 min. (VI) Kinematic amplifying via curved fold bending seen at the entrance of a constructed waterwheel. (In the rightmost photographs, the structures are completely wet since they were all immersed after being printed in dry, warm circumstances (21 °C, 18% RH, which allowed for total moisture absorption.)) [290]

excellent for soft actuators may be printed. One method to decrease material use is, for instance, direct silicone printing [306, 307].

As illustrated in Fig. 14a, Zhang et al. [308] also created a novel method for developing FRST (fast-responding, stiffness-tunable) soft actuators. The stiffness of the actuator might be raised by up to 120 times by including a layer of SMP into the completely printed actuator body while maintaining its flexibility and adaptability. The FRST actuator could finish a softening-stiffening cycle in only 32 s thanks to a printed Joule-heating circuit and fluidic cooling microchannel that allowed quick heating and cooling rates. To show the FRST actuator's high load capacity and form adaptivity, three of them were used to build a robotic gripper that could lift and grab items ranging in weight from less than 10 grammes to as much as 1.5 kilogrammes. Also, Zhang et al. [309] created structures that could be manipulated pneumatically to construct complicated 3D shapes with powerful mechanical characteristics utilising multi-material DLP 3D printing of SMPs (see Fig. 14b). The geographical distributions of SMPs are in charge of shaping the form change. Experiments have been carried out to print several structural balloons with complex established shapes, including a surface with the contour of a human face and a structure resembling a dog. This novel 4D printing method may be helpful in applications like biomedical devices, reconfigurable structures, and metamaterials because these structures also have strong mechanical rigidity and lightweight qualities.

Centrifugal multi-material (CM) 3D printing, a brand-new DLP-based 3D printing technique that can create large-volume, heterogeneous 3D objects with programmable composition, characteristics, and functionalities at the voxel scale, was also created by Cheng et al. [310] (see Fig. 15a). The CM 3D printing technology enables non-contact, high-efficiency multi-material switching without touch, in contrast to conventional multilateral switching techniques that need direct contact to remove the leftover resin. With a printing surface of up to 180 mm × 130 mm, the printer is now able to create heterogeneous 3D structures using a variety of materials, including hydrogels, functional polymers, and even ceramics. The CM 3D printing technique has shown to be a great tool for creating soft actuators. In terms of minimising material waste, while creating soft actuators with different materials, this process provides several benefits over more conventional techniques like casting or moulding. Casting or moulding techniques cannot be used to produce these outcomes without difficulty. Also, He et al. [311] created a DLP-based multi-material 3D printing capability that combines nonconductive materials with UV-curable ionic conductive elastomers (UV-ICE) (see Fig. 15b). This method made it possible to produce a variety of 3D flexible electronic devices, such as 4D ionic conductor-activated printing, flexible capacitive sensors with high sensitivity and a broad range of measured pressures, and resistive strain and force sensors. By joining ICEs with other polymers in 3D shapes, the suggested method enables the effective realisation of multifunctional flexible machinery and gadgets. However, the manufacture of soft actuators depends on the material. Reprocessable materials can reduce material waste in an appropriate manner [312]. They can be treated and remoulded several times without losing any of their original qualities, these polymers vary from conventional ones. These gadgets are perfect for use in soft robotic applications because of their special quality. The ability to easily customise these reprocessable thermoset soft actuators allows them to be moulded or printed into a variety of forms and sizes and calibrated to get the required result. As an illustration, a two-step polymerization technique has been created to produce 3D printing reprocessable thermosets (3DPRTs), which can be reshaped into a new shape, repaired by 3D printing fresh material on the damaged region, and recycled for future uses [313]. The novel methods offer an effective response to the environmental issues brought on by the expanding usage of 3D printing materials. However, this cannot be done on all materials due to the permanent covalent networks and they cannot be reshaped, repaired, or recycled. Nevertheless, these procedures enable the reduction of material usage and minimize waste, which could be advantageous for eco-friendly and sustainable flexible actuators.

Multi-material multi-nozzle 3D (MM3D) printing is a technique Skylar-Scott et al. [314] created that could produce soft voxelated matter with predetermined composition, function, and structure at the voxel size (see Fig. 16a). Their MM3D printheads could fluidly transition between up to eight different materials, making it possible to print intricate patterns with a volume that was close to the cube of the nozzle diameter. They used epoxy and silicone elastomer inks of different stiffnesses to make a Miura origami design and a soft robot that moves like a millipede. The variety of voxelated materials that might be designed and produced in intricate designs is substantially increased by this technique. While preserving the mechanical properties of a flexible actuator, this method is ideal for reducing material waste and consumption. Larson et al. [315] also introduced a brand-new technique known as rotational multi-material 3D printing (RM-3DP), which enables subvoxel control over the local orientation of azimuthally heterogeneous architected filaments. They have produced helical filaments with programmable helix angle, layer thickness, and interface area between multiple materials inside a certain cylindrical voxel by continuously spinning a multi-material nozzle with a controllable ratio of angular-to-translational velocity. Using this method, they were able to create artificial muscles that could contract and relax. These muscles were made of helical dielectric rubber actuators and hierarchical lattices, which


Helix mechanism
direction 45°
magnitude 2:5
orientation concave
Pocket mechanism
direction 20°
flap magnitude 4
flap orientation concave
base magnitude 3
base orientation convex
Meso-scale structuring
1mm
(I) BIOLOGY
(II) TECHNICAL TRANSFER
(III) APPLICATION
(a)
Flat-sawn
Veneer
Fibre alignment
Hemicellulose
Lignin
Payload
Wood sheeting
Chemical washing
Wood preparation
Wet moulding
Releasing
Drying
Mechanical moulding
(I)
(II)
Three-tailed design
Tail
Tunable coil geometry
Coiled body
Seed tip
Varying payloads and sizes
Natural Erodium seed
Engineered seed carrier
Seed
Nematode
Fungus
(III)
Tail 3
Tail 2
Tail 1
0 min
75 min
0
0.1 kPa
(IV)
Plant seed
Mycorrhizal fungi
Rain
Coiling
Uncoiling
Plant
Fungi
Deploying
Anchoring
Drilling
Establishing
Germinating
(V)
(b)

◂**Fig. 13** **a**. (I) Dioscorea bulbifera's biological properties and practical shape produce forces by twining around support and growing its stipules. (II) Computational design methods to transfer mechanism to bio-inspired motion mechanisms. (III) Combining and stacking multiple motion mechanisms to create a multifunctional 4D-printed splint [291]. **b**. (I) and (II) Creation of wood-based hygromorphic actuators with a large starting curvature: processing processes. (III) The creation of an autonomous self-drilling seeding carrier with a customised awn and specific payloads was motivated by E. guineense seed. (Scale bar represents 10 mm). (IV) Three-tailed seed carriers are captured in simulations and experiments during the first hydration cycle, which is brought on by precipitation. The body of tail 2 and the tip of tail 3 produce forces at first, then as the tails grow more hydrated, the tips of both tails 1 and 2 produce stronger forces. The contact pressure is shown by the colour bar, with values greater than 0.1 kPa. To help with contact region visibility, a little higher bond is inserted. (Scale bars represent 10 mm). (V) The three-tailed carrier is used to transfer mycorrhizal fungus as symbiotic biofertilizers together with vegetable seeds [293]

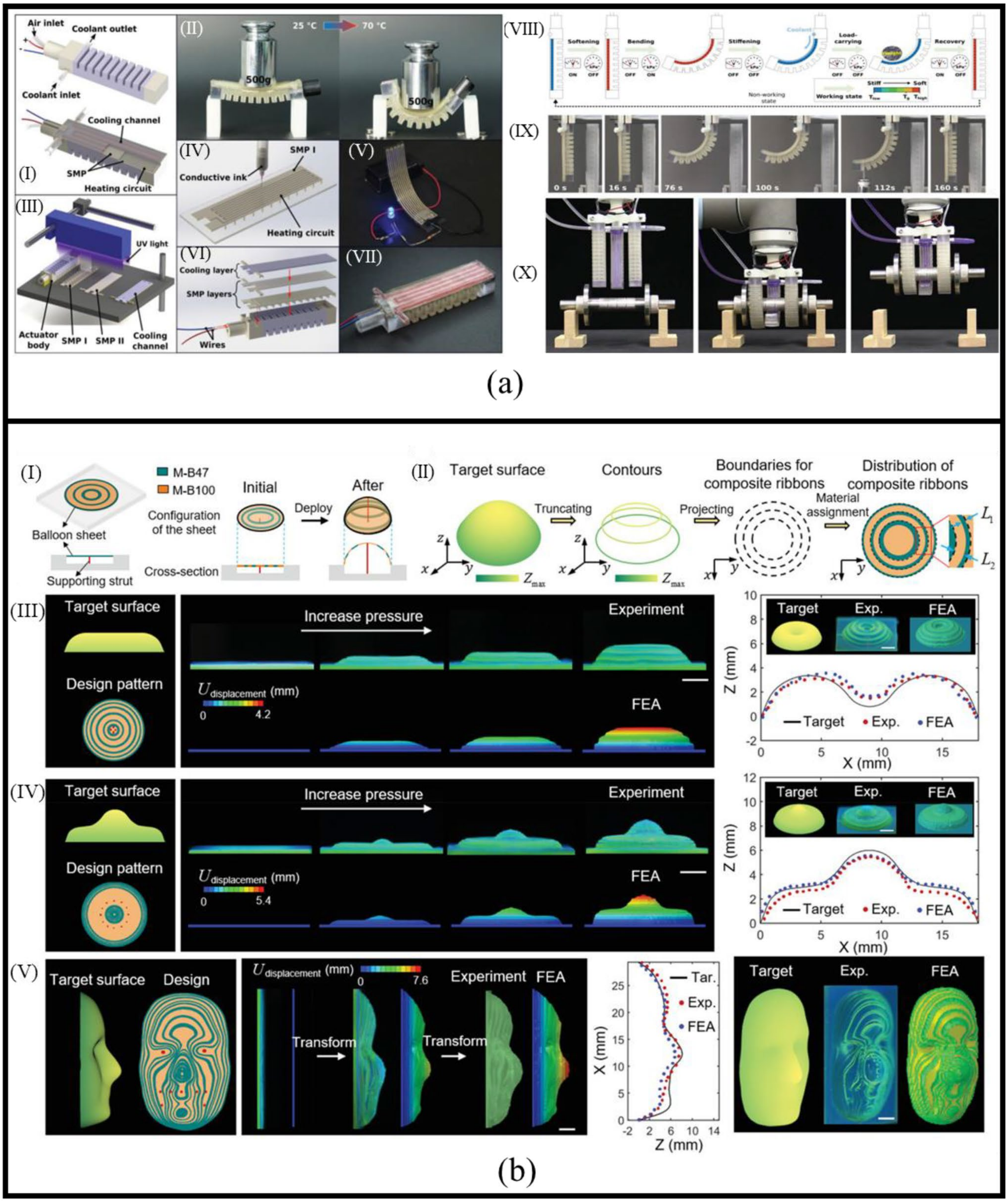
had stiff springs and helical struts that were architecturally designed. This additive manufacturing technology offers a fresh approach to manufacturing multifunctional, bioinspired, architectural materials.

Magnetic materials may also be used in a variety of sectors, such as soft robotics, actuators, metamaterials, and medicinal devices [316]. When exposed to a magnetic field, these materials may change shape quickly and reversibly and move dynamically [317]. Hard magnetic particles found in magnetic SMPs (M-SMPs) have demonstrated greater shape manipulation capabilities. They are capable of shape locking and reprogrammable, untethered, quick, and reversible shape alterations in a single material system [318]. To investigate the increased multimodal shape transformation and adjustable features of M-SMPs, Ma et al. [319] created a printing method (see Fig. 16b). Through coordinated thermal and magnetic actuation, they showed several deformation modes with different shape configurations. This method makes it possible to create active metamaterials with customizable physical characteristics, such as a change in the Poisson's ratio. The M-MSP metamaterials' multiphysics response allows them to switch between a variety of global mechanical behaviours, including growth, shrinkage, shear, and bending [320].

Meanwhile, traditional methods of creating synthetic morphing structures have struggled to balance the speed of shape change with geometric complexity. Using a 3D printing feedstock composed of PLA, thermoplastic polyurethane (TPU), and $Fe_3O_4$ particles, Liu et al. [321] created SMPs with strong mechanical characteristics and magneto-responsive behaviour. According to the findings, the 3D-printed material had a uniform distribution of magnetic particles throughout polymer mixes and showed strong tensile strength and modulus. Heat and magnetic fields might be used to trigger the printed actuators. Additionally, it possessed a high efficiency of heat generation by magnetic particles as seen by its outstanding form fix ratio, recovery ratio, and quick magnetic reaction within 40 s. The scientists created and printed intelligent structures, such as honeycomb and bionic flower-like forms, that could be programmed by an outside force and fully recovered under a contactless magnetic field. Three pedals with various $Fe_3O_4$ composites might be used to regulate the layer-by-layer restoration of the flower-bud structure.

The development of a novel method by Lalegani Dezaki et al. [322] that coupled magneto-electroactive SMP composite structures with FDM 4D printing technology allowed the construction of a variety of forms and shapes with a focus on sustainability (see Fig. 16c). These composite constructions had a short reaction time and may be remotely controlled by electricity, making them an effective choice. Low-cost 4D-printed SMPC structures might attain different stable forms and repeatedly switch between programmed temporary and permanent configurations by being remotely programmed at high temperatures. This allowed for the creation of many designs inside a single structure without wasting material. This strategy is predicated on an understanding of the magnetic response, SMPC physics, and FDM production principles. The shape morphing of magneto-electroactive SMPC structures is investigated by FDM printing of adaptive structures with 1D/2D-to-2D-to-3D shapeshifting. Characterization investigations are carried out to determine how to manage the structure with a low magnetic field. In industries like packing, this technology has the potential to lower material waste and boost productivity.

Although there have been significant advancements in MMAM soft actuators, there are still several areas that require further investigation. These actuators are typically soft and flexible, which means they possess multiple degrees of freedom. Therefore, more research is needed on the control aspect of MAMM soft actuators and their material properties. System identification, dynamics modelling, and creating precise models that accurately depict the large-deflection dynamics of such actuators are all areas that need more research. A viable study area may also focus on self-folding structures and automatic control features that prevent self-collision or self-blocking. The mechanical characteristics of 3D printed soft actuators can be improved by employing innovative biocompatible materials for high-resolution 3D printing, such as bio-gel materials and composite layers of various materials. Finally, the utilisation of 3D scanners may drastically cut down on the processing time for creating complex and atypical geometries like prosthetic fingers.


(I)
Air inlet
Coolant outlet
Coolant inlet
Cooling channel
SMP
Heating circuit
(II)
25 °C
70 °C
500g
(III)
UV light
Actuator body
SMP I
SMP II
Cooling channel
(IV)
SMP I
Conductive ink
Heating circuit
(V)
(VI)
Cooling layer
SMP layers
Wires
(VII)
(VIII)
Softening
ON OFF
Bending
OFF ON
Stiffening
OFF OFF
Coolant
Load-carrying
OFF OFF
Recovery
ON OFF
Non-working state
Working state
Stiff → Soft
$T_{low}$ $T_g$ $T_{high}$
(IX)
0 s
16 s
76 s
100 s
112s
160 s
(X)
(a)
(I)
M-B47
M-B100
Balloon sheet
Supporting strut
Configuration of the sheet
Initial
Deploy
After
Cross-section
(II)
Target surface
Truncating
Contours
Projecting
Boundaries for composite ribbons
Material assignment
Distribution of composite ribbons
$L_1$
$L_2$
$Z_{max}$
x y z
(III)
Target surface
Design pattern
Increase pressure
Experiment
FEA
$U_{displacement}$ (mm)
0 4.2
Target Exp. FEA
Z (mm)
X (mm)
Target Exp. FEA
-2 0 2 4 6 8 10
0 5 10 15
(IV)
Target surface
Design pattern
Increase pressure
Experiment
FEA
$U_{displacement}$ (mm)
0 5.4
Target Exp. FEA
Z (mm)
X (mm)
0 2 4 6 8 10 12
0 5 10 15
Target Exp. FEA
(V)
Target surface
Design
$U_{displacement}$ (mm)
0 7.6
Experiment FEA
Transform
Transform
Tar.
Exp.
FEA
X (mm)
0 5 10 15 20 25
Z (mm)
-2 2 6 10 14
Target
Exp.
FEA
(b)

◂**Fig. 14** **a**. (I) A stiffness-tunable SMP layer, a Joule-heating circuit, and a fluidic cooling microchannel are combined to make the FRST soft actuator. (II) With a temperature range of 25 to 70 °C, the FRST soft actuator can convert between stiff and soft states. (III) The procedure for utilising a polyjet multi-material 3D printer to make the four separate components of the FRST soft actuator. (IV) The stretchable Joule-heating device is created using DIW on SMP. (V) The printed Joule-heating circuit's adaptability. (VI) The FRST actuator is created by assembling its four separate components. (VII) A completed FRST soft actuator [308]. **b**. This passage describes a method of 4D printing using pneumatic pressure to create balloon structures with specific surface contours. (I) This illustration demonstrates a cuboid-shaped device that, when air is pushed into it, transforms from a flat balloon sheet into a 3D shape. The balloon sheet is supported by a flexible strut and is constructed of two different types of material, M-B47 and M-B100. (II) The method used in balloon sheet design is to arrange the components so that the blown form would match the intended target surface. (III) A balloon structure that has been printed with a doughnut-shaped surface. The goal surface and the design pattern utilised to accomplish it are displayed in the first column. The experimental data and FEM simulations are displayed in the second and third columns, respectively. For reference, a 5 mm scale bar is included. (IV) An artificial volcano appears on the surface of a printed balloon structure. A plot that contrasts the target shape's profile with simulations and experimental findings may be found in the third column of the image. There is a reference scale bar with a 5 mm width. (V) A balloon structure that has been printed with a human face-shaped surface. Beginning with the target surface, the design pattern, experimental findings, and simulations are shown in the image in left-to-right order. There is a 3 mm scale bar present [309]

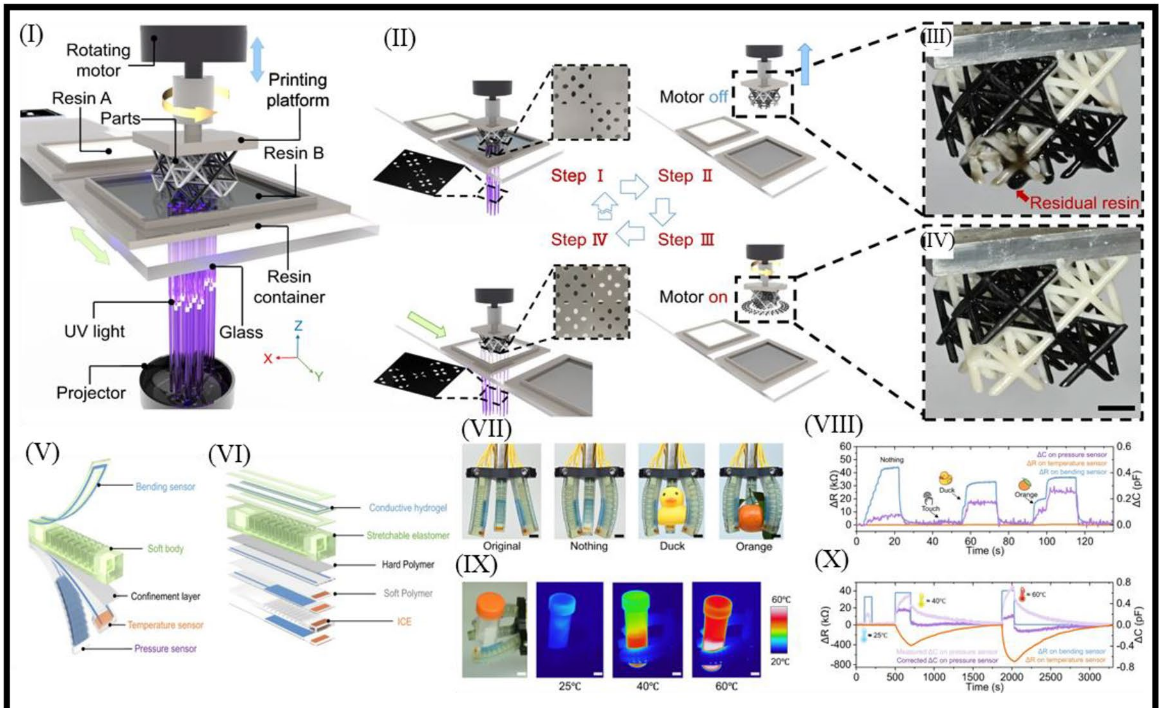
## 7 Discussion

The movement of robots requires effective communication between the robot and its surroundings. In the past, robots have relied on stiff components and precise controls to generate force and control motion. However, soft robots are now challenging this conventional approach by utilizing flexible bodies and creating new strategies for robotic movement. This article highlights some of the techniques used to reduce the amount of materials and energy used in soft actuators, which can range in size from micrometres to centimetres and beyond. The latest and most significant findings were presented, emphasizing the fundamental concepts of soft actuators with low energy consumption and the ability to respond to multiple stimuli. A broad range of materials and approaches were examined to develop SSAs. The discussed soft actuators were constructed from polymers, fluids, papers, biological substances, or combinations of these materials. Each material had its strengths and weaknesses, and they showed promise for specific applications, such as medical or manufacturing industries.

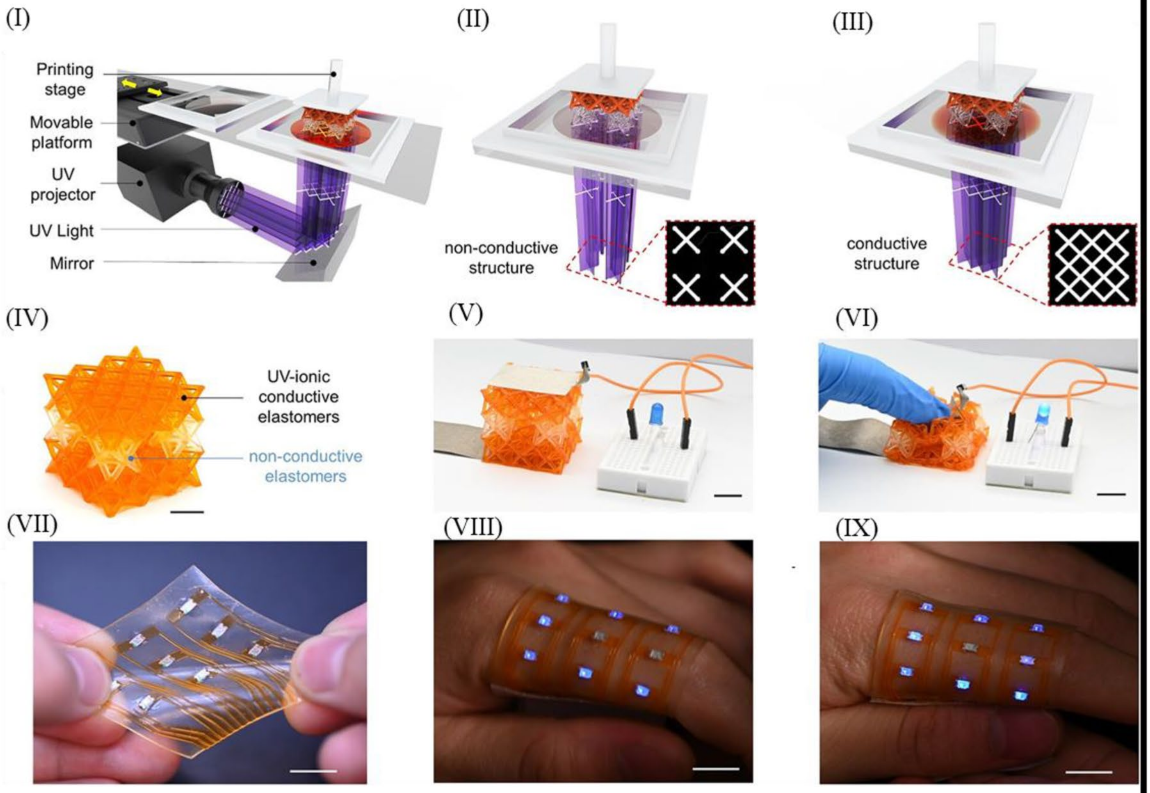
Up until now, the primary way of activating soft actuators has been through different stimuli based on their characteristics. However, many soft actuators still require a rigid energy source and continuous control systems to generate the necessary forces for their intended movements [323]. There is potential for multi-responsive soft actuators that react to external stimuli like light, temperature, or electric fields to become wireless and sustainable, but there are still obstacles that need to be resolved such as limited scalability, sensitivity to environmental factors, and limited force output. Multi-responsive soft actuators represent a revolutionary new technology that has the potential to revolutionize numerous fields, including healthcare and robotics. These highly adaptable actuators offer greater flexibility than their mono-responsive counterparts, as they can recognize and respond to a wider variety of stimuli. Additionally, Soft actuators possess advanced features such as shape locking that can help in decreasing energy usage. Shape locking technique enables the actuator to sustain its form without requiring extra energy, thereby enhancing the efficiency of the actuator and lowering its overall energy consumption.

They improve efficiency by reducing energy consumption and optimizing performance. As an example, the process of shape locking allows these actuators to maintain their shape without the need for additional energy, which can improve their efficiency and decrease overall energy consumption. By utilizing shape locking, soft actuators can save energy and hold their shape for a longer period. For example, a soft robotic gripper that uses shape locking to maintain its grasp on an object can hold onto it without consuming energy to keep it closed. This can significantly reduce the energy consumption of the gripper and prolong its lifespan [324]. In terms of sustainability, these soft actuators have numerous advantages, including their ability to adapt to changing environments, their energy efficiency, and their use of smart materials that minimize waste during production. However, the production of these devices still requires the use of certain resources and energy, which can have negative environmental impacts. To ensure that the benefits of these actuators are not outweighed by their environmental costs, it is critical to consider their entire life cycle, including disposal and opportunities for recycling or reuse [325].

Moreover, WR materials that draw inspiration from biological systems have significant potential in several fields, including energy harvesting, soft robotics, medicine, and architecture. They possess a unique ability to volumetrically expand, or contract based on changes in environmental humidity, allowing them to utilize humidity gradients and evaporation phenomena to perform a range of functions. Furthermore, these materials can be leveraged to develop humidity energy, which is critical in addressing global energy challenges and promoting sustainable development and circular economy. These materials depend on the contraction and relaxation of fibres or cellulose arrangements to move across the soil surface and reach an optimal position for germination [326]. These actuators offer several advantages over conventional actuators. They use


(I)
Rotating motor
Printing platform
Resin A
Parts
Resin B
Resin container
UV light
Glass
Projector
Z
X
Y
(II)
Motor off
Step Ⅰ
Step Ⅱ
Step Ⅳ
Step Ⅲ
Motor on
(III)
Residual resin
(IV)
(V)
Bending sensor
Soft body
Confinement layer
Temperature sensor
Pressure sensor
(VI)
Conductive hydrogel
Stretchable elastomer
Hard Polymer
Soft Polymer
ICE
(VII)
Original
Nothing
Duck
Orange
(VIII)
ΔR (kΩ)
ΔC (pF)
Time (s)
Nothing
Touch
Duck
Orange
ΔC on pressure sensor
ΔR on temperature sensor
ΔR on bending sensor
(IX)
25°C
40°C
60°C
60°C
20°C
(X)
ΔR (kΩ)
ΔC (pF)
Time (s)
25°C
40°C
60°C
Measured ΔC on pressure sensor
Corrected ΔC on pressure sensor
ΔR on bending sensor
ΔR on temperature sensor

(a)


(I)
Printing stage
Movable platform
UV projector
UV Light
Mirror
(II)
non-conductive structure
(III)
conductive structure
(IV)
UV-ionic conductive elastomers
non-conductive elastomers
(V)
(VI)
(VII)
(VIII)
(IX)

(b)

◀**Fig. 15** **a**. (I) This picture shows how the CM 3D printing technology works. (II) The procedures for 3D printing with many materials are presented. (III) After being taken out of the black resin, residual resin might adhere to printed structures. (IV) The image demonstrates how centrifugal force is used to remove the residual resin. A scale bar of 10 mm is included in images (III) and (IV). (V) The SPA has multiple sensors. (VI) The components that make up the various portions of the SPA. (VII) Images of a soft robotic gripper that can grasp various items. (VIII) The three sensors' readouts when the gripper in (VII) catches items. (IX) Pictures of a soft robotic gripper gripping various-temperature things. (X) The three sensors' readouts when the gripper in (IX) catches items. A scale bar of 10 mm is included in images (VII) and (IX) [310]. **b**. (I) An example of a multi-material 3D printing system based on DLP that was utilised to create UV-ICEs from nonconductive elastomers. (II) and (III) The procedures used to print nonconductive elastomer structures with UV-ICE. (IV) Displayed is an octet truss lattice structure that was printed using nonconductive elastomer and UV-ICE. This picture features a 10 mm scale bar. (V) and (VI) Before-and-after images of an octet truss lattice construction that has been compressed. In both photos, a scale bar with a 10 mm width is seen. (VII) This graphic shows a stretchy multi-material 3D printing circuit with a patch LED. A 10 mm scale bar is used. (VIII) and (IX) The picture displays a working LED array that has been decorated with various designs and wrapped around a human finger. Both pictures use a 10 mm scale bar [311]

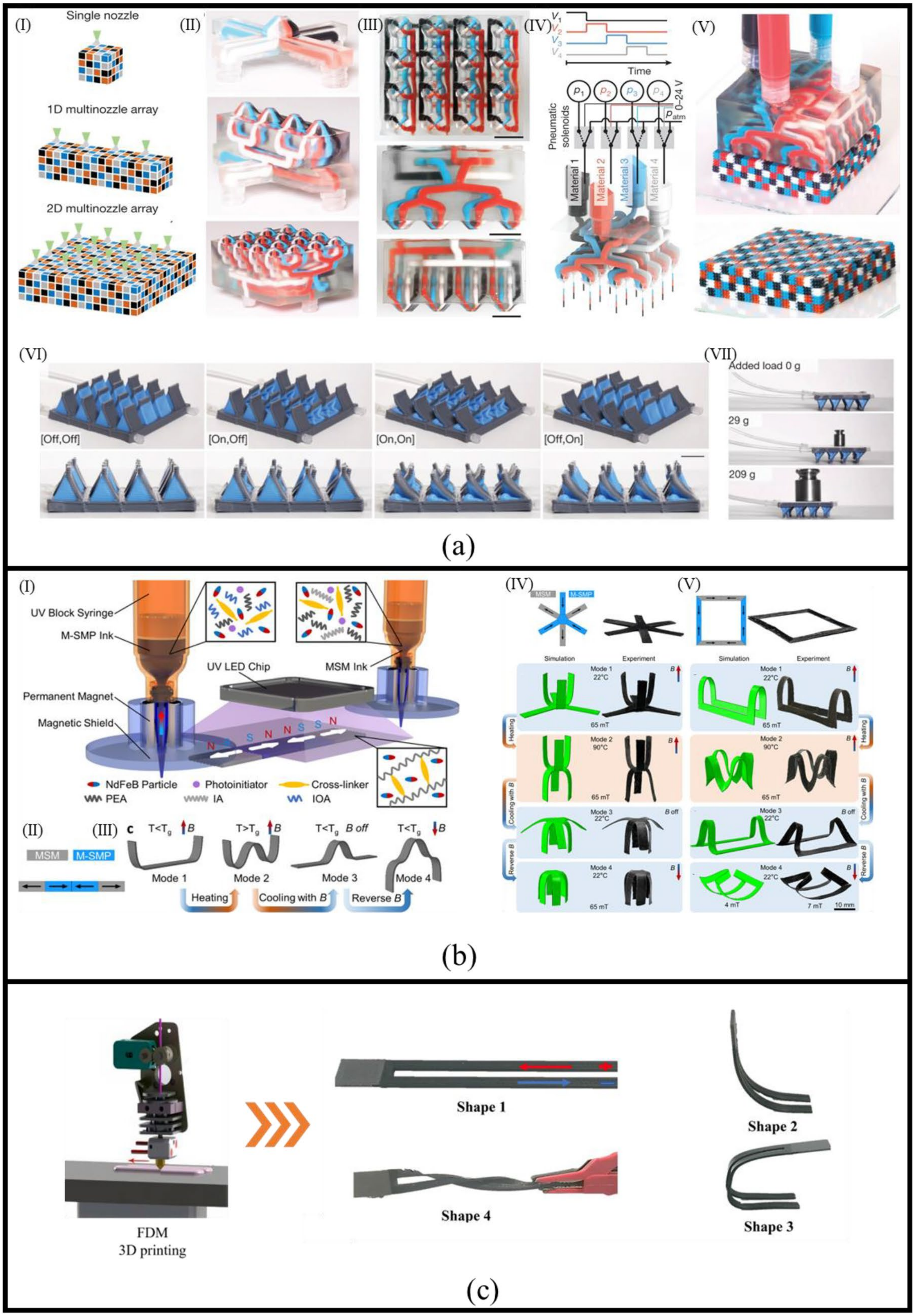
water or humidity as their primary energy source, which is readily available and renewable, making them a sustainable and environmentally friendly option, and require minimal energy to operate as they rely on ambient humidity changes rather than external power sources to move. Additionally, their adaptability to their environment, biocompatibility, and responsiveness to humidity changes make them versatile for various applications. There is still a basic problem, though, in that the actuation ability and material characteristics of WR materials are at odds. This is true despite major research efforts to improve material properties and boost actuation ability. Because the majority of WR materials are intrinsically brittle, they cannot support severe weights yet the actuator reacts swiftly. The flexibility and safety of soft actuators will be impacted by increasing the stiffness of WR materials, which will also speed up reaction times. As a result, a significant challenge in the development of WR materials is striking a compromise between mechanical characteristics and actuation abilities. Also, there are still some challenges to overcome, as external humidity gradients are complex and constantly changing, making it challenging to precisely control actuators, including their direction and distance of movement. Therefore, a new approach to stably control humidity gradients without consuming additional energy is required, as neither of the current control methods is perfect.

Furthermore, MMAM's realisation will be a pivotal moment for soft actuators. By modifying the thermal, electrical, mechanical, optical, and multifunctional aspects of components, MMAM opens up new possibilities for the design, complexity, and usefulness of soft actuators with better qualities. Potentially, MMAM may be utilised in soft actuators to combine the benefits of many materials, enabling the quick creation of high-quality structures with unique features. When compared to 3D printing with a single material, MMAM printing is more ecologically friendly, capable of producing cutting-edge 4D soft structures, and yields actuators that are stronger and more durable. MMAM may minimise waste materials and offer sustainability for soft actuators, which is important for production since it reduces material consumption and wastage. Alternative materials including elastomers and hydrogels have not been extensively researched, whereas research has mostly concentrated on specific polymer and metal-based multi-materials. In other instances, researchers have taken use of the drawbacks of connecting materials to introduce flaws into components because the advantages of using various materials in MMAM may not always provide acceptable results. Due to the diverse materials' variances in qualities like heat conductivity, melting temperatures, and expansion coefficients, regulating the additive manufacturing process can be difficult. Before MMAM processing, non-uniform qualities in intended multi-material components require work in material design, characterisation, chemical composition, and manufacturing restrictions. Other difficulties with MMAM include limited production throughput, poor scalability and surface quality, insufficient interfacial bonding, and significant cross-contamination. The lack of design rules on material compatibility and multi-material 3D printability makes it extremely difficult for AM procedures intended for single-material components to be used for MM components.

Although the techniques and features mentioned earlier are widely utilized to create SSAs, it is essential to acknowledge that there are other approaches to accomplish this as well. Researchers have delved into the use of biodegradable and recyclable materials in making soft actuators, while others have explored new manufacturing methods like 3D printing or microfabrication. Moreover, advances in materials science and engineering have led to the development of novel materials that provide improved sustainability and functionality for soft actuator applications. Thus, it is evident that there are numerous techniques and features to generate SSAs, and researchers should continue to investigate these options to propel the field forward.

## 8 Conclusion

The development of lightweight and flexible robots that primarily use renewable, environmentally friendly, and recyclable parts has increased in tandem with the movement towards SSAs. These developments help soft robotics in a variety of ways, including lowering weight, material, and energy requirements, encouraging autonomous operation, enabling in vivo deployment, and removing waste problems.


(I)
Single nozzle
1D multinozzle array
2D multinozzle array
(II)
(III)
(IV)
$V_1$
$V_2$
$V_3$
$V_4$
Time
$p_1$
$p_2$
$p_3$
$p_4$
0–24 V
$p_{atm}$
Pneumatic solenoids
Material 1
Material 2
Material 3
Material 4
(V)
(VI)
[Off,Off]
[On,Off]
[On,On]
[Off,On]
(VII)
Added load 0 g
29 g
209 g
(a)
(I)
UV Block Syringe
M-SMP Ink
Permanent Magnet
Magnetic Shield
UV LED Chip
MSM Ink
N S N S N S N
NdFeB Particle
Photoinitiator
Cross-linker
PEA
IA
IOA
(II)
MSM
M-SMP
(III)
c
T<Tg B
T>Tg B
T<Tg B off
T<Tg B
Mode 1
Mode 2
Mode 3
Mode 4
Heating
Cooling with B
Reverse B
(IV)
MSM
M-SMP
Simulation
Experiment
Mode 1 22°C
65 mT
Mode 2 90°C
65 mT
Mode 3 22°C
B off
Mode 4 22°C
65 mT
Heating
Cooling with B
Reverse B
(V)
Simulation
Experiment
Mode 1 22°C
65 mT
Mode 2 90°C
65 mT
Mode 3 22°C
B off
Mode 4 22°C
4 mT
7 mT
10 mm
(b)
FDM
3D printing
Shape 1
Shape 2
Shape 3
Shape 4
(c)

◀**Fig. 16** **a**. (I) The voxelated designs were printed utilising the 1D and 2D MM3D printheads in addition to a single nozzle (0D) (top, centre, and bottom). (II) Pictures depict the equivalent 0D, 1D, and 2D four-material MM3D printheads. (III) Images depict a 4–4 nozzle, four-material, 2D MM3D printer from the top (top) and side (middle and bottom). (IV) When the MM3D printer is in use, patm stands for atmospheric pressure, and V1–V4 indicates the voltage waveforms regulating the extrusion pressures p1–p4 for materials 1–4. (V) By employing a 4×4 nozzle, four-material, 2D printhead for MM3D printing, the voxelated material is created. Scale bars are 10 mm in width. (VI) A 4 by 1 two-material MM3D printer with several actuation states was used to MM3D print a soft robotic millipede walker. (VII) The soft-robotic millipede's walking speed was evaluated with its weight [314]. **b**. (I) The system involves the use of magnetic particles in the ink, which is then deposited using DIW to create multi-material structures. (II) A one-dimensional stripe is created with four segments, each containing different material compositions and magnetic orientations. (III) By controlling the temperature and magnetic field, the stripe can undergo four different deformation modes through cooperative magnetization and SMEs. (IV) The asterisk design was analysed with alternating material distribution and magnetization directions. (V) The inward-pointing magnetization direction was studied using a square frame design [319]. **c** FDM multi-material printing of magnetic and conductive PLA to achieve various shapes and configurations [322]

Materials scientists are focused on developing sustainable materials that can perform at a high level while keeping production costs low, which will enable these materials to be used in state-of-the-art prototypes. Research goals include creating highly stretchable yet biodegradable actuators that are produced using eco-friendly fabrication methods like MMAM. However, fully integrating these components into autonomous robots presents significant challenges and requires the rethinking of energy consumption and their design. Reduced complexity, self-healing, or biodegradable component designs are advantageous for ideas like repair, disassembly, reuse, and refabrication. Future inventions must include sustainability, which will enable a wide range of potential uses in many ecological niches. In the end, low-energy manufacture of technological items and easier recycling processes will be made possible by renewable, affordable, and conveniently accessible resources. Robotics will play a significant part in this endeavour, but more research is required to close the gap to high-performance solutions or offer whole new routes for sustainable technological development.

**Data Availability** The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare no conflict of interest.

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