Frontiers of Information Technology & Electronic Engineering
www.jzus.zju.edu.cn; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

***Review:***

# Design of plant-inspired shape-changing interfaces: a review*

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Received Feb. 25, 2025; Revision accepted July 14, 2025; Crosschecked Aug. 20, 2025

**Abstract:** Shape-changing interfaces use physical changes of shape as input or output to convey information, and interact with users. Plants are natural shape-changing interfaces, expert in adjusting their shape or modality to adapt to the environment. In this paper, plant-derived natural shape-changing phenomena are systematically analyzed. Then, several corresponding plant-inspired design strategies for shape-changing interfaces are summarized with recent advancements including material selections and syntheses, fabrication methods, and actuating mechanisms. Practical applications across diverse domains aim to prove the advantages and potential of plant-inspired shape-changing interfaces in agriculture, healthcare, architecture, robotics, etc. Furthermore, the opportunities and challenges are also discussed, such as design thinking in interdisciplinary tasks, dynamic behavior and control principles, novel materials and processes, application scenario and functionality matching, and large-scale application requirements. This paper is expected to inspire in-depth research on plant-inspired shape-changing interfaces.

**Key words:** Shape-changing interfaces; Tangible interfaces; Botanical bionics; Human–computer interaction; Smart materials
https://doi.org/10.1631/FITEE.2500118 **CLC number:** TP391.9; TB17

## 1 Introduction

Interfaces can convey information and interact with users. Common interfaces include graphic interfaces (Martinez, 2011), human–computer interfaces (Hartson and Hix, 1989), and tangible interfaces (Ishii and Ullmer, 1997). Shape-changing interfaces are tangible and interactive devices, surfaces, or spaces, and use physical change of shape as input or output (Sturdee and Alexander, 2019). They can always be self-actuated or user-actuated to convey information, meaning, or effect (Alexander et al., 2018). In comparison to conventional interfaces, shape-changing interfaces enable users to physically manipulate interfaces with their shape and materiality changing, enhancing the interaction and enriching the interface functions.

In nature, there are kinds of efficient, flexible, and multi-functional shape-changing intelligent plant systems. For example, pine cone scales open and close automatically in response to environmental humidity (Harlow et al., 1964), and the leaves of the Venus flytrap snap together in a fraction of a second to capture insects (Forterre et al., 2005). Plants are expert in adjusting their shape or modality to adapt to the environment through their physiological features. Researchers have seen the significant advantages of these phenomena of plants, and

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* Project supported by the National Natural Science Foundation of China (No. T2422021)
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kept mimicking them to design shape-changing interfaces with high adaptability, sustainability, and adjustability. The development of material science, advanced manufacturing, and information science provides more and more solutions for mimicking these smart plants. For example, four-dimensional (4D) printing techniques with anisotropic materials are used to make scale and flap structures with shape-changing ability inspired by a pine cone (Correa et al., 2020). Pneumatic actuators with bistable structures are typically used to mimic the mechanical instabilities of plants to realize the shape-changing (Zhang Z et al., 2022). The inspirations from intelligent plants benefit people in various fields such as agriculture (Luo et al., 2023), medical rehabilitation (Cheng et al., 2021), architecture (Zhan et al., 2023), and robotics (del Dottore et al., 2024).

Although nature provides an inexhaustible source of inspiration for bioinspired shape-changing technologies, persistent challenges remain in the process of effectively integrating biomimetic principles of plants into the development of shape-changing interfaces (Alexander et al., 2018). The transition from bioinspired to practical interfaces requires rethinking design frameworks. At the fabrication level, proper material selection, precise manufacture, and sustainable energy integration remain crucial for real-world viability. Furthermore, as these interfaces scale expand into broader application domains, issues concerning functionality, reliability, and ethical compliance become increasingly prominent, making the formulation of corresponding strategies crucial.

With increasing attention being paid to shape-changing interfaces across multiple fields, more and more researchers have tried to summarize systematic methods and theories from them. Rasmussen et al. (2012) first analyzed the progress and key questions for shape-changing interfaces in the early developing period. To realize more types of shape-changing behaviors and functions, plant mechanisms have been studied as inspirations for the design of interfaces. Li SY and Wang (2017) provided a brief overview of the actuation strategies and physiological features associated with plant movements and then a correspondingly comprehensive survey of the plant-inspired morphing and actuation systems. Furthermore, Ren et al. (2021) proposed an alternative categorization of morphing and actuation mechanisms of plants, while they mainly focused on soft actuation structural designs with the assistance of 4D printing. Recently, although more reviews about plant-inspired shape-changing interfaces have emerged, most of them only concentrate on one specific dimension, including plant organs such as leaves (Yu et al., 2023), interface types such as soft systems (Rabaux and Jérôme, 2025), application fields such as robotics (Roh et al., 2024), and sustainable technologies (Wijerathne et al., 2025). Therefore, this review aims to provide a systematic analysis of the latest plant-inspired shape-changing interface design from the principles of learning to fabrication methods, and application scenarios. Besides, we intend to summarize the challenges and provide possible solutions for researchers.

Drawing on previous studies of plant morphing behaviors (Li SY and Wang, 2017; Ren et al., 2021), this review establishes a coherent and transferable framework for bioinspired interface design. We systematically trace the pathway from biological shape-changing behaviors to structural mechanisms, and redesign strategies for applications, moving beyond comparative analyses to propose a standardized design methodology for bioinspired interface development (Fig. 1). Although animals can also exhibit intelligent behaviors that change with the environment, they are more based on their active regulation, which is usually mimicked to be applied for the actuation of intelligent machines. On the other hand, plant shape-changing behaviors are caused by passive structural–physiological changes driven by the environment, and are more applicable to adaptive shape-changing regulation of static interfaces under specific conditions. Therefore, we choose plants as the main bionic targets. We introduce the shape-changing mechanisms from three dimensions, including principles, stimuli, and behaviors to state how researchers convert them into design strategies correspondingly. Specifically, we propose a further analysis of the shape-changing principles by classifying them into micro tiers. For example, we divide the cell organization features into three types: cellular volume changes, cell wall thickness differences, and cellular origami-like structure. We accordingly select hundreds of papers on shape-changing interfaces with plant-inspired principles from 2010 to 2025 across diverse domains, and summarize recent advancements in plant-inspired shape-changing interfaces, including material selections and syntheses,

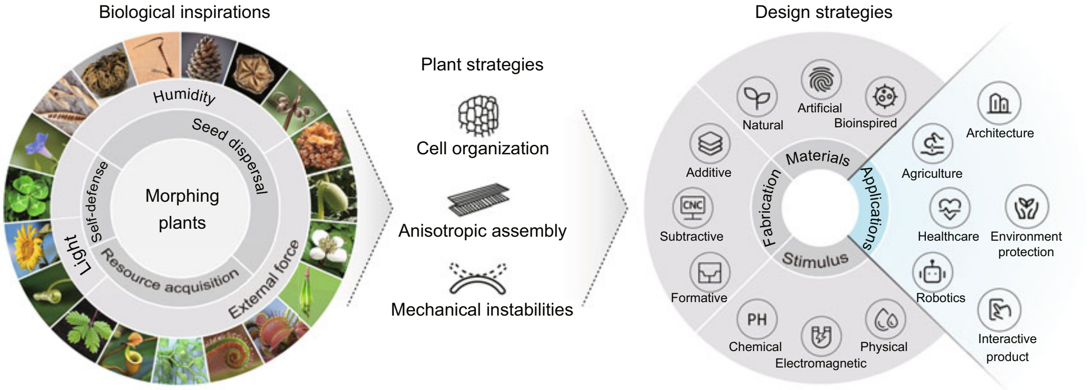


**Fig. 1 A bioinspired design framework. Biological inspirations are derived from morphing plants and their adaptive strategies (cell organization, anisotropic assembly, and mechanical instabilities) to environmental stimuli (humidity/light/external force). The primary purposes of these plant deformations include self-defense, resource acquisition, and seed dispersal. Design strategies are categorized into material systems (natural/artificial/bioinspired), fabrication methods (additive/subtractive/formative), and stimuli (physical/chemical/electromagnetic). Applications span agriculture, healthcare, architecture, robotics, environmental protection, and interactive product**

fabrication methods, and actuating mechanisms. A series of practical applications across diverse domains are displayed to prove the advantages and potential of plant-inspired shape-changing interfaces. Furthermore, this study provides a critical analysis of emerging opportunities and persistent challenges in current research paradigms, offering theoretical and technical frameworks for future work.

## 2 Shape-changing mechanisms of plants

Throughout evolution, plants have developed a range of sophisticated shape-changing behaviors to adapt to their environment, obtain resources, defend against external threats, and ensure the dispersal of their offspring (Fig. 1). These behaviors are the results of natural selection, and have long fascinated scientists. Nowadays, they have become a hot topic in interdisciplinary research. This chapter explores the structural principles and stimulus mechanisms behind plant shape-changing and the diverse behaviors that emerge from their interplay, providing inspiration and theoretical support for bioinspired shape-changing interface design.

### 2.1 Shape-changing behaviors

Plants exhibit diverse and efficient deformable behaviors, driven by their inherent structural design and external conditions. These behaviors can be categorized into linear, planar, and spatial movements, each offering different gradients in energy efficiency and functional complexity: linear for directional driving, planar for two-dimensional (2D) regulation, and spatial for adapting to complex environments. This section will systematically analyze the characteristics and mechanisms of behaviors in each dimension, providing a theoretical framework for multidimensional biomimetic design.

#### 2.1.1 Linear behaviors

Linear behaviors involve irreversible movement along a single axis, primarily driven by directional cell growth or the release of internal pressure. Phototropism and gravitropism are typical examples of linear growth behaviors. Phototropism is guided by auxin gradients, which direct the stem to extend at a rate of 5–20 mm/h (Wang QQ et al., 2022). Gravitropism relies on the sedimentation of statoliths in root cap cells to perceive the direction of gravity (Chen et al., 2023). Directional pressure release, exemplified by *Ecballium*, occurs when the fruit detaches from the stalk, instantly releasing the internal mucilaginous fluid pressure and the elastic potential energy stored in the pericarp, thereby enabling high-speed seed ejection (Box et al., 2024). Compared to planar or spatial behaviors, this uniaxial movement offers a high energy conversion efficiency but limited movement dimensions, inspiring fields such as pipe robots and polyjet three-dimensional (3D) printing.

### 2.1.2 Planar behaviors

Planar behaviors involve deformation within a 2D area, mainly including modes such as bending, curling, and catapult ejection. *Mimosa pudica* protects itself through thigmonastic, which is touch-sensitive folding (Volkov et al., 2010); *Drosera* (sundew) prevents prey from escaping through the curling of its tentacles (Bopp and Weber, 1981). The Canadian blackberry (Edwards et al., 2005) uses a projectile mechanism to launch pollen into the air. Planar movements expand the range of responses to environmental factors, inspiring innovations in soft grippers, artificial muscles, and bistable trigger switches.

### 2.1.3 Spatial behaviors

Spatial behavior is manifested as complex 3D deformation, mainly including modes such as volume mutation, coil and uncoil movements, umbrella-like opening and closing, snapping-through, and curling, followed by flattening. The Bladderwort rapidly sucks in microorganisms through the sudden volume contraction of its bladder; the seeds of *Erodium* are drilled into the soil by the 3D helical movement of their awns; dandelions control the timing of landing through the opening and closing of their pappus; morning glories protect their pollen by closing their corolla; *Selaginella lepidophylla* completes its revival by unfolding from a spherical shape to a flat one. These behaviors provide key technological pathways for self-burying robots, adaptive building skins, and deployable solar panels.

These hierarchical characteristics offer a modular strategy for biomimetic design: linear units achieve basic functions, planar units construct sensing networks, and spatial units accomplish complex tasks.

## 2.2 Shape-changing principles

### 2.2.1 Physiological features

Cell organization: local shape-changing in plants arises from mechanical differences between different cells or tissues. At the cellular level, these differences are mainly driven by the following three mechanisms (Fig. 2):

1. Cellular volume changes: regulated by the osmotic pressure of living cells, these changes lead to uneven volume fluctuations in specific regions, driving material migration and overall shape-changing. For example, in leguminous plants (such as clover), the pulvini (swollen bases of leaf stalks) facilitate the horizontal expansion of leaves during the day and their relative vertical closure at night (Bai et al., 2022) (Fig. 3a). This shape-changing results from asymmetric volume changes in the pulvinus's motor cells (extension and contraction cells), causing the pulvini to bend and thereby driving the opening and closing of the leaves.

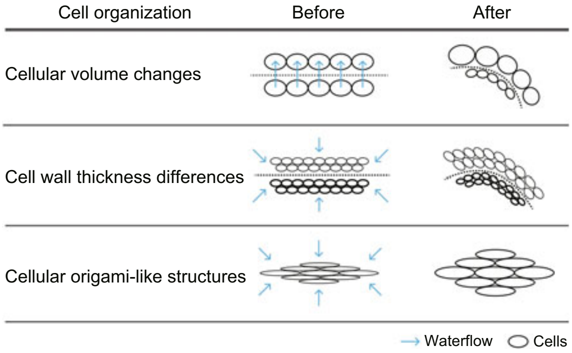


**Fig. 2 Three mechanisms of cell organization: cellular volume changes, cell wall thickness differences, and cellular origami-like structures**

2. Cell wall thickness differences: driven by the non-uniform distribution of living cells within a tissue, these differences create pressure gradients that result in shape-changing in specific directions. For instance, in the resurrection plant (*S. lepidophylla*) (Rafsanjani et al., 2015; Asgari et al., 2020) (Fig. 3b), the directional curling is primarily due to the stiffness difference between the abaxial and adaxial cell layers. The abaxial layer cells develop a secondary cell wall with higher lignification, increasing wall stiffness, reducing elasticity, and significantly decreasing water absorption capacity. In contrast, the adaxial layer cells have thinner cell walls that are rich in hemicellulose, endowing them with a stronger water absorption ability. When both layers of cells absorb water simultaneously, the adaxial layer cells expand more, thereby compressing the abaxial layer cells and prompting the stem to gradually uncurl from its spherical state. This efficient survival strategy endows *S. lepidophylla* with remarkable drought tolerance and a long lifespan.

3. Cellular origami-like structure: this mechanism is mainly observed in dead cell tissues, where the shape-changing pattern is determined by the

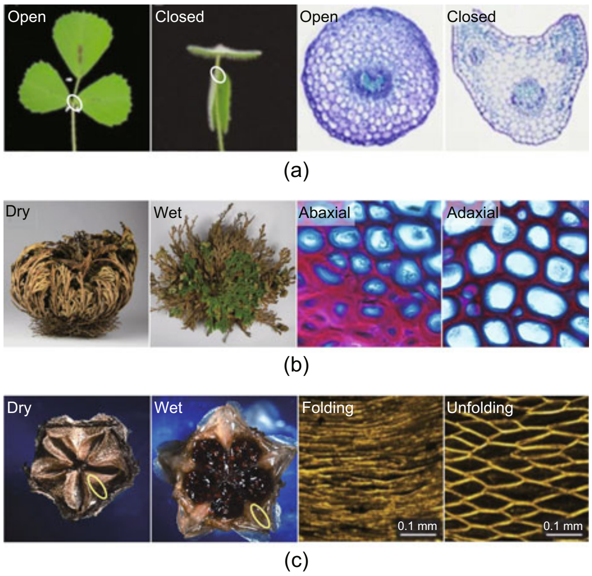


**Fig. 3 Cell organization examples: (a) the folding of leaves in leguminous plants and the cellular volume changes of the pulvinus cells; (b) the deformation process of resurrection plant (*Selaginella lepidophylla*) and the difference in cellular stiffness between the adaxial and abaxial layers; (c) the unfolding process of ice plant (*Mesembryanthemum crystallinum*) and its cellular origami-like structure. (a) is reprinted from Bai et al. (2022), Copyright 2022, with permission from the authors, licensed under CC BY 4.0. (b) is reprinted from Rafsanjani et al. (2015), Copyright 2015, with permission from the authors, licensed under CC BY 4.0, and reprinted from Asgari et al. (2020), Copyright 2020, with permission from the authors, licensed under CC BY 4.0. (c) is reprinted from Harrington et al. (2011), Copyright 2011, with permission from Springer Nature Limited**

material's initial structure. For example, the ice plant (*Mesembryanthemum crystallinum*) features an origami-like shape-changing process in its seed capsules. As the plant absorbs water, the capsules swell and unfold in an origami-like pattern. As it dries, they contract and fold back (Harrington et al., 2011) (Fig. 3c). This shape-changing, driven by the expansion and contraction of cellulose layers, has significant potential for applications in the design of programmable materials and adaptive structures.

Bi-layer anisotropic assembly: bi-layer anisotropic assembly structures are common in seeds capable of hygroscopic movement, particularly those reproduced independently after detaching from the parent plant. These structures typically comprise an active and a passive fibrous layer, each with distinct fiber orientations. The active layer expands and contracts along its long axis, while the passive layer resists deformation. Variations in humidity create differential swelling between the layers, leading to behaviors such as bending, curling, or twisting. Taking the awn of *Erodium* seeds as an example, the inner active layer swells upon absorbing water, while the outer passive layer remains stable. This swelling generates internal stress, causing the awn to straighten in humid conditions and coil into a spiral shape when the air is dry. As humidity fluctuates, the awn repeatedly coils and uncoils, acting like a miniature "drill" to push the capsule into the soil (Zhao et al., 2017; Ha et al., 2020). This mechanism helps the seed avoid predation and access a moister environment, thereby enhancing germination rates and survival.

A similar yet distinct mechanism is observed in the chiral seed pods of *Bauhinia variegata*, which also feature a bi-layer fiber structure, with the fibers oriented at ±45° angles to the long axis of the pod (Armon et al., 2011) (Fig. 4). Upon the maturation of the pod, the outer active layer of fibers contracts during dehydration, while the inner passive layer of fibers undergoes stretching. This uneven deformation leads to the accumulation of elastic potential energy within the pod. When the pod's stored elastic potential energy reaches a critical value, it ruptures at its vulnerable seam, causing the pod to split open. The stored elastic potential energy is rapidly released, propelling the seeds a considerable distance. This mechanism significantly enhances the dispersal range and reproductive efficiency of the seeds.

### 2.2.2 Mechanical instabilities

Bistability: bistability usually refers to the sudden and reversible switching between two stable

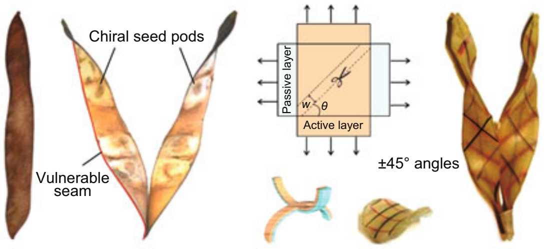
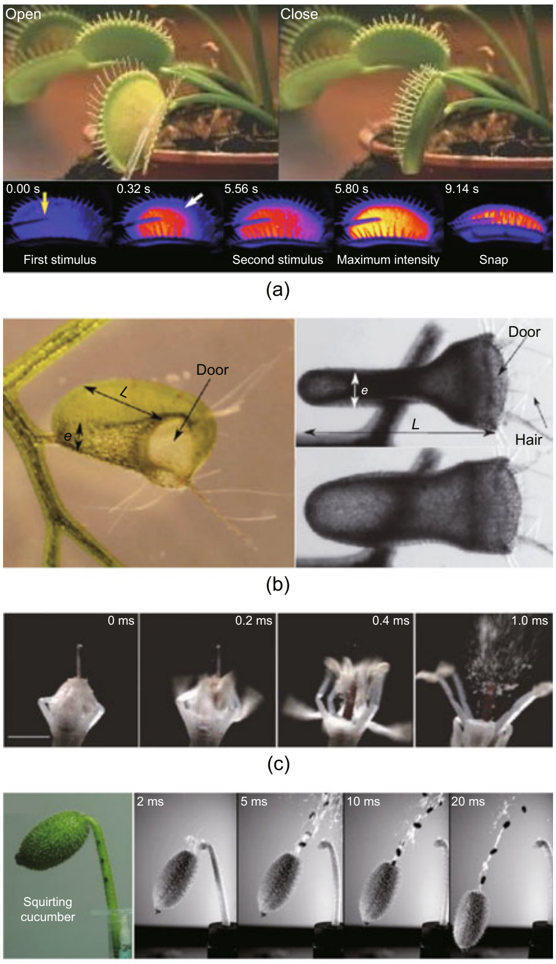


**Fig. 4 Closed and open *Bauhinia* pods, and ±45° bi-layer anisotropic assembly structure of them. Reprinted from Armon et al. (2011), Copyright 2011, with permission from AAAS**

states of a system, with state transitions typically triggered by external conditions. This mechanism is widespread in the rapid predation behavior of carnivorous plants. For example, the Venus flytrap initially keeps its lobes open. When the sensory hairs on the lobes detect an insect's touch, they trigger an electrical signal (Suda et al., 2020) (Fig. 5a), causing rapid changes in ion concentration and osmotic pressure within the cells. This leads to the lobes snapping shut within about 0.3 s (Forterre et al., 2005) (Fig. 5a), firmly trapping the prey. This abrupt transition from an open to a closed state is a classic example of bistability. In contrast, the Bladderwort utilizes a pressure-based bistable mechanism for hunting (Płachno et al., 2019). Initially, the bladder remains closed and maintains negative pressure, staying in a ready state. When a microorganism touches the trigger hairs on the bladder, the negative pressure is instantly released, causing the bladder to open rapidly. This action generates a high-speed water flow that sucks the microorganism inside (Llorens et al., 2012) (Fig. 5b). After capturing the prey, the bladder gradually restores negative pressure through osmotic regulation and cell wall elasticity, resetting itself for the next hunt. This mechanism enhances the trapping bladder's reusability, and ensures its efficient operation in underwater environments.

Fracturing: localized fracturing, often accompanied by the release of elastic potential energy, is a key mechanism in the catapult dispersal of plant pollen or seeds. A striking example is the stamen of bunchberry (*Cornus canadensis*), which functions as a high-speed catapult. When the flower matures, the stamen tip is fractured abruptly due to water potential changes, releasing stored elastic energy. This rapid energy release propels pollen outward in $< 0.5$ ms, the fastest recorded pollen dispersal process in the plant kingdom (Edwards et al., 2005) (Fig. 5c), with pollen traveling distances several times the flower's length.

In seed dispersal, the seed pods of *Impatiens* (touch-me-not) rapidly curve outward upon maturation or external touch, ejecting seeds over considerable distances. Similarly, the *Ecballium elaterium* (squirting cucumber) builds up internal pressure as its fruit matures. Upon the rupture of the fruit stalk base, the ripe fruit expels the fluid and seeds contained within its shell in a powerful, unidirectional stream, propelling them several meters away (Box et al., 2024) (Fig. 5d). Unlike the entirely spontaneous ejection in bunchberry, *Impatiens* and *Ecballium* often require minor external stimuli such as wind, rain, or physical contact to initiate fracturing.



(a)

(b)

(c)

(d)

**Fig. 5 Mechanical instabilities: (a) bistable snap closure of the Venus flytrap and the signal transduction process of sensory hairs after stimulation; (b) pressure-based bistable mechanism of the Bladderwort bladder; (c) the ultra-fast pollen ejection process of the Canadian bunchberry; (d) the rapid ejection of fluid and seeds from the fruit of the squirting cucumber after being fractured from the stalk. (a) is reprinted from Forterre et al. (2005), Copyright 2005, with permission from Macmillan Magazines Ltd., and reprinted from Suda et al. (2020), Copyright 2020, with permission from the authors, licensed under Springer Nature Limited. (b) is reprinted from Llorens et al. (2012), Copyright 2012, with permission from the Royal Society. (c) is reprinted from Edwards et al. (2005), Copyright 2005, with permission from Springer Nature Limited. (d) is reprinted from Box et al. (2024), Copyright 2024, with permission from the authors, licensed under CC BY 4.0**

These examples demonstrate how localized fracturing not only enhances dispersal efficiency but also reduces intraspecific competition by distributing propagules across broader areas, thereby promoting ecological stability and population survival.

## 2.3 Shape-changing stimuli

While plant structures inherently possess the capacity for shape-changing, it is external stimuli that activate these mechanisms and transform static configurations into dynamic responses. Environmental stimuli such as humidity, light, temperature, and mechanical force initiate diverse shape-changing behaviors across species. This section explores how these stimuli interact with plant systems to drive movement, emphasizing the essential role of environmental conditions in enabling plant shape-changing behaviors.

### 2.3.1 Humidity

Humidity-driven plant shape-changing, known as hygromorphism, occurs when plant cells absorb or lose water, causing reversible shape-changing (Fig. 6). Humidity variation directly influences plant morphology and function, driving this process. Different plants exhibit distinct humidity-responsive mechanisms. For example, pine cone scales close in dry conditions to protect seeds from water loss and open in humidity to aid germination (Dawson et al., 1997; Zhang FL et al., 2022). *Erodium* seed awns twist helically with changing air moisture (Ha et al., 2020), helping seeds penetrate the soil. *Selaginella* leaves curl up in drought to reduce evaporation and unfurl in humidity to resume photosynthesis (Asgari et al., 2020). Dandelion seed dispersal also responds to humidity (Seale et al., 2022). In dry air, the pappus opens wide to maximize wind dispersal. In humidity, the base swells, closing the pappi to reduce air resistance, allowing seeds to land quickly and germinate in moist soil. This dual mechanism ensures both wide dispersal and timely germination.

### 2.3.2 Light

Light is an essential energy source for plant growth, and a key environmental factor that triggers the plant movement. Like a sunflower tilting its face to follow the sun, plants can sense and respond to light, a process known as phototropism. For instance, a sunflower turns its flower head to follow the sun's path from sunrise to sunset. This movement is driven by auxin, a plant hormone shifted to the shaded side of the stem. It stimulates cell growth, causing the shaded side to elongate and the flower to lean toward the sun. At night, the sunflower resets its position, ready to start the cycle again the next day (Atamian et al., 2016; Kutschera and Briggs, 2016) (Fig. 7a). Vine plants also chase the light, but unlike the sunflowers' daily dance, their growth is a one-way journey. As they stretch toward sunlight, their tendrils twist and climb, keeping themselves in place.

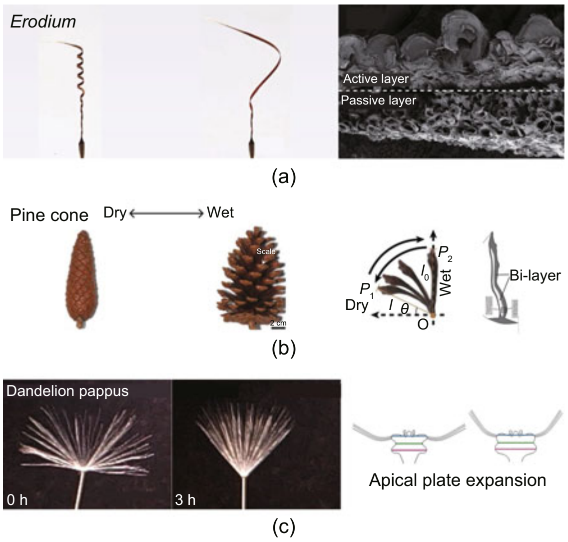


**Fig. 6 Humidity-driven behaviors: (a) the shape-changing process of *Erodium*; (b) the shape-changing process of the pine cone; (c) the open and closed states of dandelion pappus in response to the fluctuation of humidity. (a) is reprinted from Ha et al. (2020), Copyright 2020, with permission from Elsevier Ltd. (b) is reprinted from Zhang FL et al. (2022), Copyright 2022, with permission from the authors, licensed under Springer Nature Limited. (c) is reprinted from Seale et al. (2022), Copyright 2022, with permission from the authors, licensed under CC BY 4.0**

### 2.3.3 Temperature

Plants adjust their shape in response to the temperature fluctuations, a behavior known as thermonasty. Structures such as leaves and petals open or close as temperatures rise or fall, helping regulate physiological processes and optimize growth conditions. The morning glory (*Ipomoea purpurea*) exhibits a classic example of thermonastic movement. Its trumpet-shaped corolla opens in the morning and

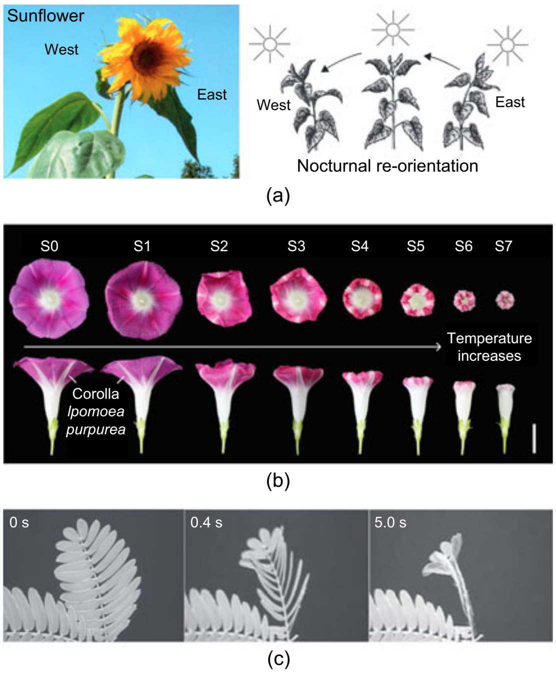


**Fig. 7 Shape-changing behaviors of plants by stimuli such as light, heat, and external forces: (a) sunflowers that track the sun and re-orient during the night; (b) the process of corolla closure; (c) the folding of *Mimosa pudica* leaves upon external force stimulation. (a) is reprinted from Kutschera and Briggs (2016), Copyright 2015, with permission from Oxford University Press. (b) is reprinted from Zhang PP et al. (2021), Copyright 2021, with permission from the authors, licensed under CC BY 4.0. (c) is reprinted from Volkov et al. (2010), Copyright 2009, with permission from Blackwell Publishing Ltd.**

closes later in the day, protecting its pollen and reproductive organs from heat damage, thereby enhancing reproductive success (Zhang PP et al., 2021) (Fig. 7b). Tulips are particularly sensitive to the temperature changes. In cold conditions, such as early morning or night, their petals close to conserve heat and safeguard reproductive structures. As temperatures rise, the flowers reopen, attracting pollinators and completing the reproductive process.

#### 2.3.4 External force

Many plants store mechanical instability or elastic potential energy within their tissues, which can be suddenly released by an external force, triggering rapid shape changes. This phenomenon, known as thigmonasty, enables plants to respond instantly to mechanical stimuli. For instance, the touch-sensitive plant *M. pudica* exhibits rapid leaf movements, a typical form of thigmonasty. In response to mechanical stimuli, the pulvinar cells lose water rapidly, leading to a sudden drop in turgor pressure and causing the leaves to fold quickly (Volkov et al., 2010) (Fig. 7c). As previously mentioned, the dispersal of fruits or seeds from *E. elaterium* (squirting cucumber) and *Impatiens balsamina* often requires a minor external force to initiate fracturing, rather than relying solely on intrinsic mechanisms.

## 3 Plant-inspired design strategies for shape-changing interfaces

To mimic the shape-changing behaviors and transfer them into physical interfaces, some key factors need to be considered, including materials, fabrication methods, and stimuli. Existing studies have been successfully using kinds of stimuli-response materials with specific properties such as sustainability, extendibility, and elasticity in interface design.

### 3.1 Design based on shape-changing behaviors

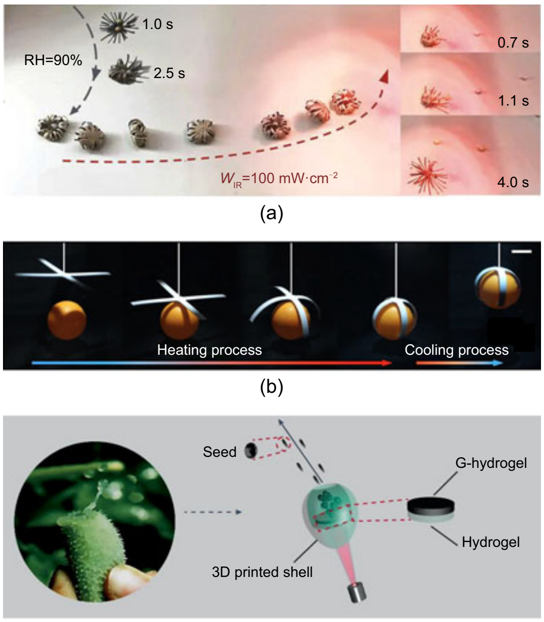
Bioinspired interface designs based on plant morphogenic behaviors typically derive inspirations from their external manifestations, subsequently informing applications in specific domains or scenarios. Consequently, such design methodologies adopt a target-oriented approach, wherein botanical deformation mechanisms are abstracted and replicated to achieve functional actualization.

#### 3.1.1 Growth and movement

Plants can grow and move in challenging surroundings adaptively, which inspires strategies for designing shape-changing interfaces used in complex scenarios (Wooten et al., 2018; Coad et al., 2020). Climbing plants are highly concerned due to their various habits to exploit diverse ecological habitats. FiloBot (del Dottore et al., 2024) contains a sensorized head to perceive gravity and the intensity and direction of light, a growing body made of polylactic acid (PLA), and a base with a spooler. The spooler can release PLA filament to build its body to mimic the growing process in response to environmental stimuli. Another example is a continuum robot for transluminal procedures driven by a programmable magnetic field (Mao LY et al., 2024). To realize higher sustainability, plant systems such as sprouts and fibers have been directly used as actuators (Murakami et al., 2024; Zhang YF et al., 2024) (Fig. 8a). Their characteristics make them drive the interfaces to move without extra power as input, paving the way for the realization of eco-friendly and sustainable interfaces and robots.

#### 3.1.2 Bending and curling

Bending and curling are the simplest and most common shape-changing behaviors that researchers have learned from for multiple purposes including gripping (Wang W et al., 2018) (Fig. 8b), assembling (Ding et al., 2018), and cell transportation (Villar et al., 2013). As plants realize these behaviors through property differences of cells or tissues, researchers mainly mimic similar results through differences in material characteristics or fabrication parameters. Aside from the bi-layer or multi-layer structures that have been introduced, another practicable method is applying pneumatically actuated soft composite materials. For instance, PneUI (Yao et al., 2013) selects materials including elastomers, paper, fabric, and wood as the structural layers. Crease patterns on the paper layer or the location of airbags define the position of the deformation. Air pressure determines the degree of curvature.



(a)

(b)

(c)

**Fig. 8 Design based on shape-changing behaviors: (a) programmable actuators of highly-aligned all-fiber membrane (HAFM) enabled by fiber alignment and "wrap-transport-release" behavior; (b) design and fabrication of polymer-paper-based shape-morphing structures; (c) schematic of the structural design of artificial *Ecballium elaterium*. (a) is reprinted from Zhang YF et al. (2024), Copyright 2024, with permission from Wiley-VCH GmbH. (b) is reprinted from Wang W et al. (2018), Copyright 2018, with permission from American Chemical Society. (c) is reprinted from Wang X et al. (2024), Copyright 2024, with permission from the authors, licensed under Springer Nature Limited**

#### 3.1.3 Inflation and explosion

Inflation and explosion of plants can generate plenty of energy in a very short time, which provides inspirations for energy storage and release. To mimic the process of energy accumulation, external input or internal response is practicable. External inputs such as pneumatic actuation enable energy storage, and provide shape-changing actuation for interfaces, making them prevalent in robotic system design (Shepherd et al., 2011). As for internal response, inspired by a squirting cucumber (*E. elaterium*), explosive fluid vibration has been utilized to mimic the turgor pressure accumulation and instant release. The vibration is triggered by the photothermal response of graphene embedded within a co-polymer hydrogel, achieving the highest acceleration and launching height of engineered mini-scale robotic devices (Wang X et al., 2024) (Fig. 8c).

### 3.2 Design based on shape-changing principles

Shape-changing principles of plants inspire material selection and structure designs of interfaces. With the development of material science, smart materials are widely used due to their ability to produce changes in shape or property and behaviors such as self-assembly, shape memory, and self-capability when exposed to stimuli (Leist and Zhou, 2016; Ali et al., 2019). These materials have been combined with 3D printing (Shahrubudin et al., 2019) as an additional dimension, introducing 4D printing (Ahmed A et al., 2021), a common method to fast fabricate shape-changing interfaces. This section mainly describes the design strategies for choosing suitable smart materials and designing ingenious structures to mimic plant systems for shape-changing interfaces.

### 3.2.1 Physiological features

As mentioned above, the main physiological features of plants for shape-changing can be classified into cell organization and anisotropic assembly, which can inspire material and structure designs of interfaces.

Design strategies inspired by cellular organization: to control the shape-changing behaviors of smart materials, two strategies are advisable according to cell organization in plants. The first is to create interfaces with local differences, which mimic the cellular differences. In fabrication, instead of uniform 3D printing, existing works realize shape-changing through setting various printing parameters such as printing density (Nishiguchi et al., 2020), printing speed, and nozzle height of direct ink writing (DIW) (Yuk and Zhao, 2018). This strategy makes the printed interfaces inhomogeneous in terms of material arrangement. When applying external stimuli to the interfaces, different regions exhibit different shape-changing capabilities, driving the entire interface's change in certain ways. Other smart materials such as liquid crystal elastomer (LCE) have been applied to realize similar shape-changing results by this strategy (Ren et al., 2020; Wang ZJ et al., 2020) (Fig. 9).

Another strategy is to use gradient external stimuli; it mimics the mechanism whereby differences in cell wall thickness cause differences in water absorption, resulting in shape-changing in specific directions (Wu W et al., 2011). Besides, some other works directly copy the biological structures, such as honeycomb, and utilize the shape-changing property of smart materials to design such interfaces (Sun et al., 2021).

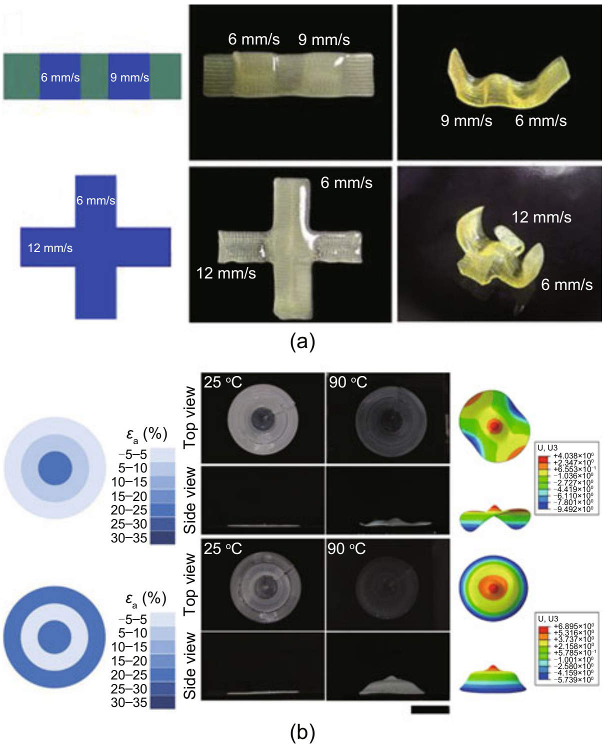


**Fig. 9 Design strategies inspired by cellular organization: (a) shape-changing patterns enabled by altering the geometry and print speed distribution of each LCE layer; (b) 3D-printed active shape-changing discs with functionally graded LCE. (a) is reprinted from Ren et al. (2020), Copyright 2020, with permission from American Chemical Society. (b) is reprinted from Wang ZJ et al. (2020), Copyright 2020, with permission from the authors, licensed under CC BY 4.0**

Design strategies inspired by bi-layer anisotropic assembly: the anisotropic assembly of cellulose inspires the bi-layer or multi-layer structure design with material anisotropy for shape-changing in a specific direction. There are two common strategies to mimic the inhomogeneity in the shape-changing of different layers. The first is to utilize different materials with different shape-changing characteristics. Inspired by pine cones, two materials with substantial hygroscopic swelling characteristics, wood polymer composite (WPC) and thermoplastic polyurethane (TPU), are chosen to form the bi-layer structure (Correa et al., 2020). WPC expands a lot under wet conditions, as the active layer, while TPU acts as the passive layer. Therefore, the bi-layer structures can bend when exposed to wet stimuli. Moreover, the bending direction and curvature can be adjusted by the combination of two materials. Aside from this, many other combinations of materials have been proven successful to form the bi-layer shape-changing structures, including PLA and TPU (An B et al., 2018) (Fig. 10a), polyurethane (PU) filaments and paper (Song et al., 2020) (Fig. 10b), shape memory polymer (SMP) and hydrogel (Mao YQ et al., 2016), etc. Other shape-changing behaviors, such as twisting, self-folding, and rolling, can also be achieved by this strategy (Janbaz et al., 2016) (Fig. 10c).

The second strategy is to fabricate two layers with different parameters or paths of the same material. For instance, PLA is observed to shrink

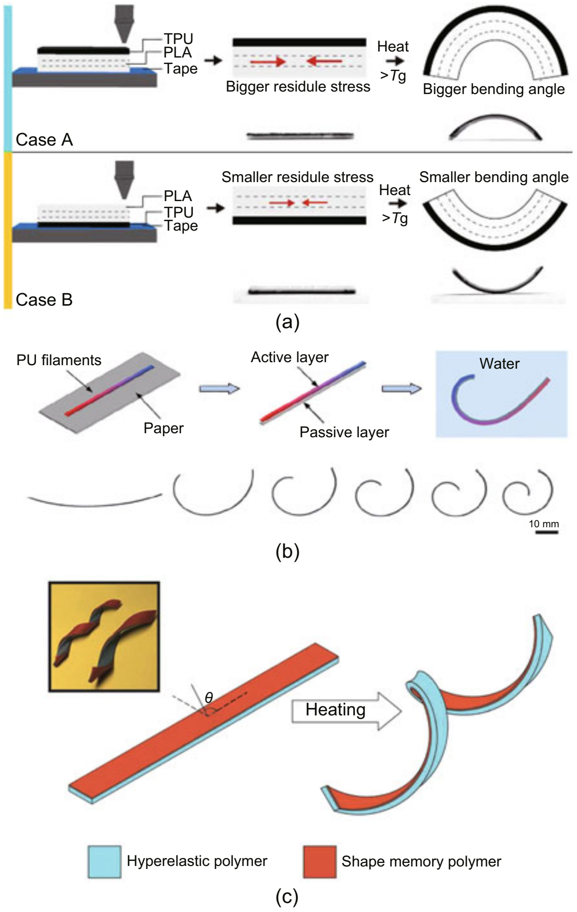


**Fig. 10 Design strategies inspired by bi-layer anisotropic assembly: (a) two printing orders of TPU and PLA result in different bending directions and angles; (b) a PU filament with a linearly varying swelling ratio along its length generates a spiral shape when immersed in water; (c) a bi-layer structure of an SMP and a hyperelastic polymer transforms into a spiral. (a) is reprinted from An B et al. (2018), Copyright 2018, with permission from ACM. (b) is reprinted from Song et al. (2020), Copyright 2020, with permission from American Chemical Society. (c) is reprinted from Janbaz et al. (2016), Copyright 2016, with permission from the authors, licensed under CC BY 3.0**

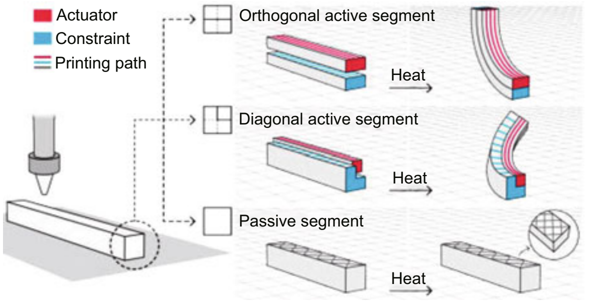


**Fig. 11 Design strategies inspired by bi-layer anisotropic assembly, using one material: the printing paths set for active and passive layers. Reprinted from Wang GY et al. (2019), Copyright 2019, with permission from ACM**

along the 3D printing direction when exposed to high temperature (van Manen et al., 2017). As Fig. 11 shows, the active layer consisting of long printing paths shrinks more than the passive layer consisting of short printing paths, causing the printed structures to bend (Wang GY et al., 2018a, 2019). Further, more shape-changing behaviors have been realized through complex combinations of printing paths (Tao et al., 2023). Similarly, other materials, including hydrogels and LCEs, are also suitable to mimic the anisotropic assembly by adjusting different printing parameters (Ren et al., 2020), printing paths (Kotikian et al., 2019), or printing patterns (Gladman AS et al., 2016).

The bi-layer structures demonstrate significant advantages in designing shape-changing interfaces, including wide material choices, accessible fabrication processes, and multiple shape-changing behaviors. However, a main limitation of bi-layer structures has been investigated; i.e., it is difficult to transform them into non-zero Gaussian curvature surfaces, especially for thin materials (Pezzulla et al., 2016). Pneumatic actuation and specific channel design have been integrated to enable bi-layer structures to bend or curve in two directions to solve this problem. Inspired by leaf bulliform cells, thin panels embedded with inflatable cells are designed to realize the programmed in-plane contraction and angular deflection, leading to stiff, 3D structures (Gao et al., 2023). Similarly, baromorph (Siéfert et al., 2019) consists of elastomer plates embedding a network of airways to precisely control local expansion under air inflation or suction, achieving complex 3D shape-changing.

### 3.2.2 Mechanical instabilities

The mechanical instabilities of plants inspire researchers to combine special material properties with mechanical and logic designs. Particularly, the snap-through bistable mechanism has been extensively used in developing high-performance bistable interfaces (Chi et al., 2022). Current implementations typically integrate pneumatic actuators with bistable structures, or combine coupled tube kinking mechanisms with bistable membrane deformations (Zhang Z et al., 2022). However, they frequently necessitate intricate configurations requiring specialized engineering interventions. A new class of bistable fabric mechanisms (BFMs) is presented which merges soft bistable actuators and valves by partially bonding two fabric chambers made of polyester fabrics with TPU and embedding tubes (Yang DZ et al., 2025) (Fig. 12). A simple way of adding point-like heat-sealed spots as constraints on a flat airbag causes the airbag to be able to switch between two states after inflation (Yang Y et al., 2024). Besides, special mechanical structures enable some stiff materials to change shape between two or more states (Sun et al., 2022).

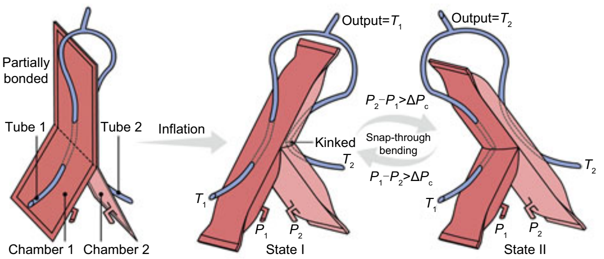


**Fig. 12 Design strategies inspired by mechanical instabilities: a BFM consisting of two partially bonded fabric chambers (pressure: $P_1$ and $P_2$) and two embedded tubes (temperature: $T_1$ and $T_2$) can make rapid transitions between two stable states when the pressure difference exceeds a critical value. Reprinted from Yang DZ et al. (2025), Copyright 2025, with permission from the authors, licensed by CC BY 4.0**

### 3.3 Design strategies of stimuli

When considering design strategies of stimuli for shape-changing interfaces, the actual scene and desired triggering conditions are main factors. Furthermore, the stimuli always relate to the materials, raising opportunities and challenges for researchers to correctly choose, synthesize, and use materials.

#### 3.3.1 Humidity-response shape-changing

As the most common stimulus for plant systems, humidity plays an important role in human-made shape-changing interfaces. It has been explored as the main stimulus for achieving agricultural and biomedical purposes due to its accessibility and harmlessness. Humidity-responsive materials widely exist in nature. Natural wood has well-studied hygromorphic properties. Inspired by *Erodium* seeds (Stamp, 1984), which can respond to variations in external humidity and self-bury into the soil, white oak lumber was chosen for its good molding quality and high tensile modulus to mimic the self-bury behaviors (Luo et al., 2023). Through material processing and customized structure design, the man-made seed carriers realize a higher drilling success rate than natural ones. Other natural materials include *Bacillus subtilis* natto and cellulose nanofibers, which can change the size of their cells in response to humidity changes. As shown in Fig. 13, a composite biofilm containing natto cells and substrate can vary the bending curvature triggered by the relative humidity (RH) change (Yao et al., 2015). Aside from natural materials, researchers also explore synthetic materials such as hydrogels, which have always been applied by combining structure design strategies to make shape-changing interfaces (Jain et al., 2021).

#### 3.3.2 Light-response shape-changing

Light as a stimulus has raised more and more interest in shape-changing interfaces due to its rapid switching, accurate focusing, and sustainable properties (Yang H et al., 2014). In most cases, the absorbed light can generate heat, which also relates to the shape-changing behaviors. Carbon black, which has excellent photothermal conversion efficiency, has been incorporated into SMP to mimic sunflowers. These man-made sunflowers can recover from a squashed state to cubic state upon suitable illumination (Yang H et al., 2017) (Fig. 14a). As one of the most promising natural materials, starch has the ability of heat-induced disintegration in water, resulting from the abundant intermolecular and intramolecular hydrogen bonds. Therefore, it can be combined with liquid metal particles (LMPs), which have excellent photothermal properties, to design a *Mimosa*-inspired photothermo-responsive interface (Hu H et al., 2023) (Fig. 14b). Other photo-responsive polymers such as azobenzene have been incorporated into thermo-responsive polymers to generate photothermo-responsive materials (Verpaalen et al., 2020).

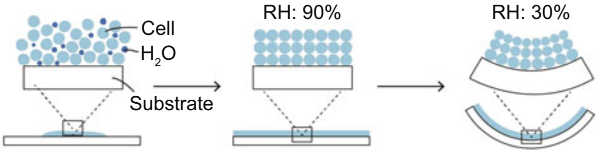
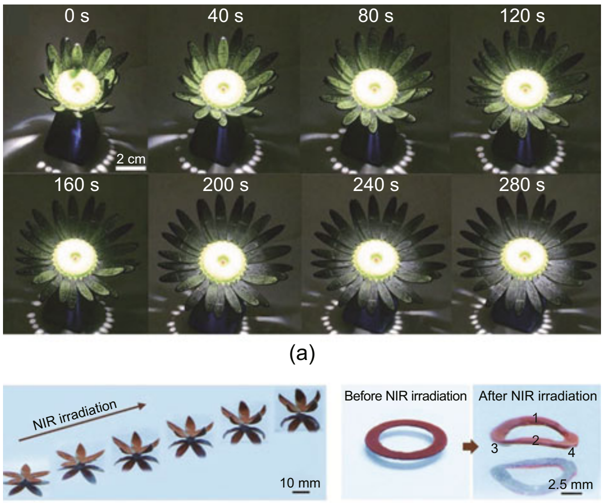


**Fig. 13 Humidity-responsive shape-changing: liquid cell solution deposition and composite biofilm bending when RH changes. Reprinted from Yao et al. (2015), Copyright 2015, with permission from ACM**



(a)

(b)

**Fig. 14 Light-responsive shape-changing: (a) 3D-printed sunflowers exhibiting different deformations with varying illumination times, transitioning from bud to bloom every 40 s; (b) light-responsive programmable folding of an artificial flower and shape-changing of a planar ring. (a) is reprinted from Yang H et al. (2017), Copyright 2017, with permission from Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) is reprinted from Hu H et al. (2023), Copyright 2023, with permission from Wiley-VCH GmbH**

#### 3.3.3 Temperature-response shape-changing

Temperature is the most studied stimulus in developing shape-changing interfaces (Lui et al., 2019). The two main mechanisms of thermo-responsive materials are the shape memory effect (SME) (Hager et al., 2015) and the shape change effect (SCE) (Zhou et al., 2015). SME indicates the transformation of a deformed material to its original state. The mentioned SMP is a typical material that has an SME when exposed to thermo stimuli (Ge et al., 2016). Another common material is called shape memory alloys (SMAs). They have a high yield strength and elasticity above the stimulus temperature (Mohd Jani et al., 2014). However, SMA has not been widely applied in shape-changing interfaces due to its high cost, low flexibility, and low biocompatibility. SCE means the material can change in shape when exposed to specific stimuli. PLA is a typical material with SCE, which shrinks at high temperatures. It has been widely used in 4D printing to fabricate interactive shape-changing interfaces, by innovative printing strategies (Gu et al., 2019; Wang GY et al., 2019) or structure designing (Sun et al., 2021).

#### 3.3.4 Shape-changing driven by external force

External force indicates that the resource of the actuation comes from users' behaviors rather than the environment. The most prevalent approaches include pneumatic, magnetic, and electric actuation. These external forces are used to simulate biological energies within plants to have similar shape-changing abilities.

Pneumatic actuation applies air pressure to establish a gradient across interfaces, thereby driving their expansion and deformation. To ensure proper deformation, materials with high elasticity and ductility, such as Ecoflex and TPU, are typically used. Precise control over deformation direction and magnitude requires careful consideration of chamber orientation, dimensions, and quantity during interface design (Shepherd et al., 2011). An alternative methodology involves constraining deformation through external shells composed of high Young's modulus materials. The manipulation of slit geometry in these confinement structures enables controlled deformation behaviors (Belding et al., 2018). Modular design strategies have been widely adopted to achieve more complex behaviors, where sophisticated deformations with higher degrees of freedom are realized through combinatorial arrangements of simple pneumatic chambers (Wang GY et al., 2024a). Another innovative strategy involves multi-phase shape-changing control through regulated inflation. PneuFab (Wang GY et al., 2023a) leverages the thermoplastic properties of PLA to create cavity-embedded models via 3D printing. Subsequent immersion in hot water facilitates material softening concurrent with air injection, enabling programmable multi-phase inflation-induced shape-changing (Fig. 15a).

Magnetic actuation uses dispersed magneto-responsive particles to drive the whole material to change its shape in a specific direction. Several fabrication methods have been proposed to create magneto-responsive shape-changing interfaces. As the conventional method, molding and casting are most common and accessible for simple geometries. Hard-magnetic soft materials can deform into a temporary shape after molding and curing. Then, a strong magnetic field is applied to saturate the composite, leading to a nonuniform magnetization profile that can revert to the programmed shape under an

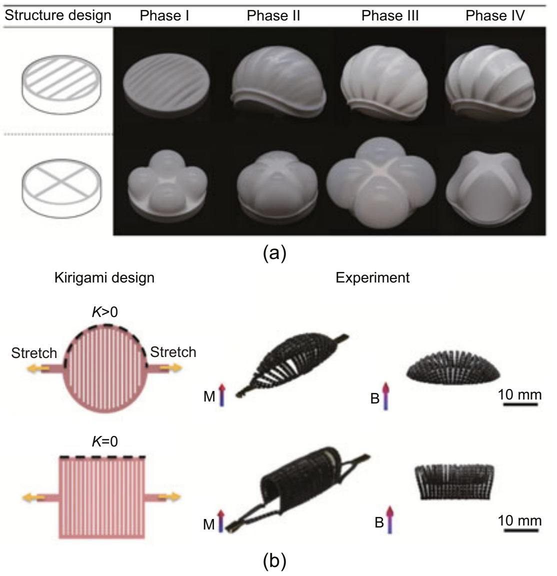


**Fig. 15 Shape-changing driven by external force: (a) basic planar structures of PneuFab achieving multi-phase inflation-induced shape-changing; (b) kirigami-inspired structures design fabricated via stretching-guided magnetization. (a) is reprinted from Wang GY et al. (2023a), Copyright 2023, with permission from ACM. (b) is reprinted from Zhu HL et al. (2022), Copyright 2022, with permission from the authors, licensed under CC BY 4.0**

actuating field (Hu WQ et al., 2018; Gong et al., 2020). Another common method is additive manufacturing, especially 3D printing. By applying weak magnetic fields during printing, the magnetized particles can be aligned in the printing path to have programmed and complex shape-changing abilities (Kim et al., 2018). Furthermore, the method can be combined with other design tricks, such as kirigami art, to achieve more complex and precise shape-changing behaviors (Zhu HL et al., 2022) (Fig. 15b).

Unlike pneumatic and magnetic actuation, electric actuation requires less programmable structure or fabrication design, but mainly depends on materials. SMPs have been mixed with other polymers to fabricate electro-active materials for soft actuators (An YJ and Okuzaki, 2020). In most cases, materials with high conductivity, including black phosphorous and carbon nanotubes (Wu G et al., 2019), are often used to realize better actuation properties. With the development of material science, more novel materials, such as ionically crosslinked MXene (2D layers of transition metal carbides, nitrides, or carbonitrides) (Umrao et al., 2019), have been created to provide wider usage potential for shape-changing interfaces.

## 4 Applications

Plants exhibit dynamic characteristics that enable them to adapt efficiently to the dynamic changes in their natural environment. Inspired by these biological attributes, many researchers have explored the development of bioinspired interfaces that are controllable, adjustable, and customizable, achieving functional characteristics comparable to, or even surpassing, those found in nature.

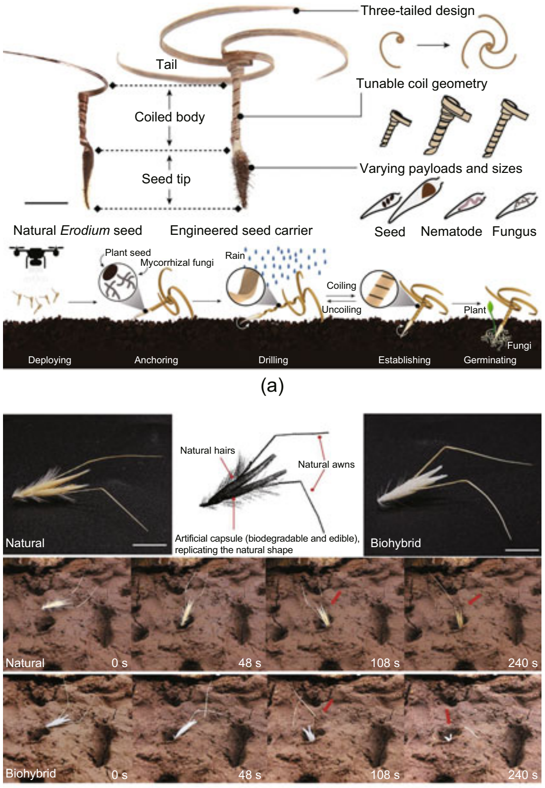
In this section, we introduce the plant-inspired shape-changing interfaces that have been applied in related areas such as agriculture, healthcare, architecture, robotics, environmental protection, and interactive product.

### 4.1 Agriculture

Plants have long been known for their ability to adapt to environmental changes, a trait that has inspired the development of plant-inspired shape-changing interfaces in agriculture.

These interfaces can be applied to enhance farming devices and techniques, particularly in precision agriculture. For example, inspired by the leaf of the fig tree *Ficus religiosa*, a precision irrigation system has been developed to reduce flow resistance, prevent blockages, and generate smaller droplets at high frequencies. This system effectively addresses the limitations of water scarcity in irrigation systems (Liu et al., 2023).

Another critical challenge in agriculture is seed dispersal and planting efficiency. Traditional methods often struggle to cover large or hard-to-reach areas, but the use of adaptive interfaces inspired by natural dispersal mechanisms can significantly improve efficiency. Some plant seeds have evolved "motion" as part of their dispersal mechanism. As shown in Fig. 16a, inspired by the spiral soil-burrowing behavior of *Erodium* seeds, autonomous self-burying seed carriers can spiral into the soil to bury biological fertilizers or plant seeds, driven by humidity, achieving a soil-burrowing success rate of up to 80%. These carriers are suitable for large-scale sowing in hard-to-reach areas, improving the efficiency of aerial seeding and helping alleviate agricultural and environmental pressure (Luo et al., 2020, 2023). Another example is the fruit of Avena shown in Fig. 16b, which can jump and penetrate the soil through two hygroscopically responsive



(a)

(b)

**Fig. 16 Agricultural applications of plant-inspired shape-changing interfaces: (a) autonomous self-burying seed carriers inspired by *Erodium* seeds, spiraling into the soil driven by humidity for efficient aerial seeding; (b) humidity-driven micro-cargo transport inspired by *Avena* fruit, navigating various soils and terrain, with potential applications in reforestation and agriculture. (a) is reprinted from Luo et al. (2023), Copyright 2023, with permission from the authors, licensed under Springer Nature Limited. (b) is reprinted from Fiorello et al. (2024), Copyright 2024, with permission from the authors, licensed under CC BY 4.0**

awns. Inspired by this mechanism, HybriBot developed a biodegradable, humidity-driven micro-cargo transport system capable of exploring various soil types and navigating irregular terrain, achieving comparable capsule drag forces up to 0.38 N and awns torque up to 100 mN/mm. Such systems have potential applications in reforestation, precision agriculture, and environmental monitoring (Fiorello et al., 2024).

## 4.2 Healthcare

In the field of personalized healthcare and rehabilitation, plant-inspired shape-changing interfaces hold significant potential for enhancing patient care. These interfaces are inspired by the self-regulating behaviors of plants, such as their ability to adapt dynamically to environmental changes without external energy input. In healthcare, this principle can be applied to create responsive systems that adjust body movements or recovery needs, offering more comfortable and effective treatments.

For instance, as shown in Fig. 17a, adaptive orthoses inspired by climbing plants can apply adjustable pressure to tailor support based on the user's activity or condition, improving comfort and rehabilitation outcomes (Cheng et al., 2021). Additionally, plant-inspired mechanical instability seen in the Venus flytrap's rapid snap mechanism has applications in emergency medical devices, such as stretcher straps that provide quick, secure, and comfortable stabilization for patients (Yang Y et al., 2024) (Fig. 17b).

Furthermore, the vascular systems of plants offer insights for synthetic microfluidic systems, such as inspiration from the genus *Oxalis*, which folds its leaves at night to reduce water loss. In a similar

(a)

(b)

**Fig. 17 Medical and rehabilitation applications of plant-inspired shape-changing interfaces: (a) adaptive orthoses inspired by climbing plants, applying adjustable pressure to improve comfort and rehabilitation outcomes; (b) venus flytrap-inspired snap mechanism in stretcher straps for quick, secure patient stabilization. (a) is reprinted from Cheng et al. (2021), Copyright 2021, with permission from the authors, licensed under CC BY 4.0. (b) is reprinted from Yang Y et al. (2024), Copyright 2024, with permission from ACM**

vein, the TransfOrigami system senses environmental stimuli and transforms its shape in response. These bioinspired systems have potential applications in dynamic artificial vascular networks, which could revolutionize treatments for conditions requiring responsive fluid flow systems (Pan et al., 2022).

### 4.3 Architecture

Plant-inspired shape-changing interfaces also hold significant potential in the field of architecture, where they can contribute to the creation of smart, responsive, and energy-efficient buildings (Reichert et al., 2015; Vailati et al., 2018; Zhan et al., 2023).

Just as plants adjust their shape to optimize sunlight exposure, buildings can incorporate shape-changing elements to regulate temperature and light. For example, inspired by the way sunflowers rotate towards the sun, rotating building facades can track the path of the sun across the sky. This strategy effectively captures natural light, improves the efficiency of solar panels, and significantly reduces the need for artificial lighting (Fan et al., 2017). In addition, adaptive materials inspired by plant cells and fibers can be used in building envelopes that self-adapt to changing environmental conditions. By regulating the openness and porosity of the facade through humidity control, these materials can adjust light transmission and visual permeability without requiring extraneous mechanical or electronic control (Fig. 18), ultimately improving energy efficiency and sustainability in urban architecture (Holstov et al., 2015; Menges and Reichert, 2015).

### 4.4 Robotics

By mimicking the growth, movement, and energy-harvesting mechanisms of plants, plant-inspired designs in robotics can lead to more adaptive, energy-efficient, and versatile systems (Meder et al., 2023; Speck et al., 2023).

**Fig. 18 Architectural applications of plant-inspired shape-changing interfaces: pine-inspired humidity-responsive architecture facades adjust light transmission for energy efficiency. Reprinted from Menges and Reichert (2015), Copyright 2015, with permission from John Wiley & Sons, Ltd.**

Many climbing plants grow upward to avoid shading from surrounding vegetation, competing for more light. This adaptive behavior has inspired the development of bioinspired deformable interfaces in robotics. For example, autonomous robots in Fig. 19a that mimic climbing plants' growth strategies are being used to navigate unstructured environments, enhancing their ability to adapt and move through complex terrains (del Dottore et al., 2024). Similarly, soft grippers that mimic the curling motion of climbing tendrils allow for dynamic object grasping, providing flexibility in handling various objects, including delicate and irregularly shaped ones (Wang W et al., 2018). Further research has focused on robots with adjustable stiffness and reversible helical behavior (Must et al., 2019), or those capable of achieving outstanding large deformations (Li WW et al., 2025).

Additionally, the moisture-responsive movements of plants inspire non-electric robotics, such as self-propulsion, self-deformation (Dierichs et al., 2017), and self-locking (Tahouni et al., 2021). For example, the microrobot hygrobot, shown in

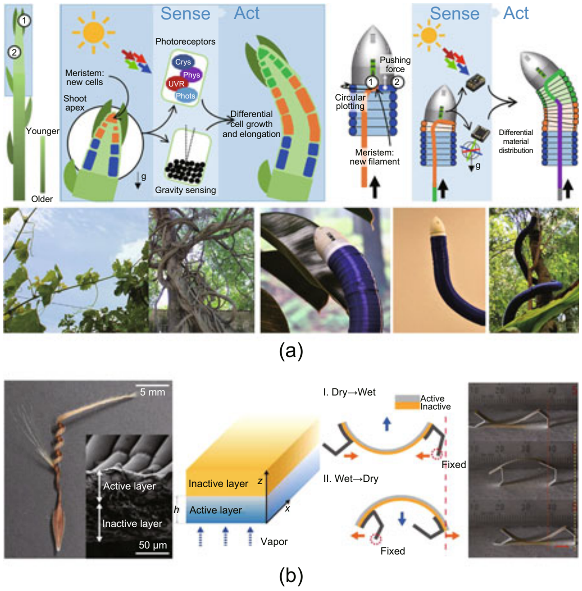


**Fig. 19 Robotic applications of plant-inspired shape-changing interfaces: (a) climbing plant-inspired autonomous robots for adaptive navigation in unstructured environments; (b) a *Pelargonium carnosum*-inspired microrobot using humidity for movement without artificial power. (a) is reprinted from del Dottore et al. (2024), Copyright 2024, with permission from AAAS. (b) is reprinted from Shin et al. (2018), Copyright 2018, with permission from AAAS**

Fig. 19b, inspired by *Pelargonium carnosum* seeds, uses environmental humidity to generate movement. Its dual-layer structure and ratchet mechanism allow it to operate without artificial power, relying solely on environmental conditions (Shin et al., 2018).

## 4.5 Environmental protection

The principles of plant adaptation can be applied to environmental protection by developing systems that monitor and respond to ecological changes. For example, shape-changing interfaces could be embedded in environmental sensors that dynamically monitor heavy metal pollution in aquatic environments and provide significant visual cues, enhancing the accuracy and responsiveness of data for ecosystem management. Such adaptive technologies offer a low-cost approach to detecting and addressing environmental contamination, providing real-time feedback to the public (Jeong et al., 2024).

Furthermore, many plants have evolved various mechanisms for resource acquisition, which can inspire reliable power solutions for devices used in environmental monitoring. As shown in Fig. 20a, an example is a wearable device for plant sap flow monitoring, powered by a self-sustaining foldable solar panel made of eight silicon solar cell petals, mimicking sunflower petals. This compact, lightweight system autonomously harvests solar energy, making it particularly suitable for use in small plants or in areas with limited access to external power sources (Wang S et al., 2024).

Additionally, environmental monitoring often relies on widespread sensor deployment, which can be challenging due to the limited mobility of most monitoring devices. However, many plants have evolved mechanisms to disperse their reproductive bodies over greater distances, offering insights into device design. For example, the lightweight dandelion seed, which is dispersed by wind, serves as inspiration for the development of wind-driven battery-free wireless devices. These small devices, as shown in Fig. 20b, weighing only 30 mg, can travel distances of 50–100 m in mild to moderate wind conditions, enabling effective applications in environmental monitoring and communication without the need for external power sources (Iyer et al., 2022).

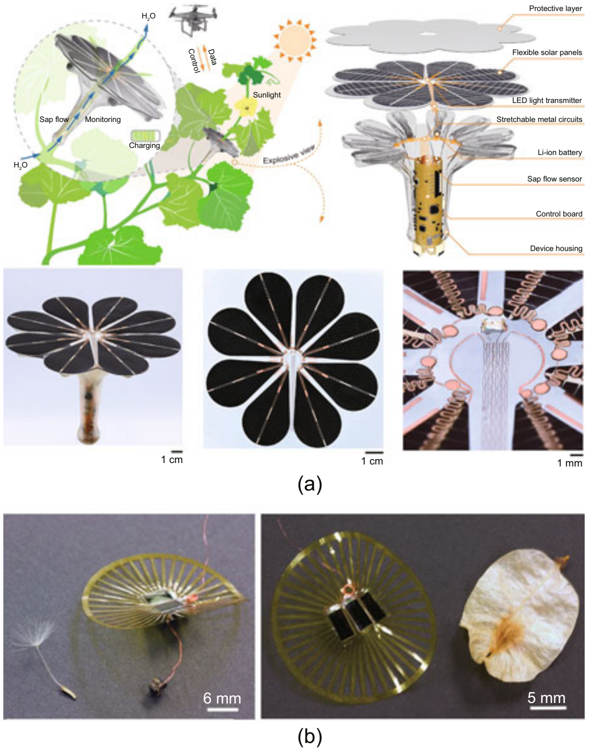
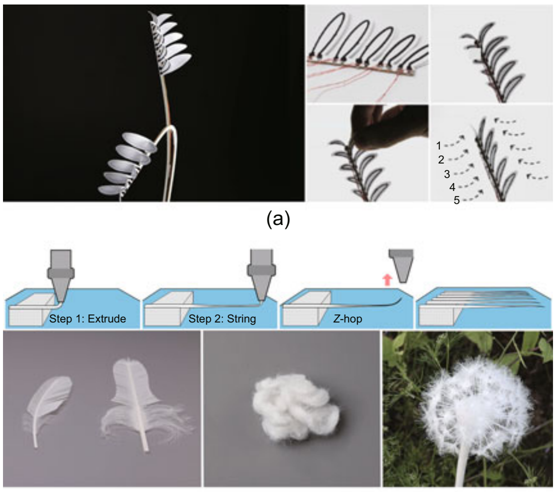


**Fig. 20 Environmental protection applications of plant-inspired shape-changing interfaces: (a) a sunflower-inspired wearable device monitors plant sap flow with a self-sustaining solar panel; (b) a dandelion-inspired wind-driven wireless device enables environmental monitoring and communication over 50–100 m. (a) is reprinted from Wang S et al. (2024), Copyright 2024, with permission from the authors, licensed under CC BY 4.0. (b) is reprinted from Iyer et al. (2022), Copyright 2022, with permission from the authors, licensed under Springer Nature Limited**

## 4.6 Interactive product

Interactive design has been enriched by the dynamic movements of plants, leading to the creation of smart products that respond to environmental stimuli. Drawing inspiration from the adaptive behaviors of plants such as altering their orientation and structure in response to environmental changes, these products foster more intuitive, responsive, and engaging user interactions.

The rapid leaf movement of *M. pudica* (Weintraub, 1952) has inspired adaptive motion in interactive systems in dynamic environments, creating innovative lighting fixtures that open and close their shades according to the changes in light (Hu H et al., 2023), as well as interactive devices (Fig. 21a) that respond to human touch (Wang GY et al., 2018b).



(a)

(b)

**Fig. 21 Interactive product applications of plant-inspired shape-changing interfaces: (a) sensitive plant-inspired systems, such as touch-reactive devices; (b) mimicking *Mimosa pudica*, and bioinspired 3D-printed structures replicating cactus spines and dandelion seed fluff for personalized fabrication. (a) is reprinted from Wang GY et al. (2018b), Copyright 2018, with permission from ACM. (b) is reprinted from Wang GY et al. (2024b), Copyright 2024, with permission from ACM**

Inspired by the bi-layer structure of pine cones, researchers have developed 4D-printed objects that undergo programmable shape transformations in response to heat. The method enables the creation of objects that dynamically change form, with applications ranging from linear structural inventions (Wang GY et al., 2019) and transportable furniture fabrication (Wang GY et al., 2018a) to interactive 3D circuit boards (Wang GY et al., 2020) and accessible modifications to daily items (Sun et al., 2021).

Furthermore, researchers have extended these bioinspired principles to fabrication processes. By studying plants, such as the spines of cacti or the fluffy structure of dandelion seeds, designers have used 3D printing technology to replicate these structures and apply them to product design (Fig. 21b), pushing the boundaries of personalized manufacturing devices (Wang GY et al., 2024b).

## 5 Challenges and opportunities

In this section, we discuss the major challenges in plant-inspired shape-changing interface research, including those in design, fabrication, and application. Moreover, these challenges open up new opportunities, pointing to future directions that could advance the field and unlock its full potential.

### 5.1 Design and control

1. Design thinking in interdisciplinary research

Challenge: the key challenge in designing plant-inspired shape-changing interfaces lies in the interdisciplinary nature of the task. Designers and engineers must first acquire a comprehensive understanding of plants and the specific principles that govern their movement. This often requires expertise across fields such as biology, physics, and materials science. Bridging the gap between the natural world and tangible interfaces presents a significant hurdle: how can dynamic plant behaviors be effectively translated into interactive systems? Moving from the theoretical principles of plant movement to practical applications necessitates a shift in mindset and a creative approach to design thinking.

Opportunity: to facilitate this, key research opportunities involve establishing a shared vocabulary for interdisciplinary teams and developing accessible software or hardware design tools and collaborative online platforms (Qamar et al., 2018, 2020) to streamline the translation of plant behaviors into tangible interactive systems.

2. Dynamic behavior and control principles

Challenge: in nature, plant movements are commonly driven by a single energy source, such as wind or sunlight, and are confined to a limited range of motion dictated by environmental forces. However, in the context of shape-changing interfaces, the driving forces become more complex and controllable, presenting new opportunities. The challenge here is not merely to provide designers with a wider array of controllable movements, but to establish a fundamental scientific understanding of the underlying principles.

Opportunity: currently, the field largely relies on phenomenological descriptions, while a predictive theoretical foundation remains a critical gap. Abstracting plant movement mechanisms into physical theories and computational models will be the key to abstracting and generalizing movement mechanisms (Prusinkiewicz and Runions, 2012). This will ultimately enable a paradigm shift from trial-and-error fabrication to the rational, predictive design of shape-changing interfaces for any desired application.

### 5.2 Material and fabrication

1. Material selection

Challenge: research on plant-inspired shape-changing interfaces often relies on the unique properties of natural materials, such as cellulose and lignin, which are abundant, biodegradable, and environment-friendly. However, translating these natural characteristics into engineered materials presents a significant challenge. The primary issue lies in selecting high-performance, eco-friendly materials that not only maintain their shape-changing capabilities over time but also exhibit reversible deformation with controllable precision across a range of environmental conditions. The challenge is compounded by the need for materials that can withstand prolonged usage while retaining their functionality under varying external factors, such as temperature and humidity.

Opportunity: future research should prioritize creating sustainable bio-composite materials and exploring their potential for programmable deformation to achieve precisely controllable shape-changing behaviors (Bell et al., 2022).

2. Fabrication processes

Challenge: plant-inspired shape-changing interfaces aim to fulfill the growing demand for personalized fabrication while maintaining the precision necessary for accurate and reproducible shape transformations. Technologies such as 3D printing enable highly customized forms, yet challenges remain in achieving consistent quality and high precision in large-scale production. Ensuring the accuracy of shape changes while maintaining material integrity requires advances in manufacturing processes that can accommodate the dynamic and flexible nature of these interfaces. Furthermore, there is a need to simplify production workflows and develop prototyping toolkits that assist with high-precision fabrication.

Opportunity: key research opportunities include fabricating novel multifunctional materials using AI-assisted technologies (Zhu ZJ et al., 2021; Faruqi et al., 2025) and developing open-source, modular design-to-fabrication toolkits (Qamar et al., 2018) that could significantly enhance the precision, reproducibility, and accessibility of these complex interfaces.

### 5.3 Energy integration

Challenge: energy consumption presents a critical challenge in the development of shape-changing interfaces. While plant-inspired systems often leverage natural energy sources (Lu et al., 2023, 2024; Wang GY et al., 2025), these sources are inherently variable and uncontrollable, limiting their widespread application. Alternative energy-driven systems, such as electric or pneumatic actuators, require complex integration of sensors, actuators, and control systems. However, such systems often face challenges related to compatibility, coordination, and long-term sustainability.

Opportunity: future research avenues could explore material-integrated energy solutions, such as developing self-actuating materials with inherent energy harvesting capabilities, or investigate hybrid energy systems and miniaturized, low-power control units (Ahmad S et al., 2024).

### 5.4 Application scenarios and requirements

1. Application scenario and functionality matching

Challenge: while plant-inspired shape-changing interfaces hold significant potential across various fields, a key challenge remains in precisely matching their functionality to the diverse demands of different application scenarios. For example, in medical applications, the interface needs to provide precise pressure feedback or adapt to the varying body shapes of patients (Tan et al., 2020; Wang GY et al., 2023b), whereas in environmental monitoring, the system needs to dynamically respond to real-time changes in environmental conditions. Traditional methods of applying biomimicry to static, non-dynamic interfaces often fall short when dealing with the complexities of shape-changing interfaces (Luther et al., 2015).

Opportunity: advancing generalizable, cross-disciplinary methodologies and adaptive design frameworks is significant, as it not only matches bioinspired behaviors with diverse application requirements but also facilitates knowledge transfer and tool development across domains.

2. Large-scale application requirements

Challenge: scaling plant-inspired shape-changing interfaces for large-scale applications, such as in agriculture, presents challenges in both production and standardization. It is difficult to achieve mass production while retaining the ability to customize for different needs, and it is challengeable to ensure consistent quality across varying environmental conditions.

Opportunity: developing processes that balance cost, customization, and standardization is key to facilitating the widespread adoption of these technologies. Research into scalable, customizable manufacturing processes and cost-effective quality assurance methods is pivotal for supporting large-scale deployment.

### 5.5 Performance and reliability

Challenge: a great challenge for plant-inspired shape-changing interfaces is to ensure that their performance surpasses that of their natural counterparts, offering greater control and superior functionality. While these interfaces may perform well in laboratory settings, their reliability and stability over extended periods in real-world environments remain uncertain. Conducting thorough evaluation tests is crucial to assess system durability and ensure consistent performance.

Opportunity: key research includes developing standardized evaluation methods and investigating adaptive mechanisms to ensure real-world performance and reliability.

### 5.6 Policy, ethics, and regulation

Challenge: ensuring the safe and ethical deployment of plant-inspired shape-changing interfaces presents a significant challenge. As an emerging technology, it requires regulatory frameworks that support innovation while maintaining public safety.

Opportunity: policies must balance safety, security, and technological progress, particularly as these interfaces expand into medical, architectural, and environmental applications.

Additionally, key concerns include safety risks to ensure that shape-changing materials do not pose harm, and control mechanisms to prevent unintended transformations. Ownership and liability must also be defined, particularly in autonomous or interactive applications. Furthermore, the non-permanency of shape-changing materials raises traceability issues, requiring compliance standards for long-term reliability.

## 6 Conclusions

Shape-changing interfaces have exhibited great potential across various fields due to their high adaptability, sustainability, and adjustability. The development of science and technology helps researchers discover the mystery of plant systems and mimic them to benefit human beings. More opportunities for designing, making, and applying such plant-inspired shape-changing interfaces are constantly emerging. However, problems and challenges also exist for researchers to solve and overcome. In the design stage, a comprehensive understanding of shape-changing principles of plants and more interdisciplinary tasks are required to help mimic natural behaviors in proper ways. Meanwhile, the emergence of more functional materials and efficient fabrication technologies in recent years has prompted researchers to apply them to shape-changing interface studies, thereby advancing the development of shape-changing interfaces. Thus, shape-changing interfaces with much higher performance and reliability can contribute to more scenarios and represent more value. In the future, shape-changing interfaces are expected to make significant progress in performance, intelligence, universality, and sustainability. Progress will be essential in the harmonious symbiosis of humans and nature, reminding humans to learn from nature and requite nature back.

In conclusion, this review offers a detailed overview of plant-derived shape-changing phenomena in nature and recent advancements in plant-inspired shape-changing interfaces including design strategies and practical applications. A critical analysis of emerging opportunities and persistent challenges offers theoretical and technical frameworks for future work. We hope that this work will serve as a valuable resource for researchers and practitioners in the field of bioinspired shape-changing interfaces.

### Contributors

Guanyun WANG initialized the idea and supervised the project. Junzhe JI and Chuang CHEN conducted the investigation and contributed to the organization of the paper. Boyu FENG performed the investigation and visualization. Ye TAO supervised the project and contributed to the organization of the paper. Junzhe JI, Chuang CHEN, and Boyu FENG drafted, revised, and finalized the paper.

## Conflict of interest

All the authors declare that they have no conflict of interest.

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