Exploring Biofoam as a Material for Tangible Interaction

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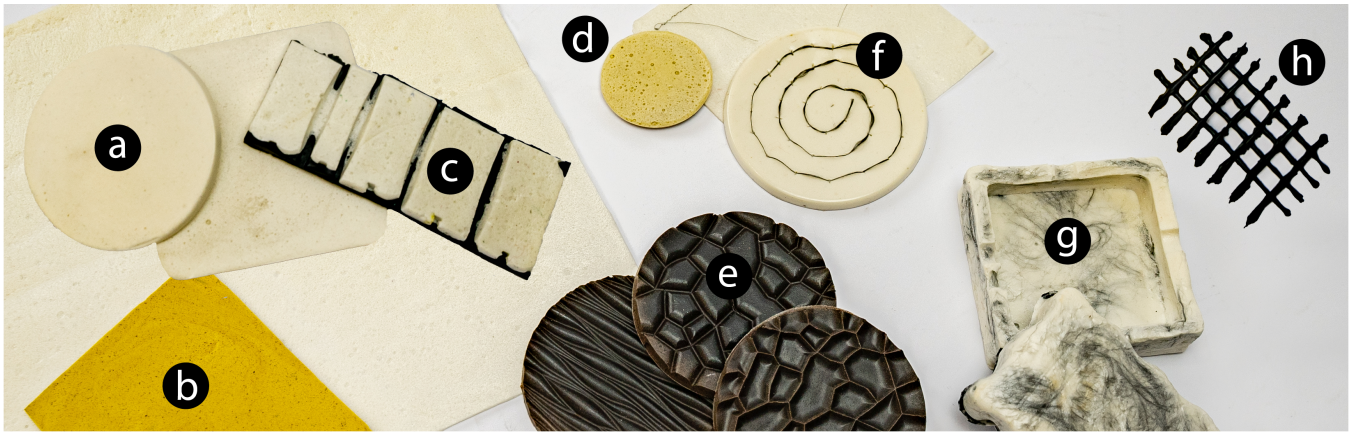

Figure 1: Various biofoam samples created with different fabrication techniques and modifications of the base recipe: a. the base recipe in various thicknesses; b. colored with turmeric; c. in segments on top of a rubbery biofoam base; d. hardened and improved water permeability with pine tree sap; e. colored with walnut powder and cast in custom molds; f. embroidered with conductive thread; g. conductive biofoam with stainless steel fibers; h. extruded into a mesh.

ABSTRACT

Each new material developed opens a broader pallet of aesthetic and functional possibilities for designers. This paper introduces DIS to biofoam, a material that is water-soluble, biodegradable, and can be made conductive. We describe the material in detail: the process of making the material from scratch, the material's fabrication into forms with hand-craft techniques, and present two HCI specific applications of the biofoam. The biofoam can be cooked, molded, layered, extruded, dissolved or recooked opening up possibilities to consider the entire life cycle of the material in the design process. We contribute design considerations to allow designers to "tune" the biofoam to the desired quality, as well as a characterization of many aspects of the biofoam such as compression, spring back time, water permeability, and electrical conductivity. Finally, we discuss the unique opportunities this material and its life cycle bring to the design and HCI communities.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; *Interaction design process and methods.*

KEYWORDS

tangible interaction, material experience, SHCI, biodesign

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1 INTRODUCTION

DIS's growing interest in sustainable design has lead designers and researchers to look for materials that cause little or no harm to the environment. Bio-based materials are materials made from substances derived from living or once-living organisms. These materials are increasingly used in fields such as product design and industrial design, and likewise, HCI researchers have been incorporating bio-based materials into small-scale projects [5, 40, 41]. Although the definition above could include many well-established materials such as wood and leather, researchers of bio-based materials have specifically defined them as materials that **biodegrade and are created from biomass** [9]. The use of bio-based materials in HCI projects has shown particular opportunities for sustainable design in HCI due to their ability to decompose or biodegrade at their end of life. Additionally, bio-based materials' exploration has opened a space for designers and researchers to conduct novel material explorations using craft, digital fabrication, and DIY techniques.

In this paper, we present an exploration of biofoam – a bio-based material that is low-density, airy, and flexible, similar to foams used in packaging and bedding – as an interactive, *tunable* [24] (able to be modified) material that inspires exciting HCI applications. Beginning with an open-source biofoam recipe [13], we extend the recipe with a variety of materials and techniques to achieve different properties in the biofoam, such as color (Figs. 1b, 1e, 1h), firmness, water permeability (Fig. 1d), and even conductivity (Fig. 1g). We detail these tunings (modifications) of the material and discuss particular applications or use cases.

Giaccardi and Karana [17] discuss the importance of understanding materials in interaction design research, separating levels of experiences with materials according to the order in which a person encounters stimuli: *sensorial, interpretive, affective, performative*. Drawing from their framework, we highlight the intrinsic sensory affordances of biofoam as an entry point to analyze interactions with the material. We aim to characterize the aesthetic qualities, temporality, physicality, performance, and potential applications of biofoam in HCI by providing extended recipes and examples of personalized use. Furthermore, by analyzing and understanding the life cycle of the biofoam we aim to guide our material investigation and seek to answer the following research questions:

(1) How can a biofoam recipe be augmented and tuned to obtain new forms and features that can be leveraged in human-computer interaction design?
(2) What new interaction and design opportunities emerge when we use biofoams for HCI applications?

In adapting and thinking with the materials [16] in the context of HCI, we highlight the particular affordances biofoam offers for tangible interaction, recyclability, and fabrication processes. Our core contribution consists of the introduction of this bio-based material to the HCI community as well as researched guidelines of how it can be meaningfully manipulated as an interactive material.

2 RELATED WORK

Our research rests on two pillars of related work in the HCI: First, the growing use of bio-based materials within growing programs of sustainable and bio-design. Second, design reflections that consider materials as actively shaping the design process and imagination. The context within which we apply our work focuses on foam, which is a common, yet often more subtle materials of use in HCI. For Example, a polyurethane foam pre-impregnated with carbon black was used to create a pressure sensing matrix [47]. Other applications leverage foams deformability to measure various biosignals in wearable applications [13]. Yet, within HCI work with foams made from bio-based materials seems virtually non-existent.

2.1 Bio-based materials in HCI

A 5-year CHI review [42] has shown that researchers still heavily rely on petroleum-based materials for prototyping physical objects. In response, and often under the banner of sustainable interaction design in HCI [8, 12], researchers have created and prototyped with several bio-based materials, including agar-based or cellulose-based bioplastics [5], SCOBY leather [30], compost based clay [7], mycelium skin [41], and mycelium composites [6, 40, 43]. These bio-based materials, with their ability to fully biodegrade, are potential replacements for less-sustainable materials, such as bioplastics for petroleum-based plastics and SCOBY leather for animal leather. While bio-based materials have achieved visual similarity to their conventional counterparts, research is still in progress to improve their physical properties, durability, and fabrication processes so that bio-based materials will be viable alternatives [15]. In this regard, recent research suggests a need to move for biomaterials beyond artistic domains, such as bioart and biodesign, by characterizing the materials for broader applications. Recent research, for instance, has characterized mycelium-composites as a functional, building material for architecture [23]. In HCI, Alganyl [5] has optimized an open-source bioplastics recipe, characterized it, and explored possible design applications.

Besides using bio-based materials in physical fabrication, HCI and design have also seen potential in using living organisms to explore and enhance embodied interactions. For instance, researchers have used microbes [25, 46] as living sensors and actuators to design interactive systems [1]. Similarly, Ofer et al. [32] has explored the unique affordances of incorporating bioluminescent algae in their design since these living organisms visibly respond to human interaction. These projects further demonstrate the community's interest in combining bio-based materials (living or non-living) with design interaction. Futhermore, this work situates interactivity as a material quality that can be accessed with our without the use of computers and broader systems of sensing.

2.2 Design and Material Experience

Our research into biofoams draws upon materiality in HCI as a medium for interaction [19]. Such an approach considers a range of material properties such as durability and fragility [36, 44] as fundamental parts of tangible interaction. We look specifically to the materials experience framework [17] which defines "materialit" as a material *experience*, highlighting the quality of the materials used beyond their physical or mechanical properties to include a broader sensory apparatus. This approach puts the designers' focus on the material and its affordances, opening space for new design consideration and material exploration with all their senses. Within this framework, we can see each new material bringing its own essence and imbuing a designer with a unique set of ideas that blend

function and aesthetic. So while, in one sense, we can see biofoams as a replacement for existing foams in, say, electronics enclosures or shoe insoles, such an approach might limit a designers imagination. While bio-based materials, such as biofoam, present opportunities to support sustainable design in such prototypes, we see opportunities to design with foam materials beyond "instrumenting" their innate functional properties, and rather "tuning" their built-in material affordances (say, *squeeze-ability*) that invite tactile interaction. Furthermore, we can consider the process of making (or cooking) the materials and/or their end-of-life bio-degrading as sites for further interaction and engagement. Furthermore, we see opportunities for bio-foams and extrudable materials to offer new approaches to soft/additive fabrication in domains where we normally may not consider foam as much as another flexible material such as silicone.

3 MATERIAL EXPERIMENTATION

We explored biofoam and its potential to be used as an interactive material, involving the material's entire life cycle: raw material use, fabrication, interactive use, and end-of-life. In this section, we detail our material experimentation which informed the design explorations in later sections. First, we describe the preparation of the base recipe in Appendix A.1, replicating an existing DIY, open-source biofoam recipe [14]. Then in subsections 3.2-3.3, we detail our modifications to the base recipe and our observations of how these modifications tuned certain properties of the biofoam, familiarizing ourselves with potential design considerations and applications of the material. In that process, we incorporated ingredients in the recipe and used various fabrication methods to achieve different materialistic qualities in the biofoam. Fig. 2 summarizes different attributes the ingredients we tested have in the biofoam recipe. Full recipes for all the biofoam variations we achieved in this study are described in detail in Appendices A and B.

Table 1: Adapted DIY open source biofoam recipe [14]: purpose and characteristics of the core ingredients

Ingredient	Quantity	Function	Characteristics
Gelatin	24 g	bio-polymer	binding and thickening agent
Glycerin	24 g	plasticizer	add flexibility, prevent cracking
Water	300 ml	solvent	carrier and mixing fluid
Dish soap	10 g	expanding (surfactant)	foaming agent, form bubbles

3.1 Base recipe preparation

The base ingredients of biofoam are: gelatin, glycerin, water, and dish soap (Table 1); all easy to find, affordable, and are mainly derived from industrial by-products [35]. Other ingredients (explained in detail in subsections 3.2-3.4) can be added to the base recipe to change properties such as density, color, aroma, water permeability or conductivity.

Step 1: Mixing: To prepare the biofoam, we started by mixing 300 ml tap water and 24 g powdered gelatin[1] in a beaker (or stainless steel pot) and stirred the gelatin powder into the water. We placed the beaker on a hot plate and continuously stirred until it reached a temperature of 80℃ (175°F), and continued stirring the mixture until the gelatin fully dissolved.

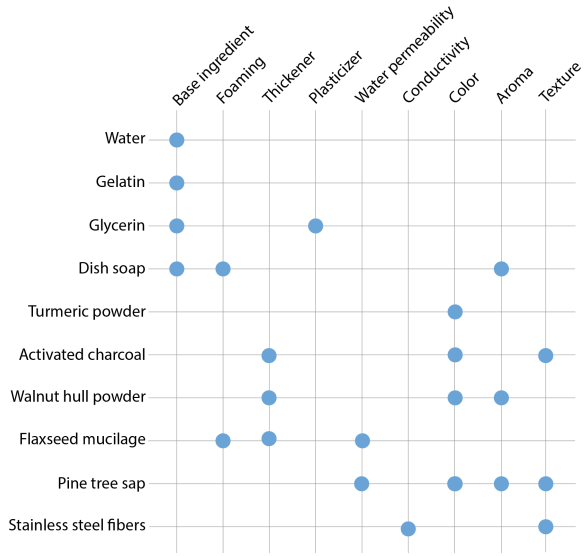

Figure 2: Possible biofoam attributes (X axis) when specific ingredients (Y axis) are added to the base recipe

Step 2: Cooking: Next, we added 24 ml glycerin, and continued stirring the mixture until it reached a syrupy or honey-like viscosity. The mixture yielded will be a third of the original volume. The cooking time required depends on the ingredient amounts and the stove used. In our process, we used a Duxtop[2] 1800 W portable induction cooktop and required about two hours to achieve the desired viscosity.

Step 3: Whisking: Once the mixture thickened to a syrupy viscosity, we added 10 g dish soap; this ingredient acts as a foaming agent, creating the foam's characteristic air bubbles. Once mixed in, we turned off the stove and whisked vigorously while keeping the beaker on the hot cooktop, incorporating and dispersing air bubbles homogeneously throughout the mixture. We whisked the mixture until it reached a foam-like consistency and larger volume. We used an electric hand blender to whisk for one and half minutes, but using a manual whisk for longer will also work.

The resulting foam from this base recipe had a creamy color due to the gelatin's natural yellow tint. Immediately after the whisking process, we poured the biofoam out of the beaker and into a mold, and let it dry for 24-48 hours in a ventilated area at room temperature. For a sample measuring 13 cm × 13 cm × 5 cm, we demolded it after 48 hours and allowed the sample to complete the drying process outside the mold for three more days. Our samples shrank 25-35% of their original volumes during the drying process.

3.2 Adding color

Following previous work of coloring bioplastics [5], we first colored the biofoam with a synthetic food-grade pigment to test its

[1]Knox Unflavored Gelatin, 16 Oz. https://www.amazon.com/Knox-Original-Gelatin-Unflavored-16-Ounces/dp/B06XDPCXYJ

[2]Duxtop 1800 W Portable Induction Cooktop. https://www.amazon.com/Duxtop-8100MC-Portable-Induction-Countertop/dp/B0045QEPYM

effectiveness in our material. Even though food-grade pigments worked well in the biofoam, we wanted to test other pigments that were not *synthetic*. We conducted several experiments using *natural* powders (i.e. *sourced directly from nature*) such as turmeric powder (Fig. 3a), walnut hull powder (Fig. 3b), and activated charcoal. We found that liquid or water-soluble pigments would be preferable for coloring the biofoam because they mix well with water which is the carrier and mixing fluid in our recipes. These natural powders are water soluble and were added in the biofoam mixing process to ensure a uniform color over the entire material.

We noticed in our exploration that other ingredients used to tune the biofoam in other ways resulted on adding color to it as well. For instance, we used pine tree sap to increase the water permeability of the biofoam (see details in section 3.3) and found that the sap added a yellow tint to the resultant sample (Fig. 3c), as well as a slight floral fragrance. Furthermore, we noticed that adding such powders could alter the recipe's proportions and/or the material's final properties. For instance, adding walnut hull powder to the base mixture made our samples brittle after drying. We researched the properties of the different natural powders we used in our exploration and found that powders' density, grain size and solubility are important characteristics to pay attention to when incorporating powders in our recipes. To illustrate, based on our observation and making experience, the biofoam with walnut hull powder added to the recipe (see Appendix A.4) requires an additional thickener or plasticizer (like glycerin) in the mixture to prevent brittleness and cracking. Thus, we added flax mucilage as a natural thickener or emulsifier [2, 34, 37] (3% of the base mixture), finding that it not only prevented brittleness and cracking but also reduced the samples' shrinkage during drying. We also found that additional dish soap (6% of the base mixture) was needed in this case to compensate for the added ingredients, in order to sufficiently generate air bubbles in the foam-making process. On the other hand, the biofoam with turmeric powder recipe (see Appendix A.2) was less prone to cracking than the samples with walnut hull powder. Understanding the intricacies of this phenomenon is reserved for future work.

We also explored adding bio-compatible thermo- and photochromic pigments to the biofoam base recipe (see subsection 6.1). We used a thermochromic blue pigment that changes color to white above 36℃ (98°F), a thermochromic orange pigment that changes color to white above 36℃ (98°F), and a photochromic white pigment that changes color to blue with UV exposure. We prepared the pigments with a ratio of 1:8 (1 g of pigment per 8 g of solvent), using Dye-Na-Flow[3], a thin water-based paint, as the solvent. We found that a 1:10 ratio of pigment-solvent mixture to biofoam mixture (i.e. 1 g of prepared pigment per 10 g of biofoam base mixture) worked well. After dissolving the biocompatible pigment in the solvent, we added it to the base mixture when it reached the syrup-like consistency on the hot plate. We stirred the prepared pigment into the biofoam mixture for two minutes with the hot plate turned off. Then, we proceeded with pouring the heat-sensitive or UV sensitive biofoam in the desired mold.

[3]Jacquard Dye-Na-Flow Liquid Color 8 oz-White. https://www.amazon.com/Jacquard-Dye-Na-Flow-Fabric-Colors-White/dp/B00A6WGS80.

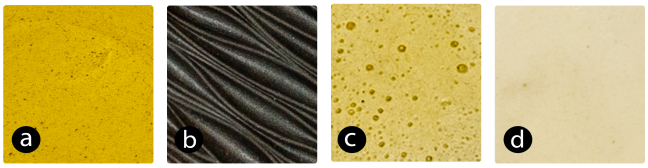

Figure 3: Natural additives used to give the biofoam color: a. turmeric powder, b. walnut hull powder, c. pine tree sap, and d. gelatin natural color

Figure 4: Attempts to incorporate stainless steel fibers into biofoam: a. whisking, b. felting, c. folding

3.3 Adding conductivity

From the start of our explorations, we were interested in producing a conductive biofoam for electronic applications. We attempted to incorporate conductive stainless steel fibers into the recipe with different techniques. The stainless steel fibers which are readily available in thread-like forms for e-textiles or as roving for use in spinning and fiber art. We tested integrating conductivity using processes of whisking, felting and folding. As shown in Fig. 4, whisking and felting were both unsuccessful techniques, resulting respectively in the fibers clumping around the whisk (Fig. 4a), and in the fibers clumping unevenly in the foam (Fig. 4b). Finally, we turned to *folding*[4], a technique commonly used in baking to incorporate ingredients with contrasting densities and successfully achieved a conductive biofoam by folding the stainless steel fibers into the foamed mixture (Fig. 4c).

Using a spatula, we folded the conductive fibers into the biofoam for two minutes and stopped when the fibers were mostly dispersed through the foam, while the mixture had a loose enough consistency to be poured into a mold (see Fig. 5a). In trials with various lengths of stainless steel fibers, we found that fibers longer than 5 cm were more likely to clump together instead of distributing throughout the material. After testing lengths ranging from 1 cm to 5 cm, our experiments found that fibers which were 2.5cm in length in average were most successfully folded into conductive biofoam. We poured the mixture into a silicone mold (see Fig. 5b) to create a 8.5 cm × 8.5 cm × 2.3 cm sample, and let it dry in a ventilated area at room temperature. We demolded the sample after 48 hours (see Fig. 5c) and allowed it to fully dry outside of the mold for three more days. Note that drying time depends on the size of the sample.

[4]https://www.washingtonpost.com/food/interactive/2021/how-to-fold-ingredients/

Table 2: Set-up experiment that compares water permeability between biofoam recipes in terms of evaporation time

	Control sample	Base recipe	Conductive	Charcoal	Walnut+Mucilage	Pine tree sap
Test 1	1h 9m	27s	7m 14s	18m	23m 44s	45m 8s
Test 2	1h 5m	24s	6m 9s	15m 12s	29m 28s	41m 50s
Test 3	1h 10m	27s	8m	21m	24m 13s	44m 9s
Average	**1h 8m**	**26s**	**7m 7s**	**18m 4s**	**25m 28s**	**43m 25s**

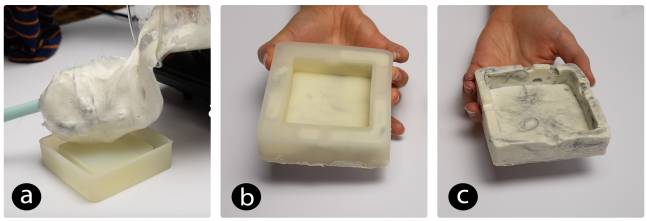

Figure 5: a. Pouring the biofoam mixture, b. Biofoam in a mold, c. Molded biofoam after 24 hours

3.4 Increasing water permeability

Through observation, we noticed that the biofoam dissolves in water, which led us to research ingredients that could help increase the water permeability of the biofoam. We discovered that adding pine tree sap [33] in a liquid form (10% of the base mixture) increases the water permeability properties of the biofoam. Some research also suggests that flaxseed mucilage may also increase water permeability [34]. To study how the different biofoam recipes we created react to water, we designed an experiment that compares the property of water permeability in terms of evaporation time. For that, we pipetted a 30 µl water droplet on a polyurethane foam piece, as a control sample and compared its evaporation time with droplets of the same size pipetted on the biofoam base recipe, biofoam with conductive fibers, biofoam with charcoal, biofoam with walnut hull powder and flax mucilage, and biofoam with pine tree sap. The results in Table 2 report the time when we stop noticing any droplet on the surface of the biofoam. As seen in Table 2, on the base recipe sample, and the charcoal sample, the droplet evaporated significantly faster than the one on the control surface, implying that part of the droplet permeated through the biofoam and got absorbed. The sap sample kept the droplet for the longest time, showing that it can resist water better, as the droplet has the hardest time permeating the membrane of the material. We acknowledge that the experiment is preliminary, providing a quick insight in the material behaviour. Further investigation needs to be made to consider the role of the contact angle at the liquid-solid interface in the evaporation of the droplet.

3.5 Recooking

Throughout our exploration, we saved material from scraps and failed experiments, and tried recooking them into new batches of biofoam. We observed that the recooked mixture did not lose its original properties, however, additional water needed to be added in the mixture. For example, for 50 g of foam scraps we added 15 ml of water and heated up the mixture at 80℃ (175℉) while constantly stirring until dissolving the scraps and getting the desired viscosity. Based on this observation, we made big batches of 2000 g of the biofoam base recipe (water, gelatin, and glycerin) and stored them in jars in the refrigerator after obtaining the syrupy viscosity in the mixture. We successfully stored the batches for up to two weeks; after that time, our batches grew mold. Cooking big batches of the base recipe was advantageous in the fabrication process, such as being able to make multiple iterations with colors, densities, and incorporating other additives in our future biofoam recipes.

4 CHARACTERIZING BIOFOAM

After producing several different kinds of biofoam we became increasingly interested in the capacity of the material to squish and slowly recover to its original shape. First, we studied this qualitatively, gaining a general assessment to describe the material to broader audiences that could help communicate the unique sensory qualities of the material. Next, we considered how this quality of the material could be used for pressure sensing, and therefore began to conduct more systematic characterizations on the conductive biofoam samples (subsection 4.4) as well as analyzing our findings with a lens on the life cycle of the material (see subsection 4.5).

4.1 Density, squishiness and spring back time

The density of the biofoam can be tuned by varying the ingredients, and the whisking time. Any additives to the base recipe (e.g. natural powders, stainless steel fibers) impact the density of the biofoam. For example, the density of the biofoam with pine tree sap varied from 0.54 g/cm^3 to 0.65 g/cm^3. When adding conductive fibers to the biofoam mixture, we achieved densities ranging from 0.35 g/cm3 to 0.48 g/cm3 depending on the whisking time which plays a role in the size and number of air bubbles incorporated in the base mixture. For instance, whisking for 30 seconds (electrically) resulted in a density of 0.30 g/cm^3, whereas whisking it for 90 seconds resulted in a density of 0.48 g/cm^3. We noticed that molding in thin layers prevents the air bubbles from bursting, and thus compensates for the higher density when incorporating additives. When we poured the biofoam with thermochromic pigment in 0.5 mm to 3mm sheets, we achieved a three fold lower density (0.13 g/cm^3).

Through observation, we tested the squishiness and spring back time by manually applying the same pressure on conductive and non-conductive samples. Then, we measured the time needed for the sample to spring back from the deformation using a stopwatch. Our test estimated the spring-back time of the non-conductive biofoam to be three seconds, when pressed with one finger on the edge of the sample (Fig. 6); by comparison, it took five seconds for the conductive biofoam to fully spring back (Fig. 7). We infer that a longer recovery time is due to the fillers the biofoam has such as the conductive fibers in the mixture in our sample.

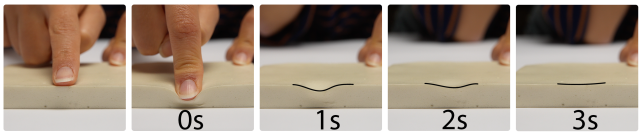

Figure 6: Non-conductive biofoam spring back time.

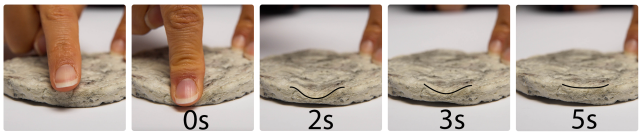

Figure 7: Conductive biofoam spring back time.

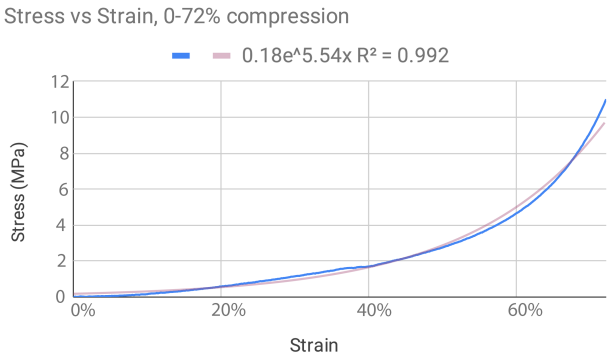

Figure 8: Compression testing performance of the conductive biofoam.

4.2 Thickness

We produced a variety of biofoam samples with varying thicknesses from 1 mm to 4 cm using the molding technique. Having a variety in thicknesses made us think about material application and limitations. For instance, the pleating technique worked best in a biofoam sheet below 1 mm thickness. In contrast, hand embroidery worked best in 2 mm thick biofoam. We also found that 1 mm biofoam sheets were translucent, useful when embroidering the biofoam (as applied in section 6.1).

4.3 Durability

After storing the samples at room temperature on a shelf for 5 months, we noticed that our biofoam samples had changed slightly–for example, the 3D-molded samples appeared more coarse on the surface, and were rougher to the touch. We did not notice significant change in the biofoam's color or spring-back time in the biofoam sheets. However, we noticed the conductive biofoam pressure sensors had become less compressible. In terms of recyclability, even our oldest, five-month-old biofoam scraps still dissolved in warm water, allowing us to make new biofoam samples from the discard.

4.4 Compression and recovery time

We characterized three samples of conductive biofoam with the ASTM D3574 - a foam compression test. Our samples had the same density of 0.29 g/cm^3 and 9.4 mm thickness (0.37"). They were conditioned undeflected and undistorted at a temperature of 23 ±2℃ (73°F) and in an atmosphere of 50 ±5 % relative humidity for at least 12 hours before being tested. All samples were produced seven days or more before the testing day. We were able to reliably predict the compression of the conductive biofoam from 0% to 72% compression. In particular, from 0% to 50% the stiffness of the material resulted in being fairly linear as shown in Fig. 8 (pink line).

The compression test started with a load of 6.5 N/sec (1.5 lb/sec) and increased to 29 N/sec (6.5 lb/sec) at 25% compression. It was 92.7 N/sec (20.76 lb/sec) at 50% compression, and 367.7 N/sec (82.67 lb/sec) at 72% compression. In regards of recovery time, it took 24 hours for the samples to fully recover their original thickness (9.7 mm) since they were 86% compressed with high loads.

The compression test results provided precise measurements that complement the previous qualitative observations we presented earlier in this section. A more precise understanding of the biofoam's properties demonstrated the material's potential both as a sensor and subject for interaction, thus guiding our later exploration of potential applications in HCI.

4.5 Assessing the Biofoam Life Cycle

We followed the Sustainable Prototyping Life Cycle [27] to perform a life cycle assessment of the biofoam. The biofoam has a closed-loop life cycle (see Fig. 10), characterized by five phases:

Raw materials: Most of the core ingredients used to make the biofoam samples can be sourced as industrial byproducts: glycerin, gelatin, and conductive fibers. While some naturally-found additives such as flax seeds and powders (turmeric, walnut hull powder, activated charcoal) are not grown or made in our immediate area, they can still be sourced from neighboring states in the region. Furthermore, these ingredients are affordable and derived with little processing.

Transportation: All of the materials we used were sourced domestically, within 800 miles. In the case of pine tree sap, we harvested it within our own neighborhoods and backyards. We also reduced transportation distances by reusing silicone molds found in our lab and using recycled stainless steel fibers collected from old lab projects.

Fabrication: We used a combination of craft and digital fabrication techniques in our design exploration and biofoam samples development. The impact of this phase lies in the energy needed when using the laser cutter and appliances needed to cook multiple biofoam recipes. The induction cooktop we used consumes 2 kW/h on average; 16 hour-long usage results in the power consumption of 32 kW. This usage is equivalent to CO_2 emissions from burning 25 pounds of coal. To sequester our footprint in this project, we would need 1219 square feet of U.S. forests for one year. Considering that all co-authors have a backyard in their houses, we would be able to sequester the CO_2 emissions generated in this phase while working in this project.

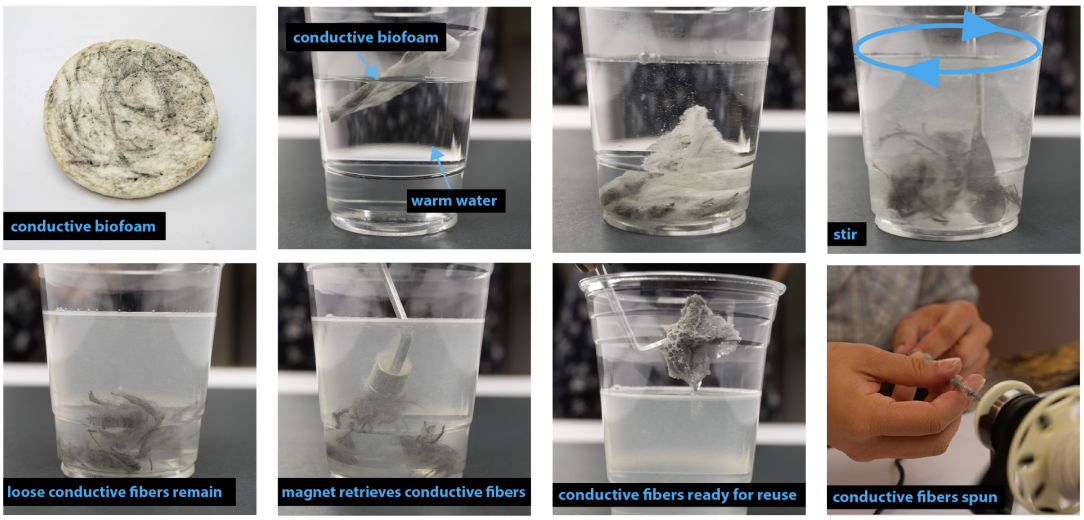

Figure 9: Biofoam dissolving process and conductive fibers reharvested.

End of life: When the biofoam is no longer in use, we can "end its life" by dissolving it in water (see Fig. 9) or composting it to biodegrade. For the samples of conductive biofoam, dissolving is the more environment-friendly choice, as the stainless steel fibers can be collected from the dissolved biofoam solution with a magnet, as shown in Fig. 9. After harvesting the conductive fibers, the remaining base ingredients as well as any natural additives (e.g., turmeric powder) can then be biodegraded. The biofoam quickly dissolves in warm water, as the main structural ingredient, gelatin, melts at 32℃-34℃ (90-93°F)–the biofoam also dissolves in cold water, albeit more slowly. We found that the additional ingredients in the modified biofoam recipes raised the optimal dissolving temperature to 50℃ (122°F). We also tested the biodegradability of biofoam in a controlled environment at 45℃ (115°F), assuming that some users would dispose of the biofoam in a landfill. Our experiment's biofoam sample degraded in 120 days. As shown in our failed experiments, biofoam waste generated during the prototyping process can be reused as raw material to make new biofoam, that being the case of biofoams that had natural, thermochromic or photochromic pigments on it.

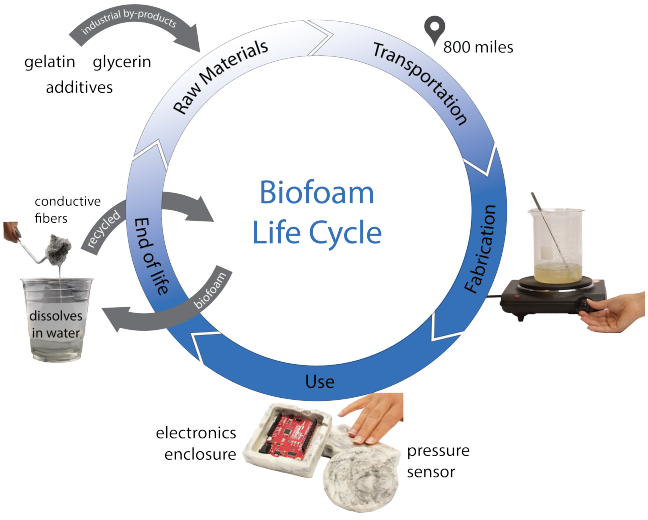

Figure 10: Biofoam life cycle

5 EXPLORING FABRICATION TECHNIQUES

In this section, we summarize the fabrication techniques used in our material experiments. Through making a variety of biofoam recipes, we noticed that the properties of biofoam and the fabrication techniques used to shape it mutually influence one another, forming a core dialogue when designing with biofoam as a material. Across our experiments, we used a combination of craft and digital fabrication techniques to shape the material. The biofoam can be molded, layered, extruded, sewn, embroidered, pleated, cut, and laser engraved. We provide detailed instructions for our most commonly-used techniques (molding, extruding, and layering) in Appendix B.

Molding: The biofoam can be cast with various details by pouring the mixture into a mold (see Fig. 11). Overall, we were most successful when we poured the biofoam mixture into the mold immediately after whisking/folding, while the mixture was still hot.

Figure 11: a. Demolding the biofoam sample. b. Biofoam acts like memory foam, c. Biofoam applied in layers.

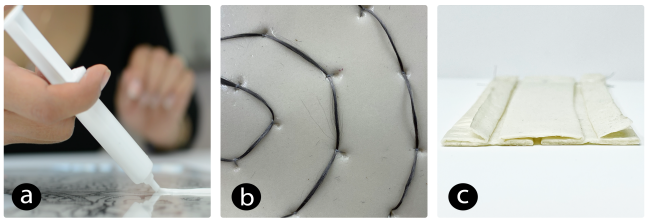

Figure 12: a. Biofoam extruded, b. Biofoam couched, c. Biofoam pleated.

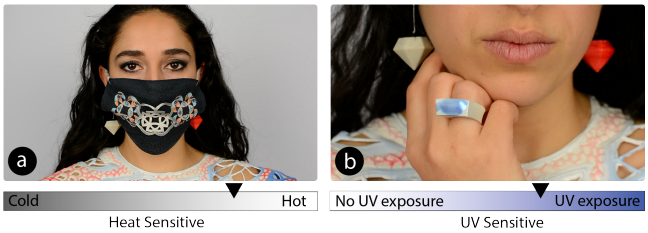

Figure 13: Thermo and UV sensitive facemask and accessories

We also used a spatula to scrape the biofoam out of the cooking container, and push the mixture into the mold, to work as quickly as possible. The biofoam is most malleable when hot, and will also begin drying and curing once exposed to air. When we delayed pouring too long, the samples conformed poorly to the mold. For these failed experiments, we recooked the sample at 80℃ (175°F) and repeated the fabrication process from there.

Layering: This technique involves pouring layers of different biofoam recipes in the same mold. For instance Fig. 12a shows a sample where the bottom layer (layer 1, color black) was made with a recipe that resulted in a more dense biofoam (longer whisking time to achieve small air bubbles in the mixture) and it was colored with activated charcoal powder. After letting the bottom layer sit for 10 minutes, we poured the upper layer (layer 2, color white) which was less dense (shorter whisking time to achieve bigger air bubbles in the mixture). This layering technique opens new possibilities for material interaction using a pleating-layering technique.

Extruding: We extruded the biofoam using a syringe (see Fig. 12b) and cutting various nozzle opening sizes too. This fabrication technique requires the biofoam mixture to be less dense than the mixture used for molding or layering. This can be achieved by whisking it for a longer time until getting a meringue consistency. In section 6.1, we show how extruding the biofoam in different thicknesses can be used to make wearables.

Sewn, pleated, laser engraved. The biofoam can be easily cut with scissors, sewn by hand 12b., or using a sewing machine. We also pleated a 2 mm thickness biofoam sheet. When working with fabric, pleating is achieved through heat-sealing the pleats into place, however, as the biofoam is by default not heat resistant, we cold-set the pleated biofoam in between books for 24 hours (results can be seen in Fig. 12c). Finally, we tested the option of laser engraving a 4 mm biofoam sample. After testing multiple parameters, we received a clean 2 mm etching without any burning marks in the biofoam surface at 7% power and 50% speed, a gentle etching at 5% power and 50% speed, and a deep 4 mm etching at 7% power and 50% speed.

6 EXPLORING HCI APPLICATIONS

Combining the various fabrication methods with the material's tunable properties allowed us to imagine several applications for biofoam in HCI. Initially, we created biofoam wearable accessories that have biocompatible thermochromic and photochromic pigments, and lastly we created pressure sensors that we characterized and envision future use as tangible interactive objects.

6.1 Chameleon Accessories

We developed a collection of accessories we called "Chameleon accessories" because of their ability to change color when they are worn. The collection includes one necklace, two bracelets, two rings, one pair of earrings, and one face mask (see Figs. 14 and 13). Each accessory in the collection contains biocompatible thermochromic and photochromic pigments (see recipes in Appendix A) to achieve material interactions, becoming visible and tangible sensors by changing color. We used a thermochromic blue pigment that changes to white 36 ℃ (98°F), a thermochromic orange pigment that changes to white above 36 ℃ (98°F), and a photochromic white pigment that changes to blue when exposed to UV light. The waste generated during the accessories' prototyping process was reused as raw material ingredients to make new biofoam and accessories.

Necklace: We used a handheld 3D extrusion technique to make the necklace (Fig. 14a). We first drew a lace-inspired pattern onto a piece of white paper, then placed a piece of translucent acrylic on top. The acrylic served as a non-stick base on which to extrude the biofoam. We used the biofoam layering technique in this process to add volume to the necklace and create areas where the UV-sensitive biofoam was more exposed.

Bracelets, rings, and earrings: We used a combination of molding and layering techniques to make these accessories, reusing existing silicone molds in the lab. We layered a photochromic biofoam mixture on the bottom and a thermochromic biofoam mixture on the top for the bracelets (see Fig. 14b). This allows us to see the material changing color when worn outside under the sun. The rings and earring were made using only biofoam with photochromic pigment (see Fig. 13b).

Face mask: We laser cut a 1 mm biofoam sheet and sewed it on top of a cloth face mask (see Fig. 13a). This biofoam sheet was made using only thermochromic pigment in the recipe. The laser cutting parameters we used were 7% power and 50% speed. The wearer was able to control the color of the biofoam on the mask by inhaling cold air using her mouth and exhaling warm air through her mouth.

Furthermore, we also tested the biofoam as a stabilizer for embroidery or patchwork. We used a biofoam sheet of 2 mm thickness to embroider a patch that was later attached to a jeans jacket. This application worked because the biofoam sheet was translucent enough, still allowing us to draw on it and use that as a path for embroidering afterwards.

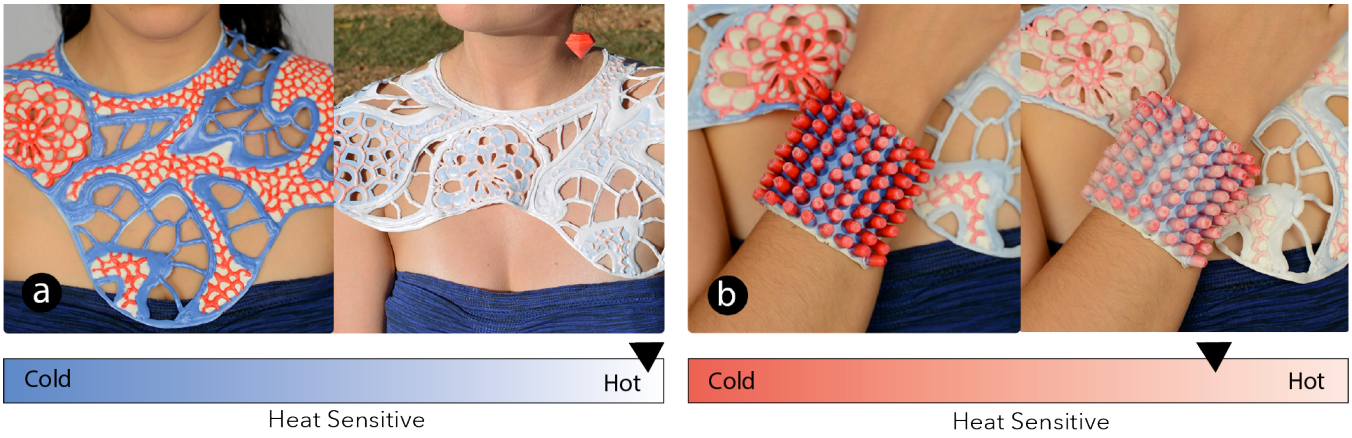

Figure 14: Thermo- and UV-sensitive biofoam wearables: a. necklace, b. bracelet

6.2 Sensing

Conductive biofoam can be used for sensors such as capacitive touch sensors and force-sensitive resistors (FSR), as well as a soft shielding material for Faraday cages and electrostatic discharge (ESD) protection. We found the FSRs particularly compelling as the compression interaction is built into the foam and conductivity, compression, and recovery time can be tuned simply by altering the recipe. The form of the sensor can also be customized by molding the mixture into specific shapes and textures lending to further play with the interaction and design. For example, Bae and West felted stainless steel fibers into various shapes to inform interactions like press, pinch, and touch[4]. There is a wide range of practical and creative uses for customizable biofoam FSRs, from smart shipping packaging to soft controllers[31] and robotic skin[26].

We molded twelve cylindrical FSRs, 5 cm in diameter and 2 cm in height, from a single recipe (see Appendix A.6) and used the *folding* technique with 5 g of 8 microns stainless steel roving fiber of average length of 2.5 cm. We randomly selected and tested four (shown in Fig. 15) out of these twelve sensors to obtain force vs. resistance performance characteristics.

Electrical Characterization: We constructed circular electrodes from a copper taffeta fabric (5 cm in diameter) and placed them on the top and bottom of the biofoam FSR. By creating a voltage divider with the biofoam FSR, as shown in Fig. 16, the variable voltage as a result of an applied pressure can be read by a microcontroller's ADC input. A normal force was applied in increments of 5 N starting with 15 N (1529.57 g) and ending with 60 N (6118.30 g) using a digital force gauge. At each increment in applied force, 100 samples were obtained at a sampling rate of 10 Hz, and then converted to a resistance value using the following formula:

$$Resistance = Rdiv * ((3.3/(ADC * 3.3/1023)) - 1),$$

where *Rdiv* is the 330 ohm fixed resistor of the voltage divider and *ADC* is the reading from the ADC pin of the microcontroller. The resistance values were then averaged to obtain the plots, as shown in Fig. 17 where sensor 1 and sensor 4 exhibited characteristics similar to typical FSRs [21], however their resistance values varied by orders of magnitude. At this time, the disbursement of the individual stainless steel conductive fibers and how they settle during molding and casting processes is uncontrolled. Additionally, the fibers may become intertwined or felted and consequently untangled during compression and recovery which potentially changes the characteristics of each sensor with each use. Interestingly, sensor 2 and sensor 3 exhibited a similar unexpected behavior of increasing instead of decreasing its resistance when 35N (3569.01 g) was applied.

Figure 15: Four force-sensitive resistors tested using a force meter to obtain force vs. resistance plots.

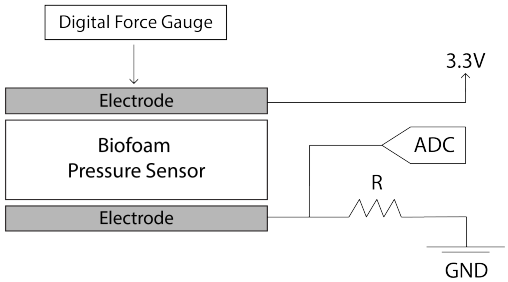

Figure 16: A digital force gauge is used to apply and measure a normal force to the sensors. A microcontroller is used to read the resistance between the two electrodes.

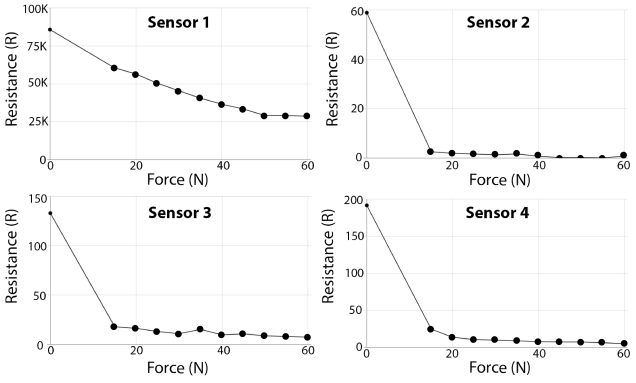

Figure 17: Force (N) vs. resistance (R) plots for each FSR sensor.

7 DISCUSSION

This discussion aims to advocate for biofoam as a tunable material for tangible interaction. Biofoam is affordable, easy-to-make and prototype with, and begins a trajectory towards the replacement synthetic-foam materials currently used in the interaction design community. Through in depth development and testing of the biofoams, we were able to explore the design considerations when working with biofoam in the context of HCI . Furthermore, this helped us understand the design opportunities that emerge when we use this material in designing HCI applications.

7.1 Design considerations of biofoam in HCI

Our approach was motivated by an attention to materiality and attuned to development and use as highly sensory and creatively productive activity. This attention was cultivated through each step of the biofoam life cycle, from cooking the materials from raw ingredients and modifying the recipe to achieve particular qualities, to using the materials in standard HCI prototyping workflows, to dissolving and experimenting with possibilities at the moment of material destruction. We believe this linear relationship through time opens up a particularly interesting perspective on the role of temporality of material interaction. Where we typically describe a material as a given set of affordances or properties, here, we followed a set of base ingredients through multiple forms and states, studying possibilities for interaction and customization along the way. For instance, during the fabrication process of the biofoam, various ingredients' materiality and properties at play made us question design considerations of durability, malleability, fragility, density, viscosity, biodegradability, and so on. This influenced reflection beyond the realm of "tangible" experience towards questioning other sociocultural and environmental considerations such as how our ingredients are sourced, the distances they travel to reach our lab, or the potential impact on people and our planet the biofoam could have at its end of life.

We compare the temporality of fabricating the biofoam to the temporality of cooking. Design considerations of tunability (ability to be modified), accessibility (easy to find), and replicability (easy to make) accompanied us throughout the fabrication process just as they do when considering making a new recipe for dinner. Since we were familiar with various cooking techniques, fabricating the biofoam from scratch was less intimidating in comparison to other hand-craft techniques that require higher levels of expertise such as pottery or quilting. The similarity of our experiences cooking food to cooking biofoam helped us set our expectation for the outcomes. Specifically, when we didn't get what we wanted to expected, the stakes did not feel as critical, and we simply started again with a new technique (often gleaned directly from our experiences cooking and baking). For instance, while looking for the right technique to embed the conductive fibers in the biofoam, we tried multiple techniques that were inspired by cooking: First, we tried whisking the conductive fibers into the mixture however the conductive fibers clumped and stuck onto the whisker. In a second attempt, we had already spent time interacting with the material and had a better idea of its possibilities; through continuous observation we found similarities in making biofoam and a meringue recipe. This led us to think of using a folding technique to was the conductive fibers in the biofoam just as one folds a dry mixture into whipped egg-whites without removing the airy texture.

7.2 Dissolving as a design opportunity

Biofoam, like most materials, has a finite lifespan – a piece of biofoam will reach a point where it has been squished, pressed, or squeezed one too many times, and will no longer recover or function. Previous research projects such as Unmaking [29] and Unfabricate [45] highlight how a design's obsolescence and breakdown does not need to mean the end of its material life. Rather, designers can embrace this inevitable decay as an agent that changes artifacts over time, provoking users and designers alike to engage with sustainability and recycling efforts [45]. In looking towards deconstruction as a design resource, we ask, "How can we design with biofoam's ability to dissolve in water, and use it as interaction?". To this effect, this material integrates well into a growing discourse within HCI on themes of decay [28], obsolescence [20, 22], living materials [11], and material drift [18, 39].

We believe that by focusing on the biofoam's entire life-cycle in design, current interactive designers' attention could shift from 'how to shape the material from a human-centric approach' to a more material-centric approach such as Being the machine [10], or Wabi-Sabi [38]. This creates space for observation and material experience which focuses on the material's temporal aspects, making it simpler to trace the relationships between different materials and the dimensions of acknowledged fabrication processes and practices [3].

7.3 Supporting sensory experiences in users

We found that fabricating the biofoam and using it as an interactive material offered unique sensory experiences. For instance, cooking provided a natural sensory-rich experience that helped us learn and develop a greater understanding of the material through an embodied experience. Other senses such smell, touch, and sound were more present in the use phase. For example, we found that additives not only played a technical role in the recipe but also effected the scent and visual profile of the material. Specifically, walnut hull

powder added a pleasant smell to the samples in addition to functioning as a binder and we found ourselves using walnut hull more often because of its nice smell. Similarly, the use of non-scented organic soap was a decision made after trying scented soaps that made the biofoam samples smell like clean dishes. Here, smell associations became a powerful part of the interaction, demanding attention whether we designed them intentionally or not.

In regards of the visual and sonic qualities of the biofoam, using the molding technique allowed for serendipitous material discoveries. For instance, when we molded the biofoam bracelets using a microcentrifuge tube rack, the outcome (see Fig. 13b) was visually inviting and the texture made us want to pull and poke the bracelet while wearing it. We wanted to enhance this inherent desire by adding heat sensing pigment which would further react to touching. When we began to interact with the cured foam samples, we realized they each possessed their own individual sound qualities that inspired us to want to record biofoam ASMR in the future. Here we found biofoam shifting our attention from the overarching scenarios of use to attending to the micro-sensory details.

8 CONCLUSION

This paper presented biofoam, a tunable bio-based material with many potential uses and reuses in interaction design. We demonstrated several options for tuning the bio-foam to have particular qualities when preparing it as well as different ways it can be made into interactive forms. Specifically we demonstrated how the base biofoam recipe could be altered for color, shape, density, compression, water-permeability, shrinkage, and conductivity. We reflect on the many senses the biofoam activated while we made with it and how that gave rise to particularly interesting moments of inspiration and experimentation.

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A APPENDIX: RECIPES

These appendices give step-by-step instructions for reproducing the biofoam samples described in the paper. This appendix lists the equipment needed for all recipes, then the base recipe (A.1), followed by all variations that the authors achieved (A.2 - A.8). Appendix B details how to combine the prepared biofoam recipes with different fabrication techniques.

Equipment

(1) **Container:** Glass beaker (or stainless steel pot)
(2) **Stove:** Hot plate (or other cooktop)
(3) Spatula
(4) Whisk (electric preferred)
(5) Scale, measuring cups and spoons, thermometer
(6) Shaping/finishing tools (see Appendix B)

A.1 Biofoam base recipe

Table 3: Adapted DIY open source biofoam recipe [14]: purpose and characteristics of the core ingredients

Ingredient	Quantity	Function	Characteristics
Gelatin	24 g	bio-polymer	binding and thickening agent
Glycerin	24 g	plasticizer	add flexibility, prevent cracking
Water	300 ml	solvent	carrier and mixing fluid
Dish soap	10 g	expanding (surfactant)	foaming agent, form bubbles

Preparation Directions.

(1) Weigh/measure ingredients.
(2) Prepare shaping/finishing tools (e.g. molds).
(3) Add water to the container, then add the gelatin.
(4) Stir mixture until the gelatin has mostly dissolved.
(5) Turn on the stove. Warm the mixture to a temperature of 80℃ (175°F).
(6) Add glycerin and continue stirring.
(7) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity. This step can take up to 3 hours depending on the

cooking set-up. Wide, shallow containers (like some pots) may require much less time to thicken the mixture.
(8) Add the dish soap, stir to incorporate, then turn off the stove.
(9) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(10) If needed, use a needle to pop any larger bubbles to achieve a more homogeneous mixture.
(11) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

Preparing Base Mixture for Recipe Variations

For the following recipe variations, we started with a large batch of "base mixture". Prepare this base mixture with the given proportions of gelatin, glycerin, and water from A.1, then follow A.1 steps 1-7 until you have the thick, syrup-like viscosity. The base mixture can be prepared in advance, and stored in the refrigerator for up to 10 days. When following one of the recipe variations, measure the required amount of base mixture from the prepared batch.

A.2 Biofoam with turmeric powder

Table 4: Biofoam recipe with turmeric.

Ingredient	Quantity	Function	Characteristics
Gelatin+glycerin+water	80 g	base mixture	syrup-like viscosity
Turmeric	1 g	color	bright yellow color
Dish soap	3 g	expanding (surfactant)	foaming agent, form bubbles

Preparation Directions.

(1) Weigh/measure ingredients.
(2) Prepare shaping/finishing tools (e.g. molds).
(3) Turn on the stove. Warm the base mixture to 80℃ (175°F).
(4) Add the turmeric powder to the base mixture.
(5) Stir mixture until the powder has fully incorporated.
(6) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity.
(7) Add the dish soap, stir to incorporate, then turn off the stove.
(8) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(9) If needed, use a needle to pop any larger bubbles to achieve a more homogeneous mixture.
(10) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

A.3 Biofoam with activated charcoal powder

Preparation Directions.

(1) Weigh/measure ingredients.
(2) Prepare shaping/finishing tools (e.g. molds).
(3) Turn on the stove. Warm the base mixture to 80℃ (175°F).
(4) Add the activated charcoal powder in small increments to the base mixture, stirring to incorporate after each bit of powder.

Table 5: Biofoam recipe with activated charcoal powder

Ingredient	Quantity	Function	Characteristics
Gelatin+glycerin+water	80 g	base mixture	syrup-like viscosity
Additional glycerin	10 g	plasticizer	add flexibility, prevent cracking
Charcoal	4 g	additive, color	increase water permeability
Dish soap	6 g	expanding (surfactant)	foaming agent, form bubbles

(5) Add the extra glycerin.
(6) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity.
(7) Add the dish soap, stir to incorporate, then turn off the stove.
(8) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(9) If needed, use a needle to pop any larger bubbles to achieve a more homogeneous mixture.
(10) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

A.4 Biofoam with walnut hull powder and flax mucilage

Table 6: Biofoam recipe with walnut hull powder and flax mucilage

Ingredient	Quantity	Function	Characteristics
Gelatin+glycerin+water	80 g	base mixture	syrup-like viscosity
Walnut hull powder	4 g	color	dark brown color
Flax mucilage	4 g	thickening	reduce shrinkage
Dish soap	3 g	expanding (surfactant)	foaming agent, form bubbles

This recipe requires additional equipment: extra pot, spoon, strainer (cheesecloth, pantyhose, or other soft material preferred).

Preparation Directions: Flax Mucilage.

(1) In a separate pot, measure 200 ml water. Add 20 g of whole raw flax seeds.
(2) Stir flax seeds into the water so they are all fully submerged.
(3) Turn on the stove, and bring mixture to a boil. As the mixture heats, continuously stir to prevent flax seeds from sticking to the pot.
(4) Continue stirring and boiling the mixture (approx. 10 minutes) until it forms thick, mucus-like strings that stick to your spoon when you lift it from the pot.
(5) Turn off the stove and remove the pot from heat. Let the mixture cool at room temperature for 1 hour.
(6) Use the strainer to separate the seeds from the mucilage. If you are using a soft straining material (e.g. pantyhose), you can squeeze the mixture to extract a greater amount of mucilage.
(7) The flax mucilage can be stored in a sealed container for up to 2 weeks.

Preparation Directions: Main Recipe.

(1) Weigh/measure ingredients.
(2) Prepare shaping/finishing tools (e.g. molds).
(3) Turn on the stove. Warm the base mixture to a temperature of 80℃ (175℉).
(4) Add the walnut hull powder to the base mixture, and stir to incorporate.
(5) Add the flax mucilage and incorporate.
(6) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity.
(7) Add the dish soap, stir to incorporate, then turn off the stove.
(8) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(9) If needed, use a needle to pop any larger bubbles to achieve a more homogeneous mixture.
(10) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

A.5 Biofoam with conductive fibers

Table 7: Biofoam recipe with conductive fibers

Ingredient	Quantity	Function	Characteristics
Gelatin+glycerin+water	80 g	base mixture	syrup-like viscosity
2.5 cm conductive fibers	4 g	conductivity	conductive, alters texture
Dish soap	3 g	expanding (surfactant)	foaming agent, form bubbles

Preparation Directions.

(1) If your conductive fiber comes in longer strands, use scissors to cut the fiber into pieces that average 2.5 cm in length.
(2) Weigh/measure ingredients.
(3) Prepare shaping/finishing tools (e.g. molds).
(4) Turn on the stove. Warm the base mixture to 80℃ (175℉).
(5) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity.
(6) Add the dish soap, stir to incorporate, then turn off the stove.
(7) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(8) Add a small amount of the conductive fibers on top of the foamed mixture. Use a spatula to fold this portion of fibers into the biofoam. Alternate adding and folding the fibers in small increments to minimize clumping, until all of the conductive fibers have been incorporated into the biofoam.
(9) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

A.6 Biofoam with conductive fibers, walnut hull powder and flax mucilage

Preparation Directions.

Table 8: Biofoam recipe with conductive fibers, walnut hull powder, and flax mucilage

Ingredient	Quantity	Function	Characteristics
Gelatin+glycerin+water	80 g	base mixture	syrup-like viscosity
2.5 cm conductive fibers	4 g	conductivity	conductive, alters texture
Walnut powder	2 g	color	dark brown color
Flax mucilage	4 g	thickening	reduce shrinkage
Dish soap	3 g	expanding (surfactant)	foaming agent, form bubbles

(1) If your conductive fiber comes in longer strands, use scissors to cut the fiber into pieces that average 2.5 cm in length.
(2) If needed, prepare flax mucilage as in Recipe A.4.
(3) Weigh/measure ingredients.
(4) Prepare shaping/finishing tools (e.g. molds).
(5) Turn on the stove. Warm the base mixture to 80℃ (175℉).
(6) Add the walnut hull powder to the base mixture, and stir to incorporate.
(7) Add the flax mucilage and incorporate.
(8) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity.
(9) Add the dish soap, stir to incorporate, then turn off the stove.
(10) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(11) Add a small amount of the conductive fibers on top of the foamed mixture. Use a spatula to fold this portion of fibers into the biofoam. Alternate adding and folding the fibers in small increments to minimize clumping, until all of the conductive fibers have been incorporated into the biofoam.
(12) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

A.7 Biofoam with pine tree sap

Table 9: Biofoam recipe with pine tree sap

Ingredient	Quantity	Function	Characteristics
Gelatin+glycerin+water	75 g	base mixture	syrup-like viscosity
Pine tree sap	15 g	moisture resistance	increase density and water permeability
70% alcohol	10 g	solvent	solvent for pine tree sap
Dish soap	3 g	expanding (surfactant)	foaming agent, form bubbles

This recipe requires additional equipment: extra pot, water bath.

Preparation Directions.

(1) Prepare the pine tree sap solution in a separate pot. Place the empty pot in a 60℃ (140℉) water bath, then dissolve 15 g of pine tree sap in 10 g of 70% alcohol. Dissolving the pine tree sap may leave residue in the pot.
(2) Weigh/measure ingredients.
(3) Prepare shaping/finishing tools (e.g. molds).
(4) Turn on the stove. Warm the base mixture to 80℃ (175℉).
(5) Add the pine tree sap solution to the base mixture, and stir to incorporate.

(6) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity.
(7) Add the dish soap, stir to incorporate, then turn off the stove.
(8) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(9) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

A.8 Biofoam with photo-/thermochromic pigments

Table 10: Biofoam recipe with photo-/thermochromic pigments

Ingredient	Quantity	Function	Characteristics
Gelatin+glycerin+water	150 g	base mixture	syrup-like viscosity
Photo-/thermochromic pigment solution	15-30 ml	color, reactivity	changes color with environmental stimuli
Dish soap	5 g	expanding (surfactant)	foaming agent, form bubbles

Preparation Directions. This recipe requires additional equipment: extra pot. It also requires an additional ingredient: Dye-Na-Flow or other thin, water-based paint.

(1) Prepare the photo-/thermochromic pigment solution in a separate pot. Mix 5 g of the pigment with 40 g of Dye-Na-Flow as the solvent.
(2) Weigh/measure ingredients.
(3) Prepare shaping/finishing tools (e.g. molds).
(4) Turn on the stove. Warm the base mixture to 80℃ (175°F).
(5) Add the pigment solution to the base mixture, and stir to incorporate.
(6) Continue to simmer the mixture at 80℃. Gently and constantly stir until the mixture is thick, like honey or syrup in viscosity.
(7) Add the dish soap, stir to incorporate, then turn off the stove.
(8) Whisk vigorously using an electric whisk for 90 seconds to create foam bubbles. Manually whisking may require more time. Whisking the mixture for longer periods will result in a denser biofoam.
(9) Proceed to Appendix B to shape the biofoam using the intended fabrication technique.

B APPENDIX: FABRICATION TECHNIQUES

These instructions assume that you have prepared biofoam(s) according to the instructions in Appendix A in order to execute these fabrication techniques.

B.1 Molding

Tools: silicone (or other non-stick material) molds, non-stick drying surface, [optional] weights

(1) Pour the biofoam into the desired mold(s).
(2) Let the sample dry and set for 48 hours.
(3) Release the sample from the mold. Turn the sample over so that the surfaces which were inside the mold are exposed to air, and rest it on a non-stick surface to fully dry all sides. If the sample is a thin sheet of biofoam, you can place weights (e.g. books) on top to ensure the sample dries flat.

B.2 Extruding

Tools: 20 ml syringe (without needle), non-stick work surface

(1) Fill the syringe approximately halfway with the prepared biofoam.
(2) Place the syringe nozzle at a 45° angle to the work surface. Apply constant pressure to the plunger while slowly moving the syringe along the surface to extrude a line of biofoam.
(3) Continue extruding biofoam in the desired pattern until the syringe is empty, or the biofoam in the syringe is too dry to extrude smoothly. The biofoam will dry quickly during the extrusion process, giving you approximately 5 minutes for each time you fill the syringe.
(4) After each extrusion segment, remove any dried biofoam from the syringe and refill with more prepared biofoam. The dried scraps of biofoam can be re-cooked with some additional water.

B.3 Layering

Tools: silicone (or other non-stick material) mold, non-stick drying surface, [optional] heat gun

(1) Prepare the different batches of biofoam you would like to use in your design.
(2) Pour the first layer of biofoam into the mold.
(3) Immediately after the first layer, pour the next layer of biofoam on top, into the same mold. **NOTE:** If you cannot pour all of the layers of biofoam in the same session, and the sample has time to dry between layers, you will need heat to fuse the dried layers. Pour the next layer and then use a heat gun to fuse it to the dried layer. Alternatively, use the heat gun to slightly melt the most recent layer in the mold, then proceed to pour the next layer.
(4) Continue pouring layers of biofoam as desired.
(5) Once the mold is filled, follow the drying instructions in B.1 steps 2-3.