SoftBioMorph: Fabricating Sustainable Shape-changing Interfaces using Soft Biopolymers

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Figure 1: We showcase four out of our five case studies: from top left to bottom right, an epidermal notification interface, a biodegradable seed dispenser, a mechanical bending actuator on a paper bird, and a replication of the soft pneumatic gripper [63]. ©Madalina Nicolae

ABSTRACT

Bio-based and bio-degradable materials have shown promising results for sustainable Human-Computer Interaction (HCI) applications, including shape-changing interfaces. However, the diversity of shape-changing behaviors achievable with these materials remains unclear as the fabrication knowledge is scattered across multiple research fields. This paper introduces SoftBioMorph, a fabrication framework that aims to integrate the fabrication know-how of sustainable soft shape-changing interfaces with biopolymers. Based on the example of Sodium Alginate, the framework contributes (1) a set of material synthesis processes that modify the biopolymer's properties to fulfill different functions; (2) a set of DIY crafting-based assembling techniques that functionalize the material and assembling properties to achieve three primitive types of change in shape; and (3) a series of application cases that demonstrate the versatility of the framework. We further discuss limitations, research

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questions, and fabrication challenges, presenting a comprehensive approach to sustainable prototyping in HCI.

CCS CONCEPTS

• **Hardware → Emerging interfaces**; • **Human-centered computing → Haptic devices**; **Interaction devices**.

KEYWORDS

bioplastics, biopolymers, biomaterials, DIY, sustainability, fabrication, prototyping, shape-changing interface, tangible interfaces

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1 INTRODUCTION

Soft materials are widely used in HCI for the fabrication of shape-changing interfaces. They present inherent mechanical properties that are highly relevant and easy to functionalize to achieve different types of change in shape using a wide range of fabrication techniques. However, shape-changing interfaces are often built with elastomers, thermoplastics, and shape memory alloys which are rarely sustainable. Furthermore, their production is often outsourced, and their end-of-life resumes to a slow or no degradation.

Recently, the use of sustainable materials has become increasingly prominent in fabrication research. This includes biopolymers, as prototyping materials. Known as *bioplastics*, biopolymer-based materials are compatible with traditional HCI digital fabrication techniques. They are biocompatible and can be manipulated to exhibit a wide range of mechanical and visual properties, such as elasticity, toughness, or transparency. Bioplastics have shown promising results for HCI applications [8, 34, 77], including first work exploring the creation of shape-changing interfaces [30, 63, 68, 69, 74].

However, the design process of shape-changing interfaces, especially when considering bioplastics, remains challenging. In the literature, compositions and fabrication techniques are typically adapted on a case-by-case basis to obtain a specific behavior. Therefore, to go beyond one-off designs and achieve a larger diversity of 3D shape-changing behaviors [54], one needs a variety of biopolymers. Additionally, for pneumatic applications, the assembling of different layers and interfacing to the inflatable device using conventional methods (e.g., glue, glue-gun, heat sealing) is often impossible as the materials can react to glue solvents, are water soluble and thermoreversible.

To address these limitations, this paper presents SoftBioMorph, a fabrication framework for creating bio-based and biodegradable, soft, shape-changing interfaces. It focuses on maximizing the types of change in shape achievable with a single biomaterial and presents the synthesis, assembling, and interfacing techniques for pneumatic and fluidic applications. SoftBioMorph derives from a structured design and prototyping exploration of fabricating sustainable shape-changing interfaces.

SoftBioMorph focuses on the use of Sodium Alginate (SA) as an example material to explore how biopolymer synthesis and crafting-based processing techniques can align with specific shape-changing behaviors for pneumatic and fluidic applications. Among the different biopolymer-based materials that have been explored so far in HCI, the properties of Sodium Alginate align best with our focus. It is a cold-gelling, low-cost, and easily accessible biopolymer extracted from brown algae. Its properties can be modified using simple synthesis processes to respond to different stimuli or to display different mechanical properties and, hence, fulfill different functions.

We demonstrate how to achieve three primitive types of topologically equivalent shape-change: *volume*, *orientation*, and *form*. Informed by the functional properties required for these shape changes, we identify synthesis processes from the Material Science literature that are doable in a do-it-yourself (DIY) environment. We then adjust those to become usable in one integrated process, tunable to different desired functions, and compatible with simple lab environments. SoftBioMorph allows for change in shape by two means: (1) the material properties that can be modified through the synthesis processes we propose (i.e. elasticity, water absorption, water resistance, and shrinking); (2) the geometry and structure that can be modified through the assembling techniques (i.e. water sealing, patterning, layer stacking, casting, heat sealing, and molding). To showcase how the synthesis and assembling processes of different associations create different behaviors, we present five application cases that cover the three primitive types of shape change.

Overall, this fabrication framework aims to integrate environmental considerations into the design process of sustainable shape-changing interfaces. It expands the spectrum of shape-changing behaviors achievable with the same material. Further, it opens up new opportunities for HCI researchers to delve into the impact of the materials used and their properties on user interactions. As a first step towards lowering the entry barrier for sustainable prototyping of shape-changing interfaces, we hope our work opens up new avenues to develop materials not only adaptive to shape changes but also responsive to environmental conditions and user interactions. In summary, we contribute:

(1) A fabrication framework focused on shape-changing behaviors that provides:
   - A set of material synthesis processes that modify the biopolymer's properties to display different mechanical properties
   - A set of crafting-based assembling techniques that functionalize the material properties to allow for different types of change in shape
(2) Several examples that demonstrate how synthesis and assembling techniques can be combined to create sustainable shape-changing interfaces using soft biopolymers

2 RELATED WORK

2.1 Shape-Changing behaviors and taxonomies

The field of shape-changing interface research is at the intersection of material science, mechanics, and human-computer interaction [1]. Many devices have been proposed, with different shapes, types of actuation, or materials. These include linear actuators [17, 28, 32, 44], inflatable surfaces [53, 59, 72] that changes volume, or grippers that changes orientation [22, 58, 70, 75]. Taxonomy of the type of shape change is a key aspect as it serves as an entry point for designers and researchers. Several taxonomies have been proposed or used to frame the design of shape-changing interfaces, each with a specific approach. Rasmussen et. al. [54] reference 8 types of changes in shape, among which 6 are topologically equivalent (Orientation, Form, Volume, Texture, Viscosity, Spatiality). Their approach considers both macro-scale change and micro-scale perceptual surface change. In our work, we primarily focus on macro-scale visible shape change. Other taxonomies rely on the mechanisms of shape-change from the properties of the materials [9], or present actuation strategies from a hardware perspective [57]. Recent taxonomies extended the space of the Shape-Changing interface to encompass manufacturing and end-of-life considerations [52].

2.2 Prototyping with biopolymers in HCI

The maker community has adopted the term "bioplastics" which encompasses materials that are "bio-based" and/or "bio-degradable" [14] to refer to DIY-crafted sustainable materials made with natural polymers. The accessibility has been lowered thanks to various design formulations shared as books [12, 13], community archives [42] or research papers [2, 34]. Being bio-based and bio-degradable, bioplastics, along with other biomaterials such as bacterial cellulose and mycelium, are explored for the creation of sustainable tangible interfaces [3, 5, 34, 46]. These sources propose formulations often adapted to create sheets of materials, which are enough to create complex and fine-tuned materials.

"Biopolymer"-based materials have been extensively studied in Material Science [6, 11, 29, 51]. Researchers proposed materials for the creation of films [27, 41, 73, 79], soft actuators and sensors [7, 71] and for 3D printing [24, 26]. However, their formulations and fabrication processes often include advanced lab-grade solutions, or dangerous manipulation in a DIY environment. Therefore, finding the proper material formulation for a precise application doable in a DIY environment is still challenging. Moreover, understanding the process for a beginner can also be challenging. Recent work in Human-Computer Interaction bridges the gap between these two communities and consolidates the knowledge of prototyping with biopolymers for applications ranging from sustainable electronics [8, 34], shape-changing [30, 63, 68], interactive food [69, 74], or just as design material [2].

2.3 Fabrication of Shape-Changing Interfaces

In this paper we focus on Shape-Changing Interfaces that can be fabricated with raw material. Hence we exclude the robotic-actuated interfaces. We concentrate on those that leverage either the inherent properties of materials or specific geometric configurations to achieve transformation. We divide these shape-changing interfaces into two main categories: the first interfaces that have a material-induced shape change and the second interfaces that change shape due to their geometry.

The material-induced shape change consists of assemblies of materials that react to stimuli. For instance, humidity [69, 74, 78], heat [45] have been used to bend or twist the surfaces. These transformations are typically observed in thin-film structures, which are either composed of multi-materials or multi-layered materials. Electroactive Polymers (EAPs) are notable for their ability to undergo substantial deformation and are easily fabricated by combining silicon and carbon.

Other types of materials have a shape change induced by the geometry. In this case, the shape change is induced by the fabrication or assembly process [19, 40, 63–65, 68]. A wide variety of works and systems presented 3D printed auxetic structures [33, 38, 49]. These are easy to fabricate with a 3D printer but use plastic as base material.

Molding, particularly with silicone, emerges as a common practice for fabricating soft actuators [20, 61, 64], enabling precise control over the shape transformation at a macro-scale. These geometrical modifications are not limited to large structures but also extend to textural patterns [69, 74] on the interface, developing mechanisms and structures that, upon actuation, deform in a pre-defined manner.

In this work, our main focus is on proposing a fabrication framework for soft biopolymers intended for shape-changing interfaces. This framework aims to support non-hazardous DIY fabrication using a versatile material and could potentially enable global or localized control of the shape change.

3 SOFTBIOMORPH FRAMEWORK

SoftBioMorph is a fabrication framework that derives from a structured exploration of creating bio-based and bio-degradable shape-changing interfaces using biopolymers, here Sodium Alginate. In this section, we first present an overview of our framework and its properties. The next sections of this paper present in detail the fabrication aspects of our framework and explain the process that led to their selection.

3.1 Overview

Figure 2 illustrates our fabrication framework relying on three main strategies to design a shape-changing interface. These strategies are the main entry points of the framework (**bold** in Figure 2) and choices the designer has to make.

Strategy by type of change in shape The designers or researchers often use the desired movement or shape changes as the entry point of any design requirement. Therefore, our fabrication framework encourages exploration following the diversity of types of change in shape [54] that shape-changing interfaces can exhibit, particularly by topological equivalent types. We identify **volume**, **form** and **orientation** in Figure 2) as some of the most common and versatile types of change in shape. These are often used as target references in traditional shape-changing materials [47] and have also been explored with biomaterials [30, 63, 69]. Although the change in **texture** is also a common reference, this case is discussed in the section 7.1 as it can occur systematically and simultaneously with the other types of changes due to the nature of materials.

Strategy by Material In traditional fabrication, designers dispose of a bank of materials from which they choose. In the case of biopolymer-based fabrication, they can synthesize the material and change its formulation. We refer to *material parametrization* as the

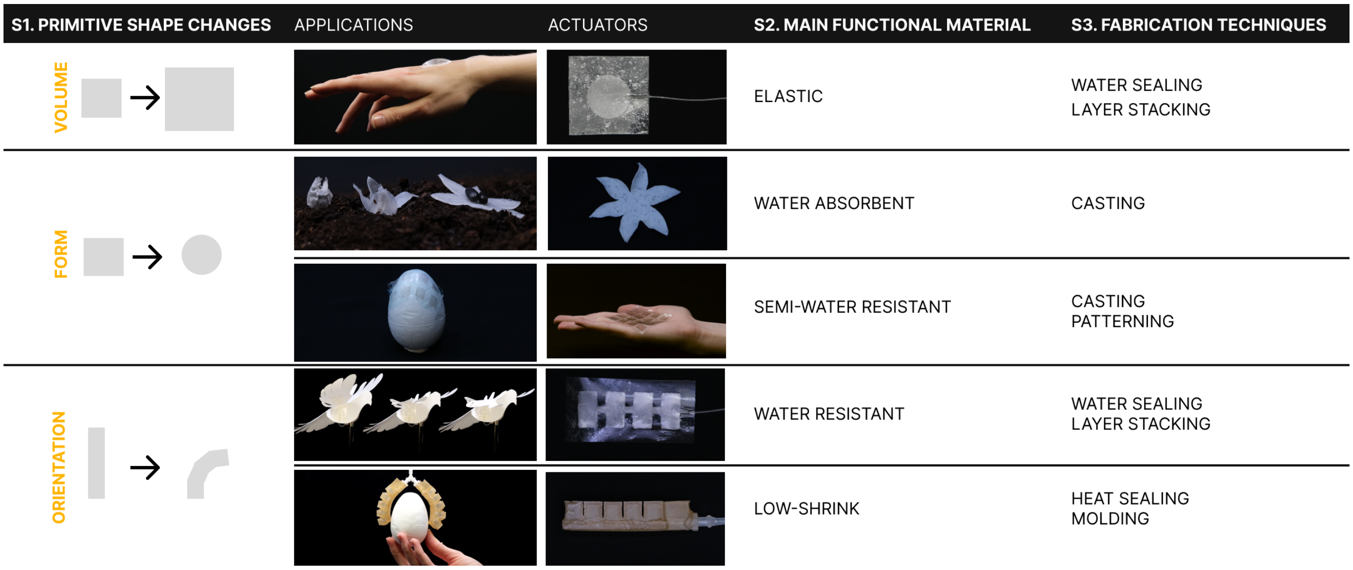

Figure 2: Fabrication framework based on Sodium Alginate for sustainable shape-changing interfaces, in bold the design strategies, in yellow the primitive shape change. ©Madalina Nicolae

process through which one material can be modified to respond to different stimuli or locally display different mechanical properties and, therefore, fulfill different functional properties. The material synthesis should go beyond surface customization and allow the modification of mechanical, visual, and chemical properties of the material, such as elasticity, water resistance, water absorption, and volumic shrinking.

Strategy by Fabrication Technique Each formulation based on Sodium Alginate presents unique benefits for soft device prototyping. However, compared to well-established techniques for synthetic polymers, processing techniques for biopolymer-based materials are unclear and adapted case-by-case precisely to their infinite diversity. Therefore our framework proposes processing techniques that allow creating assemblies while preserving the benefits each layer offers. From the existing literature [52], we identify compatible assembling processes such as **layer stacking**, **casting**, **heat sealing** and **molding** and complement them with two processes related to biopolymers' strong relationship with water, **water sealing** and **patterning**.

3.2 Design & Fabrications Challenges

Our related work demonstrates that while shape-changing interfaces are increasingly used, design & fabrication challenges still remain. Our goal was thus to design a framework for HCI researchers, designers and makers. It equally targets novice users with an easy entry point, and expert users. With this in mind, our sub-goals were the following.

DC1: Democratization of the fabrication technique. SoftBioMorph aims to democratize the fabrication know-how of bio-based and bio-degradable soft shape-changing interfaces. First, we tackle this objective by integrating knowledge of material synthesis and assembling processes gathered from multiple fields such as material science, bioengineering, robotics, and design. Second, we foster democratization by making these processes accessible and reproducible in do-it-yourself (DIY) environments, notably using basic lab equipment and food-grade market-available products. This increases the accessibility for novice users.

DC2: Use of Versatile Material. By focusing on a single biomaterial, we go beyond "customization" or "personalization" of the visual properties of the material and aim for a multidimensional functionalization. This unique opportunity is brought by the use of different additives that allow mechanical and structural properties such as elasticity, water resistance, absorbance, shrinking, and transparency. This widens the spectrum of shape-changing behaviors achievable using a single material and lets the designer be focused on its design goals and desired shape-change.

DC3: Global or Localized Control of Shape-Change Biopolymer-based materials such as Sodium Alginate can be modified at specific locations. As a result, it is possible to create different mechanical properties that allow for different types of change in shape within the same sheet of material. Therefore, the SoftBioMorph framework enables a fine-grained approach to design and opens up new opportunities for shape-changing interfaces or multi-modal interactions.

3.3 Method

Our approach followed a two-step process. First, we started by engaging with potential users through a focus group to better understand the potential usage of biopolymers. We then followed a mixed method of Research Through Design (RtD) and Material Driven Design (MDD) to initiate a systematic DIY experimentation and exploration of the fabrication techniques.

3.3.1 *Focus group.*

To inform our design exploration, we first conducted a one-hour focus group with 22 experts from design, fabrication, robotics, material science, and Human-Computer Interaction.Our goal was to understand how researchers could use shape-changing biopolymer structures in the field by gathering opinion [48], guiding the focus group to generate new ideas, and identifying potential application cases and relevant materials and shapes. Participants were first provided with basic knowledge of what are biopolymers. To support the discussion, we designed and brought several sheet samples of material, and a few pouch-like actuators, which the participants could freely manipulate. The participants were asked to reflect in groups of 4-5 people on potential applications of biopolymer shape-changing interfaces while being guided by 2 organizers. The collected data was analyzed thematically.

The participants discussed about the properties and limits of the material but also issues relative to the fabrication and assembling processes available. Among 36 designs generated, 20 of them were shape-changing interfaces, while the remaining 16 were replacements of traditional plastic parts with biopolymer-based ones. The most reported shape-changing behaviors were changes in form, orientation, and volume. Most of the participants reported difficulty in finding the appropriate techniques to produce the desired shape-changing behaviors.

3.3.2 Research Through Design and Material Driven Design. Inspired by the exchange during the focus group, we initiated a systematic DIY experimentation and exploration with the goal of both 1) discovering new techniques for the desired shape-changing behaviors and 2) establishing a structure to present these techniques. Our exploration followed a mixed method of Research Through Design (RtD) and Material Driven Design (MDD) [23, 31, 80].

In the design exploration phases, we relied equally on an interdisciplinary literature review, our expertise in using the material, and findings from iterative prototyping. The systematic documentation of the distinct phases of our design process allowed us to consolidate our knowledge and fine-tune our design framework. This, in turn, helped us to define relevant fabrication processes, materials formulations, and new functional opportunities for shape-changing devices.

Next, we conducted several cycles (approx. 10) of material synthesis to find the most appropriate formulations. Every time we informally asked other lab members to manipulate the material and inform us if they felt the material would match their expectations. This process allowed us to fine-tune the overall material composition, such as the additives. Once all the formulations were confirmed qualitatively, we moved to cycles of fabrication and assembly to inform the detailed composition, i.e. the exact percentage of each additive. Overall, this mixed approach process allowed us to gain better knowledge of the design process before and during fabrication.

4 SYNTHESIS TECHNIQUES

Accessible synthesis techniques are a primordial aspect of this framework as they allow designers to fabricate the materials according to their objective. Therefore, guided by the democratization objective of the framework, we identify and adapt material science synthesizing processes of sodium-alginate-based materials to make them accessible and reproducible in DIY environments, which require basic lab equipment and food-grade off-the-shelves products.

In this section, we describe the principles of having a single biopolymer solution as a base; the five declined formulations, and their synthesis processes. The functionalizable properties obtained include **elasticity** - for change in shape through expansion in multi-layered systems, **water resistance** - for fluid and pneumatic applications of multi-layered systems, **semi-water resistance** and **water absorption** - for change in shape trough hygroscopy in single-layered systems, and **low-shrinking** allowing for volumetric applications.

These key properties will be used as descriptive appellations of the five formulations. Their complete composition, properties, and compatible processing techniques are detailed in Figure 3 and their synthesis processes in Figure 4.

4.1 Base Solution Principles

Having a single biopolymer solution as a synthesis base facilitates understanding the impact of each additive and fastens the overall synthesis process. Our synthesis base is a Sodium Alginate gel with a concentration of 4% (i.e. 4g of Sodium Alginate for 100g of water) that relies on previous HCI [34] and material science literature [27]. This gel and the resulting films will be referred to as *SA gel* and *SA films*.

To this base, we add different additives and use cross-liker agents (Figure 3) to provide different mechanical properties (Figure 3 column *Properties*), which allow different processing techniques (Figure 3 column *Peocessing Techniques*). The additives we use are plasticizers (e.g., Glycerin (**GLY**) for elasticity) or other biopolymers (e.g., Carboxymethyl Cellulose (**CMC**) for water absorbance, Gelatin (**GEL**) for low-shrinking). The cross-linking agents are molecules that facilitate the creation of different bonds between the biopolymer chains. Sodium Alginate gels react almost instantaneously to Calcium Lactate (**CL**), Calcium Chloride (**CA**) and Acetic Acid (**AA**). CL and CA create ionic links via the Ca2+ ions, while AA creates water-insoluble alginic acid microcrystals, a form of physical links [37, 60, 79]. They thus impact the gel solubility, i.e. the water resistance or semi-water resistance.

The synthesis process of each composition ends with the creation of thin films via solvent casting method [16, 56] or 3D molded structures. They are then shaped or assembled using the processing techniques in the following section. The synthesis and evaluation are effectuated in a fab-lab environment with 30% humidity and temperature approximating 25°C.

4.2 Elasticity

Elastic films are necessary for applications where high deformation is required such as change in volume and change in orientation. GLY is an organic compound that acts as a humectant, preserving the moisture content of biopolymer gels and films. Adding GLY to SA-based gels increases their softness and elasticity [15, 18, 21, 34]. Therefore to create elastic films, 5% (by mass, i.e. 5g for 100g of water) of GLY is added to the base SA gel. After pouring the film, a solution of 6% CL is sprayed over (see Figure 4 ELASTIC) to fasten the drying process while preserving the elasticity. Compared to a CA, CL has a slower linking process [37], which avoids the creation of lumps on the film. The dry ELASTIC films we obtain can elongate by approx. 50% of the initial size.

NAME	GEL FORMULATION concentration of each component in the gel				CROSS-LINKERS concentration of cross-linking solutions			PROPERTIES only relevant							PROCESSING TECHNIQUES allowed by the properties				
	BASE	ADDITIVES						ELASTIC	WATER RESISTANT	SEMI-WATER RESISTANT	WATER ABSORBENT	LOW-SHRINK	THERMO-REVERSIBLE	ALCOHOL RESISTANT	WATER SEALING	PATTERNING	FORMING	MOLDING	HEAT SEALING
	SA	GLY	CMC	GEL	CL	CA	AA												
ELASTIC	4%	5%			6%			✓	✗					✓	✓	✓			
WATER RESISTANT		5%			6%	3%		✗	✓					✓			✓		
SEMI-WATER RESISTANT		5%			6%		20%	–		✓				✓			✓		
WATER ABSORBENT			25% of a solution of 5%			3%					✓			✓			✓		
LOW-SHRINK		30%		50%				✓				✓	✓					✓	✓

SA: Sodium Alginate E401 - Algizoon, Biozoon Shop. **GLY**: Glycerin E422 - Bio Glycerin 99.7%, Doktor-Klaus. **GEL**: Gelatin E441 - Granulated Bovine Gelatin Bloom 250, InkaFoods. **CMC**: Carboxymethyl Cellulose E466 - Carboxymethylcellulose, Würzteufel. **CL**: Calcium Lactate E327 - Calazoon, Biozoon Shop. **CA**: Calcium Chloride E509 - Kalziumchlorid, Würzteufel. **AA**: Acetic Acid E260 - Vinegar Essence 20%, Hengstenberg.

Figure 3: Formulations of the five Sodium Alginate-based gels with the relevant properties and processing techniques. The properties and the techniques allowed by each are paired via colored (blue and yellow) marks.

4.3 Water-resistance and semi-water resistance

Water-resistant and semi-water-resistant films are necessary for fluidic and underwater applications and, respectively, water-induced shape-change. CA and AA are cross-linking agents that create strong bonds within SA-based gels, impacting their water solubility (i.e. level of disintegration upon submerging into water). When SA films are submerged into CA and AA solutions their water solubility measured by the mass loss approximates 28% and respectively 73% compared to 93% for SA films [79]. Therefore, to create WATER RESISTANT and SEMI-WATER RESISTANT films, we submerge ELASTIC dried films in CA 3% and respectively AA 20% solutions for 30 seconds, then in distilled water to clean the residues (Figure 4 WATER RESISTANT and SEMI-WATER RESISTANT). Compared to SA films, ELASTIC films limit the deformation and wrapping of the film during the cross-linking reaction. The films obtained are transparent, flexible, stiff, and display shape memory properties: they conserve the shape in which they've been dried. The WATER-RESISTANT and SEMI-WATER-RESISTANT films we obtain can last up to several hours and respectively 30min submerged in water (low stirring) compared to ELASTIC films that disintegrate under 2min. SEMI-WATER-RESISTANT films can temporarily recover their elasticity in the presence of water.

4.4 Water absorption

WATER ABSORBENT films use the hygroscopic properties of biopolymers as design parameters to create shape-change via swelling [30, 69]. CMC is a highly hydrophilic cellulose derivative obtained from natural cellulose sources like wood pulp, cotton, or other plant materials. Adding CMC to SA-based gels increases their swelling capabilities [27]. Therefore, to create WATER ABSORBENT films we modify the composition and process proposed by He et al. [27]: we add to the SA gel 25% of its mass of a 5% CMC solution prepared in parralel (Figure 4 WATER ABSORBENT). The resulting films have a white shade when hydrated and become translucent, stiff, and brittle when dried. They display shape memory properties: they conserve the shape in which they've been dried and can be reshaped upon rehydration. The WATER ABSORBENT films we obtain can absorb up to 10 times their dry mass when submerged in water in 15 min compared to 1 time and 2 times for WATER RESISTANT and SEMI-WATER RESISTANT films.

4.5 Volumic Shrinking

LOW-SHRINKING materials are essential for volumic applications and stronger actuators. However, **SA**-based gels' water content accounts for 85% to 95% of the gel [27, 34, 37, 60, 79]. This implies a high mass and volume loss of the gel upon evaporation (e.g. 70% mass loss [63]), causing an important shrinking of the casted or molded forms. GEL is a hot-gelling, protein-based natural polymer obtained from bones and cartilage. In the existing literature, CMC [24] and GEL [73] are used to enhance printability and indirectly reduce the shrinking of SA-based gels. Therefore to create a LOW-SHRINK gel, we rely on the suggestions made by Shintake et al. [63] and modify the compositions and process proposed by Wang et al. [73]: we add to the SA-gel 30% of GEL and 50% of GLY (see Figure. 4 LOW-SHRINK). The obtained gel possesses volumic stability and thermoreversible properties. Its shrinking percentage approximates 20% after 48 hours. The other formulations presented in this work are not moldable as the gel needs cross-linkers.

4.6 Degradability

Aiming to create sustainable interfaces that can degrade naturally through decay, the raw materials we use are natural polymers. Due to the need for specialized equipment, we do not determine the biodegradability of our formulations. However, the degradability of the DIY materials obtained from these biopolymers is estimated to 60 days [2] and has been more extensively covered in prior work from materials science [4, 26, 62, 67] where Sodium Alginate is reported to take approx. 7 days to degrade up to 70% [35] while Gelatin is reported to take approx. 20 to 35 days [10]. Additionally, cross-linked Sodium Alginate has been explored as a substitute for soil and as a plant growth substrate [66] and reported to be safe for rodent consumption.

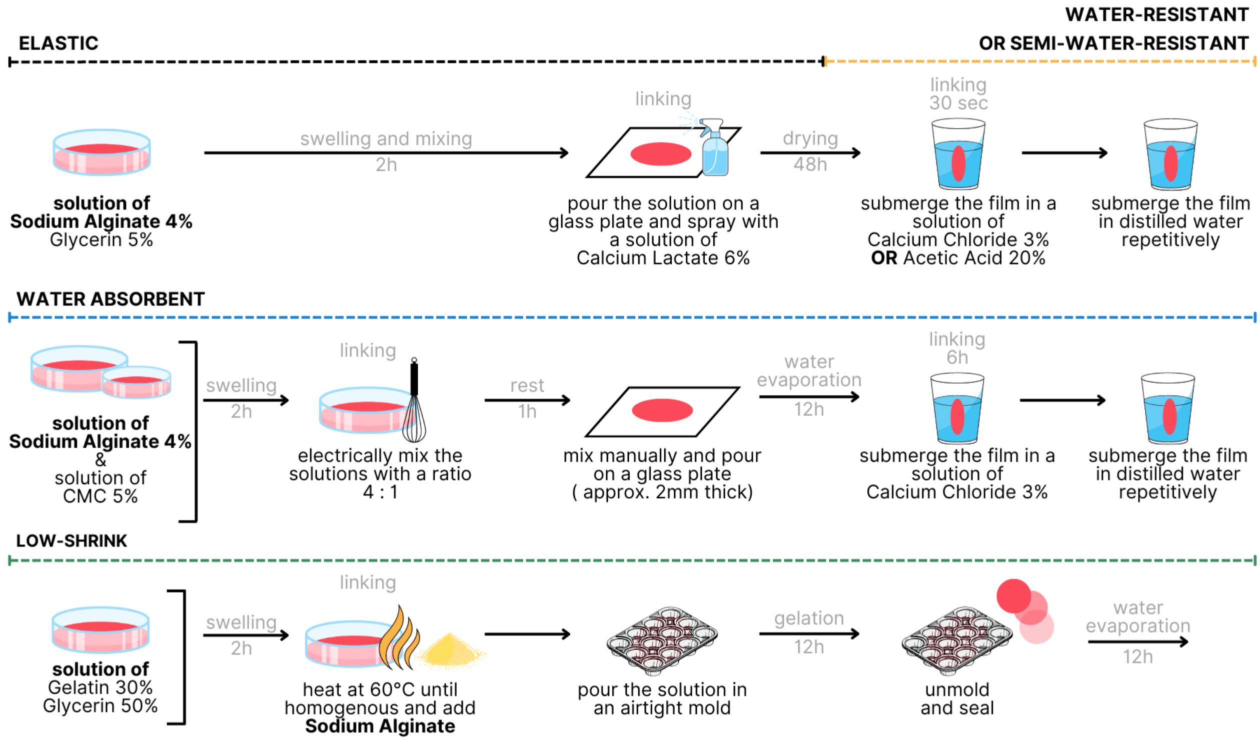

Figure 4: In this figure, we present the five material synthesis techniques and fabrication processes outlined in the framework.

5 PROCESSING AND ASSEMBLING TECHNIQUES

In addition to synthesis techniques, specific processing and assembly techniques are required to program the change in shape. Processing techniques are a central contribution and an entry point of the SoftBioMorph framework. They allow the transformation and assembly of the films into deployable applications. In this section, we first tackle the **connection** of these assemblies to pneumatic or fluidic systems. Then we describe how the different material properties can be functionalized to achieve the three types of changes in shape, via **water sealing** to create layered applications, **casting** for re-shapable applications, **patterning** for locally multi-functional applications and **molding** for 3D applications.

5.1 Connecting air Channels

The connection between the actuation systems and the shape-changing material is a challenge that has been highlighted in traditional Shape-Changing interfaces. In the following demonstrators, we rely on pneumatic systems. In this case, an air channel needs to be connected to cavities in the materials.

In the case of connecting biopolymer-based materials to pneumatic or fluidic systems, we face a similar difficulty. Our materials cannot be sealed with classic glue or heat (except the formulations that include thermoreversible biopolymers such as gelatin). We use a soft food-grade silicone tube as an air channel. The tube has an internal diameter of ⌀0.5mm and an external diameter of ⌀1mm. In the case of sheet-fabrication and pneumatic actuation, the tube is placed between the layers during the assembling of the actuators, and after they dry, the tube is sealed using a bio-based glue (CléoBio, Cléopatre water reversible glue based on starch) pushed between the layers through a 25G long needle. In the case of fluidic applications, we use a classic multi-material glue (SCOTCH extra multi-material glue). The glue dries in 12 hours and allows for a robust connection during use.

For molding, we use a Luer Lock adaptor(screw connection that care providers use on syringes to easily connect needles and tubing) to allow the connection to the inflation system while limiting the mechanical stress.

5.2 Water sealing

We leveraged the partial water solubility of ELASTIC films as an assembling method. In contact with water, the film hydrates on the surface and partially become a gel. When in contact, two moisturized films can fuse during the drying phase. We dispense water with a manual spray to have a homogeneous moist layer. We use talc powder to create patterns or zones that we want to exclude from the moisturizing process. This technique allows local control of the fusing, hence maintaining the layers separated in specific areas and sealing them in others. This allows the creation of pockets to design water sealing, pneumatic, or microfluidic actuators.

We use this method for the actuators in Figure 5 using two ELASTIC films, one WATER RESISTANT, and one ELASTIC. To design actuators, we create various sealing patterns using talc powder, which we spread over the hydrated WATER RESISTANT films using a dry brush and an acetate stencil. Then we use the negative of the

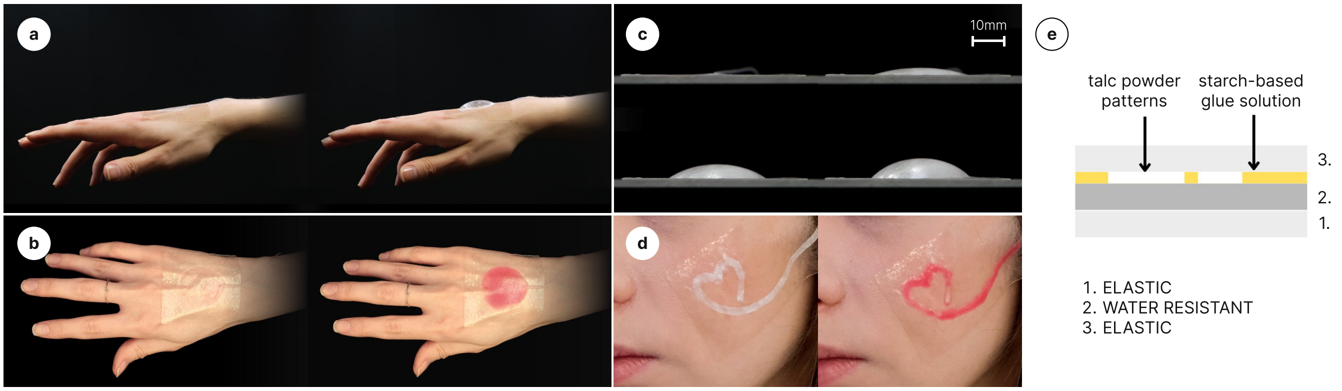

Figure 5: Pneumatic and fluidic on-skin actuators for epidermal silent notifications (a, b, d) with resting, partially inflated, and fully inflated details of the change in volume of the pneumatic actuator (c) and their structure (e). ©Madalina Nicolae

stencil to protect the talc area and spray the sealing areas with a solution of water mixed with 20% bio-based glue (CléoBio, Cléopatre water reversible glue based on starch). We then place the silicone tube connector and the top ELASTIC film, andleave the assembly to dry for 12h, then secure the tube as described above.

5.3 Patterning

Patterning takes advantage of the high and quick water absorption capabilities of the ELASTIC films.A liquid solution can penetrate almost immediately the thin film in depth with limited dissipation. Thus, the ELASTIC film can be locally transformed into WATER RESISTANT or SEMI-WATER RESISTANT using 3% CA and respectively 20% AA cross-linking solutions (Fig. 3). A single film can thus exhibit different localized mechanical properties depending on the patterns.

We use this method to create multi-functional anisotropic sheets (Fig. 7 b) that combine locally the adhesiveness and elasticity of ELASTIC, toughness and water resistance of WATER RESISTANT, and malleability of partial water soluble SEMI-WATER RESISTANT. The cross-linkers are sprayed on the driedELASTIC sheet via stencils. For a better visualization of the areas that reacted to each cross-liker, we mix the cross-linking solutions with a few drops of food coloring and spray every 30 seconds until the coloring becomes clearly visible (Fig. 7 b).

5.4 Forming

As they contain a high amount of water, sodium-alginate based gels can be cast into sheets but are in general too liquid to be cast in thick layers or on volumic shapes.However, the shape-memory properties of WATER RESISTANT, SEMI-WATER RESISTANT and WATER ABSORBENT can be used to shape the material upon drying via water evaporation. As the films dry and become stiff, if they're placed on top of an object, they'll take the shape of the object.

We use this method to design a biodegradable seed dispenser (Fig. 7 a). We cut flower patterns into hydrated WATER ABSORBENT films and use this method to dry the flowers in a bud shape, enclosing (or not) different grains inside. Anisotropic patterned sheets can be also formed by rehydrating the cross-liked areas for 10 seconds and placing them on different objects as in Figure 7 b.

5.5 Molding

This process is typically used for soft-robotic actuators and consists of encapsulating a gel material in a mold. Despite the lower shrinking ratio of the LOW-SHRINK formulation, molding is yet challenging as the gel needs to maintain its volume and viscosity during drying. Early findings on biopolymer molding [63] reported that the mass loss of the films is the highest in the first 24h and reaches an equilibrium after 48h. Therefore, the molds used should be airtight so the solution can cool down and finish the gelling process without deformations.

We prepare a LOW-SHRINK solution following the method in Figure 4 and two 3D-printed airtight TPU molds, one part that contains the creases and one that is flat. We pour the solution and let it set for 12h at room temperature, then unmold and glue the two parts using a fresh LOW-SHRINK solution, letting it set again for 12h. To avoid possible deformations during the drying process due to the adhesiveness of the actuator to the surface it is placed on, we brush talk powder on all the surfaces of the actuator to ensure uniform shrinking. Finally, place the Luer Lock connector. We used this technique to mold a finger-like actuator (Fig. 6), a typical actuator for soft robotics.

6 APPLICATIONS EXAMPLES

To demonstrate the framework's potential, we designed several applications that illustrate each type of change in shape. The applications highlight the unique properties provided by the association of material synthesizing and assembling processes.

6.1 Volume

We created two On-Skin actuators to illustrate the change in volume (Fig. 5). On-Skin actuators are used for in HCI for interaction [76], haptic and kinesthetic feedback. To create epidermal notification interfaces (Fig. 5 a), we put a pneumatic actuator on the top of the hand of a user. The actuator acts as a discreet silent notification device. Depending on the importance of the notification, the actuator can inflate to be only noticeable when brushing with the other hand (tactile feedback) or can create direct pressure on the wearing hand (kinesthetic feedback). These demonstrations highlight the

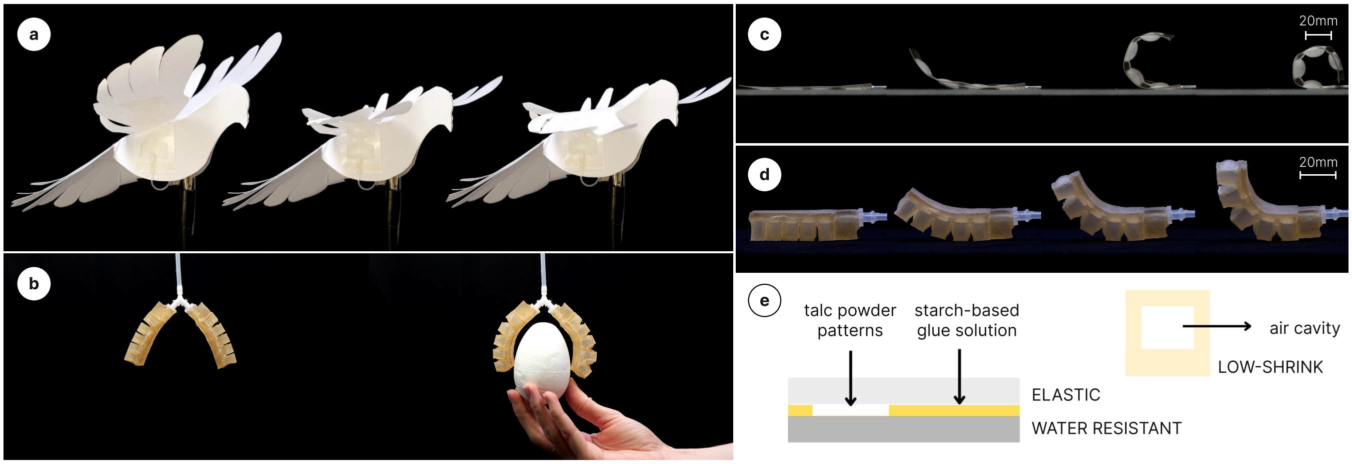

Figure 6: Soft bending actuators displaying the mechanical movement induced on a biodegradable lightweight structure by a planar actuator (a) and the movement of a volumic gripper actuator (b), with detailed bending angles (c,d) and structure (e) . ©Madalina Nicolae

biocompatibility, transparency, and wearability of Sodium Alginate films.

The shape change is achieved by synthesizing ELASTIC and WATER RESISTANT films and processing them through water sealing and layer stacking methods. Each actuator comprises three sheets fulfilling different roles (ELASTIC for adhesiveness to the skin, WATER RESISTANT for structural support, and an expandable ELASTIC). They are attached to the hand by spraying water on the skin.

The inflatable section is circular with a diameter of ⌀30mm and can expand up to 6.2mm when laid on a flat surface. Above this volume, lamination appears on the edges of the inflatable section. When placed on the hand, a feeling of pressure starts to feel at

Using the films' low alcohol solubility, fluidic versions have been created (Fig. 5 b and d) for visual feedback by filling the actuator with colored alcohol or haptic thermal feedback with low-temperature alcohol.

6.2 Orientation

We take inspiration from [47] and use change in orientation to induce mechanical movement through soft bending actuators (Fig. 6). The actuators are composed of several pouches on the same sheet material that, upon inflation, bend and, therefore, move different parts of lightweight objects. The thin actuators highlight customization opportunities and precise control of the inflatable area.

The change in shape is achieved by associating the elasticity of ELASTIC and stiffness of WATER RESISTANT films processed through water sealing and layer stacking. The WATER RESISTANT acts as a strain-limiting layer while ELASTIC allows inflation without linear contraction.

The bending angle is dependent on the pouch number and their sizes. In our demo, we made an actuator with four pouches of 20mm*40mm separated by 5mm sealed areas, the actuators can bend up to 360° free of charge. However, it is suitable only for the actuation of lightweight mechanisms.

For applications that require sturdier bending actuators such as grippers [63], volumic shapes can be achieved using the low shrinking rate and thermoreversibility property of LOW-SHRINK. Using molding and water sealing we create a gripper with two creased actuators.

The freshly molded actuator has 1.5mm thick walls, a 5mm thick base, five chambers of 7mm*17mm*13mm, and the following overall dimensions: 20mm width, 70mm length, and 20mm height, which after 48 hours become 16mm, 59mm, 16mm, i.e. an average shrinking of 18%. The actuators can bend up to 90° free of charge.

6.3 Form

Inspired by visions using soft robotics for nutrient delivery in agriculture and shape change as germination rate enhancer [40], we use change in form for environment-actuated applications. We create highly absorbent and nutriment-enriched grain pockets that protect the grains until environmental conditions are favorable for grain release, i.e. extended period of rain. The encasing absorbs water and, under payload, opens up delivering nutrients, then biodegrades.

The change in shape is archived using the high swelling capabilities of WATER ABSORBENT associated with casting. Fully submerged in water, the flowers open up completely in approx. 15 minutes.

Also, other relevant changes in form are offered by auxetic and bi-layered structures [45, 69, 74] as the applications can be stored flat and be deployed only when necessary using heat and/or water. They offer storage and space-saving benefits which is rarely the case of bioplastics [34]. Therefore, inspired by these structures, we created patterned, anisotropic sheets (Figure 7).

The change in shape is achieved through patterning and casting using simple cold water. A single sheet displays locally the properties and associates the water resistance of WATER RESISTANT (gray), the partial solubility of SEMI-WATER RESISTANT (light blue), and the elasticity and adhesiveness of ELASTIC (dark blue) (Fig. 7). Dry, it can be stored stacked flat, and upon hydration, it can be stretched and cast on the desired shape.

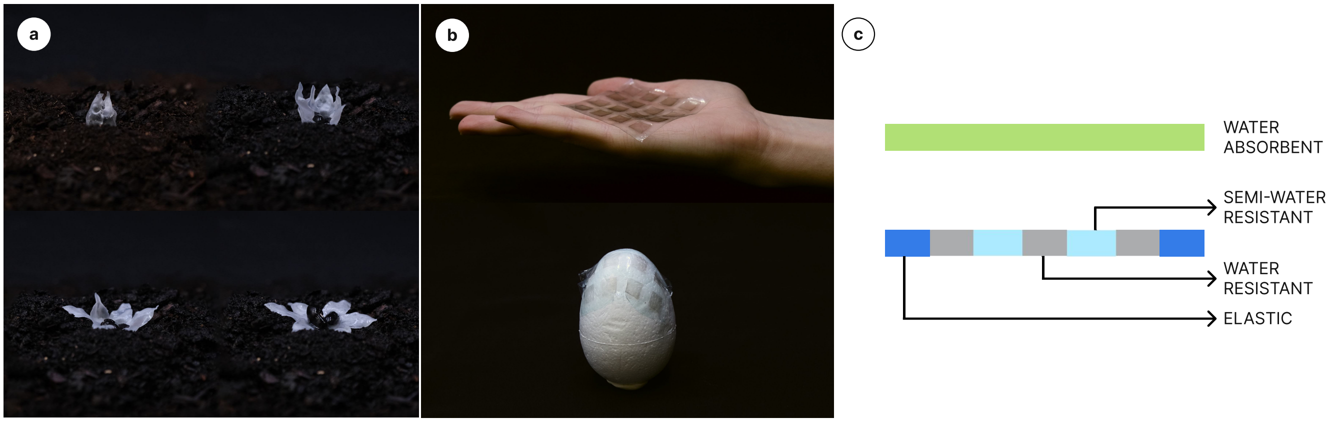

Figure 7: Soft shape-changing materials displaying the humidity-triggered opening of a biodegradable seed dispenser (a) and the anisotropic properties that can be designed on Sodium Alginate sheets (b) with their corresponding material structure (c). ©Madalina Nicolae

7 DISCUSSION AND CONCLUSION

Our research addresses challenges in designing more sustainable shape-changing interfaces by proposing SoftBioMorph, a framework for democratizing fabrication techniques using biopolymers and enhancing material versatility.

7.1 Addressing the design challenges

Our main objectives are to provide a resource accessible to both novice and expert users. The goal of the framework is to address the challenges mentioned in Section 3.2. First, we address the (DC1) democratization of fabrication technique challenge by 1) creating a framework that organizes different fabrication techniques (Figure 2) and 2) providing detailed descriptions of the fabrication techniques in Figure 4. We integrated knowledge from various engineering fields and made processes reproducible in DIY environments, enhancing accessibility for designers, makers, and researchers who are novices in soft biopolymers. We demonstrate (DC2) the versatility of the material and framework by creating five application examples that showcase a variety of achievable mechanical and structural properties. By incorporating additives, SoftBioMorph enables modifications of mechanical and structural properties, broadening the range of achievable shape-changing behaviors with a single material. Our formulations can serve as a starting point for expert designers, makers, and researchers in soft biopolymers. Additionally, the framework could be extended by experts through the addition of new additives or shape change primitives. These five applications also illustrate the possibility of achieving diverse shape-change primitive movements, addressing our last design challenge (DC3). Our approach facilitates both global and localized control of shape-change in materials, supporting a fine-grained approach to design and opening new opportunities for shape-changing interfaces. We now discuss the implications of our research and opportunities for future exploration.

7.2 Design possibilities and opportunities

Sustainable Soft Biopolymers are relatively new in HCI and even more in shape-changing interfaces. Even if we do not claim that our framework is specifically made for generativity, we believe that organizing, describing, and democratizing these fabrication techniques could support designers, makers, and researchers in the exploration and iterative prototyping of novel devices. This is particularly the case because sustainable soft biopolymers offer novel, interesting material properties, including biodegradation, biocompatibility, and edible and digestible in the case of Sodium Alginate. Bio-degradation provides new avenues for degradable objects such as sensor deployment in the wild [39], bio-degradable citizen seed [25] or cellular colonization [51]. Its biocompatibility property offers a unique venue for designing devices that could be carried by humans and animals, such as fashion [50], or even including even biomedical application [36, 55]. The edible and digestible properties make them an interesting material for human-food Interaction [43].

Overall, there can be several entry points when prototyping a SoftBioMorph device. Here, we demonstrate from a shape-changing interfaces perspective how each strategy can be used as a starting point when designing a new prototype. We showed that several materials or fabrication techniques can be used to make a similar primitive shape change. We encourage designers, makers, researchers, and particularly novice users to carefully consider the tools and materials available in their workshop (or kitchen) before fabricating a device. This will help them select appropriate strategies. We believe that materials and fabrication techniques strategies offer a wide range of possibilities that can be confusing for entry-level designers. Therefore, the exploration of different use cases should combine material and fabrication-driven design processes that focus on the functionalization of the properties to maximize the types of change in shape achievable with a single biomaterial.

7.3 Tension between Shape-Change and Sustainability

Although Rasmussen et. al. [54] reference 8 types of change in shape, among which 6 are topologically equivalent; when working with biomaterials, the difference between material property and change in shape is blurry. For example, ELASTIC and WATER RESISTANT films are used in different configurations to achieve shape changes in orientation, form, and volume. However, when ELASTIC and self-adhesive films are submerged in the CaCl solution, they become resistant to water (change in permeability), stronger (change in viscosity), and non-adhesive (change in texture). In this case, the changes are part of the material synthesis process, which question if can/should all these changes truly be considered as changes in shape. While several taxonomies exist to classify the types of shape-changing interfaces, the introduction of new materials in the field needs to be accompanied by an update of these taxonomies. Further methodological and theoretical discussion within the community should tackle the question of the delimitation of material properties, system properties, and behaviors.

In addition, the use of biopolymers or "sustainable" materials has intrinsic limitations. There are materials available that achieve remarkable shape changes, are easier to process, and have more predictable outcomes, but they are not sustainable. Conversely, sustainable materials may have limitations in their ability to achieve complex shape changes; compared to classic materials, they have lower mechanical strength which limits their ability to undergo extensive or repetitive deformations. When produced in a DIY environment, inconsistencies can appear in the material, which impacts their behavior under stress (e.g., lumps in alginate films are weak points). Moreover, the applications we propose address the sustainability of the actuator itself (biodegradable) and its connections (recoverable and reusable), but still rely on classic actuation devices such as pumps.

As designers, makers, or researchers, we must carefully consider whether we prioritize a wide range of deformations or opt for designed products that explore a smaller range of shape changes but are beneficial for both society and the planet. This dilemma prompts us to question the balance between innovation and sustainability in our material choices, challenging us to seek solutions that are not only technologically advanced but also environmentally responsible. In any case, those two approaches are compatible, as SoftBioMorph can be used for quick prototyping iteration to demonstrate a principle, shape, or form.

7.4 Sustainable material as a design advantage

Procurement of materials poses significant challenges for designers, hackers, and engineers in the field of Human-Computer Interaction (HCI). Relying on more easily available, mundane materials could potentially simplify the material sourcing process and reduce costs. However, the materials used in this paper are sourced from off-the-shelf components that still necessitate processing industries. The accessibility of materials is not the only consideration; health and safety concerns also play a crucial role. Currently, there are no limited standards for do-it-yourself and hacker communities, which raises questions about the safety of materials and fabrication processes. Utilizing food-grade materials like those discussed in this paper could enhance safety by leveraging established properties and minimizing health risks associated with unknown materials. We hope this could inspire other researchers to explore other materials.

Expanding on the importance of bio-compatibility and sustainability in material selection for fabrication, it is crucial to consider the entire lifecycle of a material, not just its fabrication process. This holistic approach encompasses not only the potential health impacts during usage, such as whether a material is toxic for users to wear or have in contact with their skin but also its environmental impact at the end of its lifecycle, including recycling considerations. By prioritizing materials with known bio-compatibility and sustainability attributes, designers and engineers can mitigate risks associated with human health and environmental harm throughout the entire lifecycle of a product. Sustainable materials not only minimize adverse effects on human health during usage but also reduce environmental pollution and resource depletion at the end of their life cycle. Nevertheless, although previous works on bioplastics have already demonstrated natural biodegradability, the term 'sustainable material' doesn't inherently guarantee bio-compatibility, although it may contribute. In our research, we conducted a preliminary assessment of biodegradability. Further exploration is necessary to understand the relationship between sustainability and bio-compatibility in fabrication materials.

Overall, our fabrication framework objective is to broaden the collaborative community working on sustainable soft shape-changing interfaces from novice users to experts and allow for a comprehensive exploration of both the scientific and practical aspects of biomaterials, empowering designers with a solid fabrication basis that can be extended with new materials and fabrication techniques.

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