

Biomaterials for More-Than-Human Futures

by

Fiona Allyn Bell

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Committee Members:

Mirela Alistar, Chair

Laura Devendorf

Daniel Leithinger

Stacey Kuznetsov

Katia Cánepa Vega

Bell, Fiona Allyn (Ph.D., Creative Technology and Design)

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Thesis directed by Prof. Mirela Alistar

We live in a time of ecological uncertainty due to the impacts of the industrial age. In the last century, humans have not been very responsible stewards of the planet, and the impact on our natural environment has become increasingly indelible and unsustainable. In an effort to stop and potentially reverse this trend, we will need a variety of relational solutions, one of which is to prioritize sustainability in the design and production of materials and artifacts that we use every day. Accordingly, this dissertation focuses on processes for developing and designing biomaterials, materials that are derived from living organisms and can easily biodegrade in the environment. While the biomaterials presented here have traditional non-biological material counterparts, I use these biomaterials to inspire non-traditional, post-Anthropocentric making practices that support the unique agencies and affordances of each biomaterial.

Drawing from material science, biodesign, Human-Computer Interaction (HCI), and posthumanism, I use this dissertation to present my process for making and making-with biomaterials. I exemplify this process through three biomaterials for more-than-human futures: (1) Alganyl, an algae-based vinyl-like bioplastic, (2) ReClaym, a personal food waste-based bioclay, and (3) SCOBY, a bio-leather grown from a symbiotic culture of bacteria and yeast. For each biomaterial, I describe its recipe, properties, fabrication methods, potential uses, and life cycle from generation to decay.

This work not only adds new biomaterials to the ever-growing library of expressive materials in HCI, but also grounds biomaterial research and development in more-than-human design practices that encourage makers to design in more nurturing and sustainable ways. I close this work by reflecting and speculating on how biomaterials and the practices we use to make and make with biomaterials can lead to more-than-human futures—futures in which humans, nonhumans,

and technology entangle to create a supportive network for sustainable collaborative survival.

Dedication

This dissertation is dedicated to my parents.

Thank you for nurturing my love of making, cooking, playing, growing, and exploring.

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Chapter 1

Introduction

*The history of life on earth has been a history of interaction
between living things and their surroundings.*

—Rachel Carson, Silent Spring

As the world becomes more conscious of the impact of human activities on the environment, sustainable materials have become an increasingly important area of research. Materials play a significant role in shaping the world around us, from the products we use to the buildings we inhabit. Traditional materials and the human-centered processes we use to produce them often have negative impacts on the environment. For example, the world produces approximately 400 million tons of plastic every year [72], with these petroleum-based plastics taking about 500 years to decompose in a landfill as they release toxins into the environment [183]. Subsequently, the development and utilization of sustainable materials that take into account more than just humans are crucial for mitigating the environmental impact of our making practices.

My research accordingly centers around *making* biomaterials and *making-with* with biomaterials that come from biological sources and can rapidly biodegrade in the natural environment. When it comes to *making* biomaterials, I am referring to the development of the biomaterial itself through methods such as cooking or growing. When it comes to *making-with* biomaterials, I am referring to crafting and creating artifacts made from the biomaterial. In these making practices, I look to see how I impact not only the biomaterial itself, but also other nonhuman actors (including

the environment). By doing so, I challenge the human-centered design paradigm [159] that has led to vast environmental damage. As such, my work takes a posthumanist approach to making and making-with biomaterials that advocates for the recognition of nonhuman voices in the design process.

In this dissertation, I specifically unpack both how to *make* and *make with* three different biomaterials (Figure 1.1): *Alganyl*, an algae-based bioplastic, *ReClaym*, a compost-based bioclay, and *SCOBY*, a cellulose-based bioleather. For each biomaterial (Chapters 4, 5, and 6), I present my making and making-with process that intentionally utilizes *accessible* ingredients (e.g., food waste, kombucha, agar, food dye), methods (e.g., cooking, stirring, ironing, cutting, sculpting), and tools (e.g., scissors, fabric irons, paint brushes, piping bags). I further showcase a broad design space via a series of artifacts that demonstrate how each biomaterial can be applied and utilized in the real-world. Through this, *I encourage makers of any age or expertise reading this dissertation to incorporate these biomaterials, methods, and design considerations into their own creative, making practices*. By engaging makers far and wide with these biomaterials, I believe that we can take steps toward more sustainable futures.



Figure 1.1: Biomaterials for more-than-human futures: Alganyl, ReClaym, and SCOBY.

1.1 Towards More-Than-Human Futures

I define more-than-human futures as speculative futures that acknowledge the interdependence and interconnectedness of all living and non-living beings and work towards a more sustain-

able world for all.

In these futures, humans no longer see themselves as separate from nature but as part of a larger ecological system that includes all forms of life. More-than-human futures involve a shift away from human-centered, anthropocentric perspectives and towards recognizing the agency and importance of nonhumans. This vision of the future emphasizes the need for collective responsibility and action to address the pressing environmental and social challenges we face, such as climate change, biodiversity loss, and social inequality. Ultimately, more-than-human futures offer a path toward a more just, equitable, and sustainable world in which all beings can flourish.

One such more-than-human future is Donna Haraway’s “Chthulucene”—a speculative geological epoch “made up of ongoing multispecies stories and practices of becoming-with” [94]. Haraway frames “becoming-with” as a method for collaborative survival that is the only solution to combat the existential crises that arise from the Anthropocene era, our current geological epoch defined by the indelible impact of humans on our natural environment. “Becoming-with” involves cultivating acts of kindness, care, and intimacy towards others, ultimately fostering *kinship* between humans and the natural environment at large. Through this, Haraway envisions a more-than-human future where humans, nonhumans, and technology entangle and interconnect to create a supportive network that upholds ecological preservation and restoration.

To reach these sustainable, more-than-human futures, posthumanist design aims to shift away from traditionally human-centered design approaches [159] towards *more-than-human* design approaches [54, 94, 138, 163, 164, 203, 222]. Posthuman design ultimately recognizes that humans are not the only actors in shaping the future and that human actions and decisions have significant impacts on the nonhuman world. As such, posthuman design (as well as more-than-human and post-anthropocentric design) challenges human makers to not only include nonhumans in their design and research practices but to “*shar[e] the center*” with nonhumans [222], viewing nonhumans as another maker with agency and voice in the design process. In this light, humans and nonhumans (e.g., materials) have equal importance in the creation of new artifacts.

However, it can be difficult for us as humans to de-center ourselves and share the design pro-

cess with nonhumans, especially when traditional design and engineering education often overlooks the roles that nonhumans play in making practices. Wakkary’s greatest recommendation in this regard is for humans to approach the practice of making things from a position of “humility” and “generosity” [222], as to better recognize, understand, and ultimately support the agencies of the nonhuman makers.

Ultimately, by considering the perspectives of nonhuman beings and entities, more-than-human futures open up new possibilities for sustainable material development that takes into account the ecological and social implications of materials. These futures encourage makers, designers, and researchers to *make* and *make with* materials that are not only biodegradable and/or renewable but also considerate of the needs and perspectives of the material itself and its impact on the ecosystem at large.

1.2 The Role of Biomaterials in More-Than-Human Futures

I define biomaterials as materials that are *bio-based* (i.e., come from a renewable, biological source) and *biodegradable* (i.e., break down into biomass, carbon dioxide, and water without leaving behind any toxic residues).

In my work, biomaterials play a crucial in designing for more-than-human futures. By designing with biomaterials as opposed to conventional materials (e.g., plastic, glass, metal, fabric), I envision a future where we as humans reduce our dependence on non-renewable resources, minimize our waste streams, and decrease our carbon footprint. In Figure 1.2 I provide a map of common materials that indicates their general sustainability, using renewability and biodegradability as the key determinants [200]. While this graphic provides a general overview of different types of sustainable materials—biomaterials falling in the top right corner—each material case is unique and must be analyzed separately and independently. For example, PLA is bio-based and biodegradable, however, PLA is only biodegradable under very specific conditions. Moreover, the making practices used in conjunction with the biomaterial can impact its sustainability. For example, cotton is bio-based and takes one week to five months to biodegrade. However, when cotton is manu-

factured into a textile, integrated with elastane fibers, dyed with chemicals, and fabricated into a pair of jeans, those cotton-based jeans can no longer be considered a biomaterial since they include non-renewable materials that take about 200 years to degrade [64]. I, in turn, challenge myself to not only make sustainable biomaterials, but to also embrace making-with practices that lead to sustainable biomaterial artifacts.

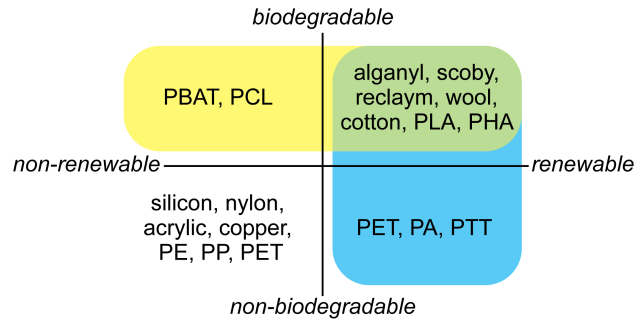


Figure 1.2: Biomaterials are both bio-based (i.e., renewable) and biodegradable.

Beyond being a more sustainable replacement for traditional materials (i.e., non-renewable, non-biodegradable materials), biomaterials also inspire post-anthropocentric design practices. Biomaterials, especially the biomaterials that I discuss later in this dissertation, often have imperfections, inconsistencies, and unpredictabilities that serve as reminders of their natural, bio-based origins. Rather than viewing these attributes as material limitations, they can be seen as material affordances that invite human makers to adjust their making practices accordingly. This approach encourages humans to work with biomaterials, supporting their agencies and needs, which aligns with the concept of making as a “correspondence” between the human and nonhuman material [99, 100]. Prioritizing the agency of biomaterials may range from slowing down the rate of human-determined making to synchronize with the growth rate of the biomaterial and/or using hands-on fabrication techniques to physically support the biomaterial. In each case, it is important to realize that the biomaterial has agency in the design process and identify their affordances so as to give space for the biomaterial to participate. By involving nonhuman participation in the design process, I envision future making practices that harmonize, rather than clash, with the natural

world.

Furthermore, by better understanding and highlighting the agencies and affordances of biomaterials, I envision providing a foundation for novel modes of interaction and collaboration among humans, nonhumans, and technology, particularly in the realm of Human-Computer Interaction (HCI). Through leveraging the unique, expressive qualities of biomaterials, interfaces can be created to enable food waste to play music [28], microbes to store digital data [45], or plants to sense and display environmental information [98]. This convergence of biology and technology can generate novel interfaces that benefit both human and nonhuman entities, as well as the broader environment that they inhabit. It also generates new opportunities for co-creation, co-evolution, and co-existence between humans and nonhumans.

Through designing with biomaterials, I speculate on more-than-futures in which biomaterials not only provide a sustainable alternative to conventional materials, but prompt corresponding making practices that prioritize the agency of nonhumans in the design process, thus leading to technologically innovative and ecologically sustainable world.

1.3 Alganyl, ReClaym, and SCOBY

To more deeply examine how biomaterials support my vision of more-than-human futures, I present a process for making and making with biomaterials in a thoughtful and sustainable way. My process draws from my personal experience and knowledge of mechanical engineering, material science, food chemistry, horticulture, and biodesign, that culminated in a practice of working with biomaterials during my PhD in the context of Human-Computer Interaction (HCI). My design process begins with biomaterial development and characterization, followed by identification of supportive fabrication techniques, exploration of design possibilities, and lastly, analysis of sustainability from generation to decay. While I discuss this as a chronological manner, the reality is much messier and actions often happen in nonlinear, overlapping orders. I further highlight actions that human designers can take to de-center themselves in the design process to promote recognizing and supporting nonhuman participation.

I demonstrate this process via *Alganyl*, a bioplastic made from algae [21, 22, 27]; *ReClaym*, a personal bioclay made from my composted food waste [28, 29]; and *SCOBY*, a cellulose biofilm formed by a symbiotic culture of bacteria and yeast [23, 24].

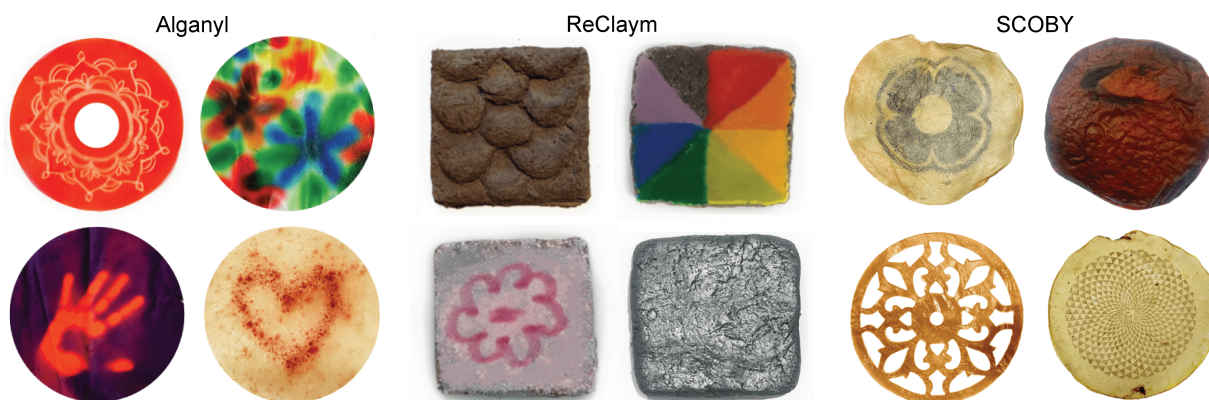


Figure 1.3: Samples of Alganyl, an algae-based bioplastic; ReClaym, a compost-based bioclay; and SCOBY a cellulose-based bioleather.

Alganyl is a vinyl-like biomaterial cooked from three food-grade ingredients: agar (an algae derivative), glycerin (a soybean derivative), and water. To develop Alganyl, I varied the ratios of ingredients until the desired mechanical properties such as strength and flexibility were achieved. I then identified fabrication methods such as heat sealing and laser cutting to aid making Alganyl artifacts. Through the creation of Alganyl artifacts (i.e., swatches, products, etc.) I explored how Alganyl could be customized with color, texture, sensing pigments, and electrical conductivity. The resulting artifacts range from do-it-yourself clothing items and environment-sensing accessories to biodegradable circuits and aesthetic sculptures. Once Alganyl and Alganyl artifacts are used they can be sustainably disposed of through composting or fully recycled through re-cooking.

ReClaym is a clay-like biomaterial made from my degraded food waste (i.e., compost). ReClaym is sustainable through the inherent biodegradability and circular life cycle of compost, and personal through the food preferences and habits the material visually and texturally reveals. Because ReClaym often changes based on one's personal compost (and in turn food/eating habits), it is imperfect and unpredictable. I support these characteristics of ReClaym by using hands-on

making techniques, such as sculpting, molding, and hand-held extruding to make-with ReClaym. I implemented these techniques to create a range of artifacts that were customized via sterility, electrical conductivity, sensing pigments, color, and texture. Example artifacts range from plant pots and photoluminescent garden sculptures to musical instruments and board games. ReClaym’s circular life cycle both begins and ends with composting, thus encouraging sustainable making practices.

SCOBY is a leather-like biomaterial that grows during the kombucha fermentation process. The SCOBY (Symbiotic Culture of Bacteria and Yeast) forms at the liquid-air interface of a kombucha culture over the course of 2-4 weeks depending on the kombucha recipe used and environmental factors such as temperature. When removed from the kombucha culture, the SCOBY dries into a biomaterial with properties and behaviors similar to leather. I leverage SCOBY’s slow growth to encourage a more intentional and reflective approach to making-with SCOBY. Accordingly, my design space exploration was much more pointed—identifying ways to tune the shape, color, and electrical conductivity of SCOBY in a purposeful effort to guide and inform the creation of an interactive SCOBY breastplate that senses touch interactions and displays corresponding light responses. SCOBY is sustainably disposed of through composting.

In Table 1.1 I summarize key qualities of Alganyl, ReClaym, and SCOBY to highlight their similarities and differences.

	Alganyl	ReClaym	SCOBY
<i>Primary Ingredient</i>	agar (red algae)	compost (food waste)	bacteria + yeast (cellulose)
<i>Making Method</i>	assembling	assembling	growing
<i>Material Alternative</i>	vinyl	clay	leather
<i>Tensile Strength (MPa)</i>	12.53	n/a	8.06
<i>Flexibility (%)</i>	13.04	n/a	27.13
<i>Density (g/cm³)</i>	1.21	1.26	0.63
<i>Biodegradability (days)</i>	~60	~3	~30

Table 1.1: Comparison of Alganyl, ReClaym, and SCOBY.

1.4 Overview

In this dissertation, I draw upon my experiences making and making-with biomaterials to bring attention to sustainable, more-than-human futures. Chapter 2, *Expressive Materials*, provides notable related work regarding computational materials and biomaterials, highlighting how biomaterials fit into the wider landscape of HCI, biodesign, and DIYbio. Chapter 3, *Design Process for Biomaterials*, presents my personal process for working with biomaterials, which covers how to make biomaterials, how to make-with biomaterials, and how to examine the sustainability of biomaterials. I also use this process to sensitize more-than-human design practices that I also use this process to sensitize more-than-human design practices that I incorporate along the way such as gaining an embodied understanding of the biomaterial, using sensory-rich fabrication techniques to correspond with the biomaterial, and designing slowly and intentionally at the rate of the biomaterial. Chapters 4, 5, and 6 describe how the process is applied to working with Alganyl, ReClaym, and SCOPY, respectively. Chapter 7, *Reflections and Aspirations*, concludes my dissertation with my thoughts on the future of sustainable material development, the often overlooked natures of biomaterials, and future more-than-human practices that I want to incorporate into my research with biomaterials. Through this work, I hope to offer a pathway towards more diverse, inclusive, and sustainable futures and relationships with the natural world.

Chapter 2

Expressive Materials

Materiality is becoming increasingly important in Human-Computer Interaction (HCI) and design as researchers have begun to recognize the importance of the material itself in a push towards ubiquitous, tangible interfaces [179, 185, 217, 229]. Accordingly, there has been a significant amount of research surrounding expressive, interactive, smart, vibrant, computational materials, which in turn has led to a deeper utilization of biomaterials. In the large scheme of things, these expressive materials (and biomaterials) are incredibly important in envisioning futures that are both technologically innovative and ecologically sustainable. Moreover, the ‘livingness’ [107] of these vibrant materials encourages new opportunities for human-material interaction and collaboration.

2.1 Materials in Human-Computer Interaction

Tangible Bits and Radical Atoms, introduced by Ishii, proposes a future in which “all digital information has physical manifestation so that we can interact directly with it” [101]. Tangible Bits specifically envisions tangible interfaces being made from materials that embody digital information [102]. By giving digital information a tangible form made from physical materials, Tangible Bits aim to make the digital world more accessible, understandable, and engaging for users. Radical Atoms expands on this vision by suggesting that tangible interfaces be made from dynamic, reconfigurable materials that can change in real-time in response to digital information [101].

Accordingly, there has been a surge of research focused on *materials* to seamlessly integrate computers into our physical everyday world, highlighting a “material turn” in HCI [185, 230].

By posing computers as materials for design, Vallgård and Redström further this paradigm shift in HCI by encouraging practitioners to explore the boundaries of the digital and physical world through new materials that expand the expressive range of physical, interactive systems [217]. They specifically describe these new, expressive materials as Computational Composites, which are materials that are integrated with computational capabilities, allowing them to sense, actuate, and communicate with the digital world [217]. Computational Composites are also designed to be flexible, stretchable, and deformable, enabling them to adapt to different forms and shapes for tangible interfaces. Moreover, these materials respond to user input, environmental conditions, or other contextual cues, indicating their expressiveness.

Notable everyday Computational Composites include paper coated in carbon that senses bends and folds [236], paper embedded with shape memory alloy to change shape with temperature [180], paper drawn on with conductive ink to create circuits [154], textiles dyed with thermochromic ink to that change color in response to temperature [59], textiles coated with photocatalytic nanoparticles to degrade the color of organic dyes [25], and ceramics glazed with conductive ink circuits [235]. Each of these examples showcase everyday materials and objects that are transformed into interfaces that have computational capabilities (e.g., sensing, actuating, displaying).

Weiser, a pioneer in ubiquitous computing, stated that *“The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it”* [227]. Accordingly, the flexible, everyday nature of computational composites and other ‘smart materials’ [1, 17] allow computers to become more invisible, ambient, and unobtrusive. These concepts have inspired the development of new materials, technologies, and design methods that expand the expressive range of interactive systems and make computing more accessible and meaningful for users.

2.2 Biomaterials in Biological Human-Computer Interaction

In light of the push towards expressive, computational materials, biomaterials act as an *elegant* and *sustainable* spring-board for the conception of new tangible interfaces that fit in naturally

with our everyday world—as biomaterials, especially living organisms, are rich with natural sensing, actuation, and computational abilities [155]. This has been most obviously highlighted by the concept of Living Bits and Radical Aminos [77, 173], a play on Tangible Bits and Radical Atoms [101, 102], which frames the living cell as a programmable computational material. As all living organisms are made up of twenty amino acids that build on each other to create a vast library of biomaterials, each with its own unique properties and affordances.

The nascent field of Biological Human-Computer Interaction (Bio-HCI) [29, 107, 113, 155, 172] is a field of research that explores the interactive capabilities that arise from combining biological materials with digital technologies. Common biomaterials in Bio-HCI, some of which I showcase in Figure 2.1, include plants [44, 74, 90, 98, 120, 191, 193], bacteria [15, 36, 86, 114, 117, 121, 146, 220, 233], slime mold [145], algae [18, 29, 49, 111, 135, 163], mycelium [26, 53, 79, 91, 133, 132, 138, 184, 226], symbiotic cultures of bacteria and yeast [5, 23, 24, 83, 158, 171], and bioplastics [21, 22, 27, 40, 116, 131].

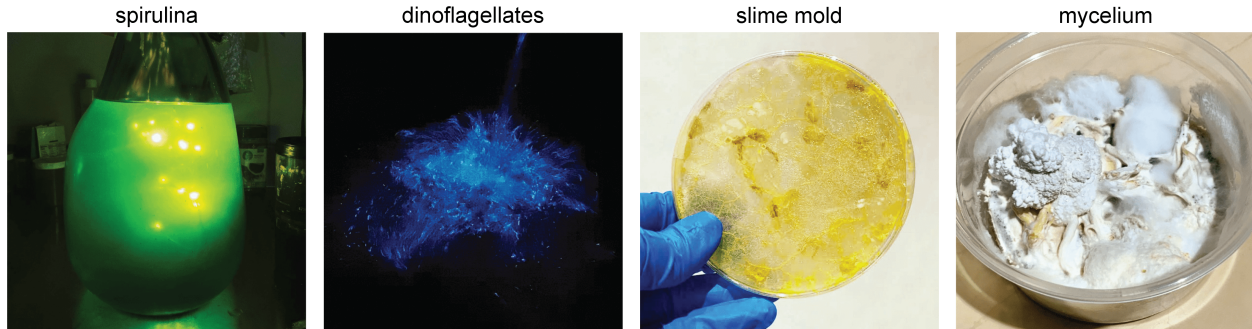


Figure 2.1: Examples of living organisms used in Bio-HCI: Spirulina, a blue-green algae [29]; dinoflagellates, a bioluminescent algae [163]; slime mold, a single-celled protist; and mycelium, a root-like structure of fungi [26].

The application space for these expressive, computational biomaterials includes, but is not limited to interactive displays [18, 33, 25, 86, 98, 120, 146], wearable devices [15, 23, 27, 71, 133, 158, 221, 233], art [42, 121, 162], instruments [117], games [49, 91, 111, 114, 135, 163], robots [104, 171], and data storage devices [5, 46, 92, 112].

Most of these works fall within the category of Living Media Interfaces (LMIs) [155], which

leverage the responsiveness of living materials to both sense and display information in an effort to support human-digital interactions. For example, cabbage that changes color based on pH [74], house plants that physically move toward light sources [98, 120], dinoflagellates that bioluminesce when physically stimulated [18, 163], and flavobacteria that display different amounts of growth depending on temperature and humidity [86]. Other LMIs use living organisms as functional components such as natto cell actuators for shape-changing fabric [233] or slime mold wires for a smartwatch [145]. Meanwhile, some works such as Nukabot [45], Biota Beats [117], and Project Florence [207] digitize biosignals from nonhuman organisms to encourage human-nonhuman interactions.

Biomaterials derived from once-living organisms (i.e., non-living biomaterials) have also begun to gain popularity in Bio-HCI. Non-living biomaterials do not typically have innate computational abilities afforded by living organisms. As such, researchers have used non-living biomaterials in combination with traditional electronic components or smart materials to create sustainable interfaces such as mycelium wearables [133] and breadboards [132], SCOBY leather wearables [158, 196], shape-changing pasta [211], bend-sensing bioplastics [116], pH-reactive “Organic Primitives” [106], and impact-sensing biofoam [131]. *Alganyl* [21], *ReClaym* [28], and *SCOBY* [23] fit into this category of non-living biomaterials in Bio-HCI. As such, I explore how they can act as sustainable housing for traditional electronics such as LEDs or be integrated with other sustainable, expressive materials such as activated charcoal [75, 201] or photochromic pigments [39].

2.3 Biomaterials in Do-It-Yourself Biology and Biodesign

Bio-HCI has benefited from drawing knowledge and resources from the more established Do-It-Yourself biology (DIYbio) [124] and biodesign [43] communities. DIYbio, like the broader DIY community, encourages the ethos of self-making, independent thinking, and problem solving [123, 202] and acts as an agent of democracy by giving people the independence, opportunity, and resources to create things that reflect their personal tastes and needs [14]. The DIYbio movement specifically aims to enable access to knowledge, techniques, and equipment

for biology [57, 122, 175]. One of the most important aspects of DIYbio is the community wet labs [55, 65, 66] and virtual platforms that provide open-source protocols and support [166] that provide amateurs and experts with tools, resources, and support. Thus, through shared bio-protocols, educational workshops in community wetlabs, and open-source equipment such as incubators, centrifuges, PCR machines, spectrometers, microfluidic devices [4], and machines to replicate DNA [165], DIYbio has encouraged people from various backgrounds to incorporate biology into their making practices.

The biodesign community has also been a huge proponent of accessible biology knowledge and open-source resources [8]. The field of biodesign is focused on incorporating biological materials into traditional design and artistic practices to solve specific problems in sustainable and aesthetically pleasing ways [157]. Instead of providing critical solutions, bioart, in turn, provokes questions regarding the use of biotechnology to manipulate other living organisms for human-centered purposes [234]. Notable works in this space blur the boundaries of biodesign, bioart, and bioengineering (and Bio-HCI) such as Eduardo Kac’s GFP Bunny [105], Anna Dumitriu’s bacterial dyed textiles [68], and Oron Catts and Ionat Zurr’s, Tissue Culture & Art Project [42].

As a trained mechanical engineer with minimal traditional biology knowledge, the DIYbio and biodesign communities provided me an accessible entry point into which I could research *biomaterials*. My first official biomaterial-oriented project was a group project titled MyCo Domicilia [26], which went on to be presented at the 2020 Biodesign Challenge [43]. As shown in Figure 2.2, MyCo Domicilia is a DIY resource for fabricating common household artifacts from mycelium, which is the root-like structure of fungi. Created during the COVID-19 pandemic when at-home experimentation was at an all-time high, we purposely chose to format MyCo Domicilia as a recipe book to help grow the creative biology market and as a result, promote sustainable practices and empowerment through accessibility. The MyCo Domicilia recipe book unpacks various design fundamentals for mycelium, including an explanation of what mycelium is, a list of materials and steps for growing mycelium, instructions for fabricating various mycelium household items, and personal reflections and insights to help guide others in their respective mycelium journeys. Through this project, I

familiarized myself with notable biodesign and Bio-HCI works as well as learned how to design with a living organism.



Figure 2.2: MyCo Domicilia is a recipe book for fabricating common household artifacts from mycelium at home and was created for the 2020 international Biodesign Challenge during the COVID-19 pandemic. This project introduced me to the world of biomaterial research and development.

The three biomaterials that I will go on to describe in later chapters (Alganyl, ReClaym, and SCOBY) are all heavily grounded in DIYbio as they utilize accessible equipment and materials (e.g., kitchen utensils, crafting tools, household ingredients) and open-source biology procedures (e.g., sterility testing, kombucha fermentation). For Alganyl and ReClaym, the recipes themselves drew from other open-source biomaterial recipes from the biodesign community, Alganyl primarily from Dunne’s *Bioplastic Cook Book* [70] and ReClaym from a variety of bio-based clay recipes on Materiom’s “Material Library” [152]. Meanwhile, I took cues from online cooking recipes to grow SCOBY, most notably being inspired by the Bon Appétit video “How to Brew Your Own Kombucha with Brad” [7]. Other prominent open-source, DIY biomaterial resources include *The CHEMARTS Cookbook* [126], Cecilia Raspanti’s “BioFabricating Materials” workshops [181], and Materiability’s tutorials [119].

I drew inspiration from a variety of biodesign works relating to bioplastics, bio-based clays, and SCOBY respectively. For Alganyl, I was influenced by AlgiKnit’s seaweed-based bioplastic yarn [3], GreenGear’s sugarcane-based bioplastic “EcoRain Poncho” [19], McCurdy’s algae-

based bioplastic “Carbon-Negative” raincoat [63], and Tomtex’s chitin-based bio-leather [214]. For ReClaym, I was motivated by Asut’s olive pomace-based clay [13], Otero’s eggshell-based clay [167], Georgiou’s oyster shell-based clay [80], Sauerwein’s mussel shells [195], and Andreola’s coffee grounds-based clay [6]. Lastly, for SCOBY, I was guided by Lee’s “BioCouture” [136], Giulini’s “Bodypuppets” [84], Lynch’s “Gut Feelings” [147], Laurin’s “Kombucha Couture” [130], and Baker’s kombucha jacket [16].

Chapter 3

Design Process for Biomaterials

Design has traditionally focused on creating objects, spaces, and systems that center around human needs and desires. However, this anthropocentric approach to design has led to significant environmental destruction. To address these issues, a growing body of design research has turned towards more-than-human approaches such as “organism-centered” interaction design [50, 163], the “art of noticing” [32, 141, 164, 216], collaborative survival [137, 138], multispecies cohabitation [139, 203], and symbiotic encounters [140].

In this chapter, I present a design process for making and making with sustainable biomaterials garnered from my personal experiences working with a variety of different biomaterials during my PhD. This process accordingly addresses designing with biomaterials in ways that broadly supports more-than-human design agendas regarding sustainability and nonhuman collaboration. As such, I draw inspiration from existing processes, methodologies, and theories regarding new materialisms [31] and material-centered design [108], which both recognize the agency and vitality of materials, through which materials can “actively contribute to the way that design activity unfolds” [213].

New materialist theory focuses on the materiality of the world and how materials and matter play a role in shaping human interactions and relationships with the environment [31]. As such, new materialisms pose humans as radically interconnected and interdependent with others [76], challenging traditional dualisms between subject | object, mind | body, and nature | culture [218]. Haraway famously uses the cyborg as a metaphor to describe the network of relationality between

humans, nonhumans, and technology [93]. By breaking down these dualisms and hierarchies that separate humans from others, new materialisms offer a way of thinking about the world that goes beyond traditional human-centered perspectives. For example, Bennett’s “thing-power” notably bringing awareness to aliveness and agency of things/materials [30]. Through new materialisms, new opportunities arise for makers to collaborate with materials in new ways by recognizing their inherent properties and capacities and exploring their potential for novel forms of expression and innovation.

In light of new materialist notions, material-centered design aims to bring attention to the *power* and agency of the material in the design process—the material having an *active* role in the practice, that guides and inspires the maker. Accordingly, material-centered design challenges traditional design practices that consider it the hierarchical job of the maker to shape materials into predetermined artifacts. This point of view is highly limiting, bringing attention to the agency of the human maker and disregarding the agency of the material. Instead, material-centered design takes inspiration and guidance from the material to arrive at a specific design outcome. Notable material-centered methods include Material-Driven Design (MDD) [108], material tinkering [170, 186], designing material experiences [82], and material correspondence [61, 99, 100].

Taking inspiration from these perspectives, I accordingly view biomaterials as another active participant in my design process that human makers collaborate with to arrive at a design artifact. As such, this process challenges previously human-centered notions of designing with materials, while still incorporating traditional material characterization techniques (e.g., mechanical testing) and fabrication methods (e.g., sculpting).

In the following sections, I describe each step of my biomaterial design process: *identifying a biomaterial, optimizing the biomaterial, testing the biomaterial, benchmarking the biomaterial, fabricating artifacts made from the biomaterial, exploring biomaterial artifact outcomes, and then disposing of the biomaterial*. I illustrate this process and how it fits into making, making-with, and examining the sustainability of biomaterials in Figure 3.1. I also note that while this process could be potentially applied to the development of any material, it addresses design implications specific

to biomaterials such as their temporality/slowness, imperfection/unpredictability, and biodegradability/circularity. Ultimately, I envision this design process being used to support and guide makers (e.g., biodesigners, HCI practitioners, DIY enthusiasts) in incorporating biomaterials into their own practices, thus promoting more sustainable futures.

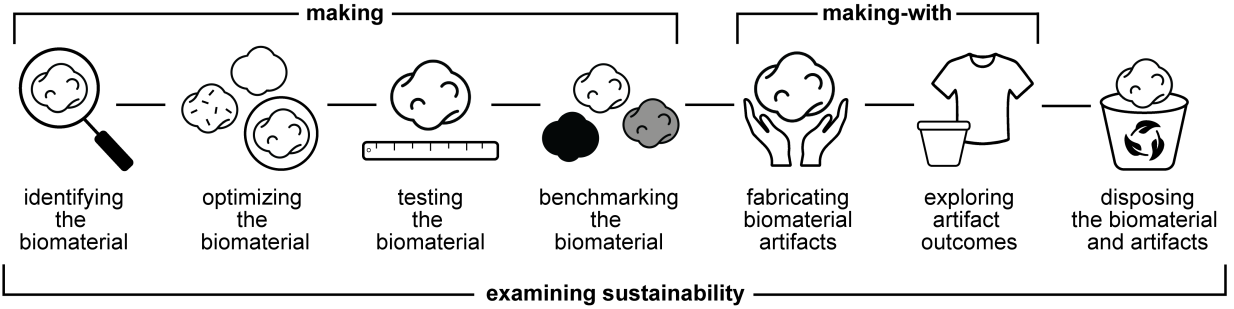


Figure 3.1: Process for Biomaterials

3.1 Making Biomaterials

Making biomaterials refers to the development of the biomaterial itself through methods such as cooking or growing. To make biomaterials, I derived recipes, optimized and identified properties, and benchmarked each biomaterial. In this process, making each biomaterial, served as a way to gain *understanding* of the biomaterial (i.e., knowledge of its affordances, behaviors, and properties). To gain an understanding of a material during the development stage, other researchers have focused on *designing material experiences* that give insight into the unique properties of the material rather than focusing on the end applications [82, 109, 174] and *material tinkering* to learn about the material through an iterative, hands-on approach [170, 186]. Through gaining material understanding, the maker can better *make-with* the biomaterial in the future. As such, making the biomaterial from scratch, and thus understanding the biomaterial, is foundational to a more-than-human design practice.

3.1.1 Identifying Biomaterials

In the case of biomaterials that are assembled from a mixture of ingredients, such as Alganyl or ReClaym, the recipe is the exact ratio of ingredients that make up the biomaterial. Accordingly, the properties of each ingredient and the ways in which those ingredients interact with each other determine the properties of the resulting biomaterial. To identify a recipe, I begin by imagining specific properties, behaviors, and experiences that the envisioned biomaterial would afford. For example with Alganyl, I envisioned the flexible plastic that makes up sandwich bags. As such, I knew the biomaterial would have to be strong, flexible, smooth, and clear. These properties can then inform search criteria to look for existing, related biomaterials. When sifting through existing recipes, I recommend that makers pay extra attention to the ingredients and ratios of ingredients used. By further learning the purpose of each ingredient (e.g., algae for gelifying, glycerin for plasticizing, calcium for stabilizing) makers can then identify which ingredients and recipes would potentially lead to the envisioned biomaterial.

In the case of biomaterials that are grown and then used as is (i.e., they are *not* an assembly of ingredients) such as SCOBY, a recipe is still required to create an appropriate environment for the biomaterial to grow in. For example, I followed a recipe to make sweet tea for the living cultures of bacteria and yeast to grow in and form the SCOBY biofilm. These recipes are often widely available and do not require an optimization process because the living organism (e.g., the SCOBY, the plant, the mycelium) already has a proven, ideal living environment. However, recipes for the growing environment can be finely tuned to control aspects of the organism, such as adding fertilizer to soil to increase the growth rate of plants.

3.1.2 Optimizing Biomaterials

Biomaterial optimization plays a significant role in the development of recipes for biomaterials that are assembled from a mixture of ingredients. To arrive at an “optimal” recipe, it is first important to define what “optimal” is, which might be a combination of the human vision and

the properties implied by specific ingredients (i.e., soil-like compost implies a clay). As such optimization is a conversational process where the human works to balance both their vision and the affordances of the ingredient properties by iterating through different recipes. In the case of Alganyl “optimal” was a strong yet flexible plastic-like biomaterial afforded by the properties of agar and glycerin, while ReClaym was a sculptable and extrudable clay-like biomaterial that was afforded by compost and an alginate-based gel. To arrive at this recipe, I recommend that makers rely on sensory feedback. This process looks like making a recipe and then interacting with it (i.e., feeling it, looking at it, smelling it, etc.) to get a general sense of its expressive-sensorial dimension [187]. Based on the sensorial experience, the maker gains an inherent, embodied knowledge of the biomaterial’s behaviors and properties. When paired with the knowledge of what each ingredient does (i.e., its scientific purpose as an ingredient), the maker can iterate on the recipe accordingly. For example, through my embodied, tactile experiences with Alganyl, I gained tacit knowledge about the material early in its development, which led to my observation that there was a direct correlation between the behavior and the feel of Alganyl (i.e., stronger samples felt smoother, while weaker samples felt stickier). Guided by the feel of Alganyl, I continued to iteratively adjust the amounts of glycerin (i.e., the ingredient that determines plasticity and stickiness) until I obtained smooth, yet flexible samples. This optimization practice echos material tinkering [170, 186], experience prototyping [38], bodystorming [197], kinesthetic-based prototyping [142], and intuition-based iterative design [73].

3.1.3 Testing Biomaterials

Biomaterial testing further supports material optimization as well as the next step in the process, material benchmarking. Material testing specifically refers to quantitative testing that extends past the qualitative testing that initially drives the iterative optimization process. These quantitative tests characterize the mechanical properties of the material such as tensile strength, compressive strength, flexibility, density, brittleness, and more. By gaining quantitative insight into the biomaterial, the maker can validate the qualitative results (i.e., the perceived properties

and behaviors that were intuited through feel). The mechanical results can then assist in finely tuning the optimal recipe. Moreover, these results allow technical comparisons to be drawn to other materials, thus facilitating material benchmarking.

From a human-centered perspective, material testing simply leads to *measurements* of the biomaterial, however from a more-than-human perspective, material testing leads to an understanding of the biomaterial’s *traits*, which are unique just like personality traits of humans. Through material testing, the maker gets to learn and identify the unique traits of the nonhuman biomaterial, thus getting to *understand* the biomaterial in a deeper way. By understanding the biomaterial, the human maker learns to work with the biomaterial in supportive and effective ways, just as they would learn to work with any other human team member on a group project. Accordingly, material testing, and ultimately *material understanding*, facilitates more-than-human making-with practices.

3.1.4 Benchmarking Biomaterials

Biomaterial benchmarking is comparing the traits of the biomaterial to other, similar materials. The goal with benchmarking is not to necessarily see how to transform the biomaterial into a sustainable/biodegradable replica of traditional materials, but to instead gain a better *understanding* of the biomaterial’s unique affordances by looking at what sets it apart from similar materials. By *understanding* the unique physical properties, mechanical behaviors, and somaesthetic qualities of the biomaterial, the maker is led to work *with* the biomaterial in supportive and inclusive ways.

3.2 Making-With Biomaterials

Making-with biomaterials refers to the crafting and creation of artifacts made from the biomaterial. The act of *making-with* a material has been positioned in prior work as a “correspondence”, where the maker and the material work together “in anticipation of what might emerge” [99, 100]. More simply put, the maker and the material work together to arrive at a final artifact, as opposed to the maker forcing the biomaterial to fit a predetermined design concept. Making-with

correspondingly aligns with other more-than-human design approaches such as “sympoiesis” [94] and “design-with” [222], which focus on the entanglements and interdependencies of humans and nonhumans and their equal importance in the creation of new things.

3.2.1 Fabricating Biomaterial Artifacts

When it comes to making-with biomaterials I often leverage fabrication techniques that are familiar and do not require specialized knowledge or equipment, thus encouraging people of all experience levels to participate. These techniques are often sensory-rich and improvisational (e.g., sculpting, ironing, layering, cutting) to accommodate for the unpredictable and imperfect nature of biomaterials caused by their biological origins. As such, improvisational fabrication techniques allow makers to adjust their actions to account for and support these natural inconsistencies. By supporting the biomaterial with these techniques, the maker in turn gains more insight into the biomaterial based on their experiences during the fabrication process—similar to how the maker gains understanding of the biomaterial during the optimization and testing phases.

The engagement of the body and senses while fabricating sequentially facilitates communication between the material and the maker. Prior research suggests that the maker is in a “conversation” with the material during the making process [198], where the desires of the maker and desires of the material are “spoken” through the physical properties of the material [61]. Accordingly, I see the communication between the maker and the biomaterial as a real-time feedback loop—the makers’ actions providing the material a way to actively disclose its’ capabilities and limitations [17] and the resulting actions of the material providing the maker with sensory feedback. For instance, ReClaym might begin to dry out as it is being sculpted, in which case the maker can add a splash of water to keep it at a sculptable moistness. Or, if there is a crack in the ReClaym, the maker can patch it before continuing to fabricate their artifact. By utilizing this feedback loop, the maker learns to “speak” with the material.

By communicating with the biomaterial through physical engagement, the maker gets to truly immerse their senses in the performance of the biomaterial, leading to a deeper, inherent, embodied

knowledge of it [142, 197]. This understanding of the biomaterial encourages the maker to work in tandem with the material, rather than force the material into predetermined forms. For example, I found my envisioned artifacts changing during the fabrication process, as the biomaterial would naturally perform in ways that inspired new forms, resulting in *unique artifacts in the way they reflect both the agency of the material and the maker’s vision*. Ultimately, I felt emotionally tied to my resulting artifacts because of this intimate relationship that formed through bodily engagement between maker and material.

3.2.2 Exploring Biomaterial Artifact Outcomes

Because this process encourages sensory-rich, improvisational making-with techniques as opposed to more digitally-driven techniques that are planned and precise, the maker can better support the unpredictabilities of biomaterials. However, imperfect biomaterials paired with imprecise fabrication techniques often results in artifacts that are *imprecise* and *imperfect* themselves. Instead of seeing these aspects as a bad thing, I encourage makers to let these imperfections drive deeper reflection, inspiration, and creativity [149].

There is also a notable absence of instruction (i.e., dictation of how to create an envisioned artifact) when making-with biomaterials—further encouraging *improvisation* [81] and *personalization* [188]. Makers can personalize and customize the biomaterial by exploring its design space; which can be used to enhance the already existing properties and affordances of the biomaterial (e.g., growing SCOBY into different shapes or exploring the sterility of ReClaym) and extend the affordances of the biomaterial (e.g., adding thermochromic powder to Alganyl to make it heat-sensitive or activated charcoal to SCOBY to make it electrically conductive). Furthermore, the improvisation that occurs during the making-with process almost acts as a performance [60], which can sometimes lead to a final artifact that is an unexpected, yet exciting departure from the initially envisioned artifact that reflects both the *will of the maker* and the *will of the biomaterial*.

3.3 Examining Sustainability of Biomaterials

Sustainability is my primary motivation for making and making-with biomaterials. As such, I make a point of actively examining the sustainability (i.e., the ecological impact) of each biomaterial I work with. While *Examining Sustainability* comes last in this process, I encourage makers to consider sustainability before, during, and after the *Making* and *Making-With* stages. When considering and examining sustainability, I employ one of the most widely accepted methodologies for analyzing ecological impact: the *life cycle analysis (LCA)*, which looks at the environmental impacts associated with each stage of an artifact's/biomaterial's life [88]. Beyond the life cycle, I also identify other ways and practices that impact the sustainability of a biomaterial such as its accessibility and/or its slowness.

3.3.1 Life Cycle Analysis

By analyzing each stage of life—sourcing ingredients, making the biomaterial, making artifacts from the biomaterial, using the artifact, and disposing of the artifact and any unused or unwanted biomaterial—both the biomaterial and the artifact can be intentionally designed to reduce environmental impact [150]. During the sourcing phase, key factors to look at include energy footprint, fuel consumption, and emissions, associated with manufacturing and transporting the ingredients, as well as other materials and tools that are needed. During the making and making-with, use stages, equipment and the artifact itself might require power, which leads to energy consumption. While it is important to identify these environmental impacts caused at each step in the life cycle, my analysis of a biomaterial's sustainability focuses primarily on the beginning and end of the life cycle and how they can be woven together.

3.3.2 Connecting Beginning of Life to End of Life

To sustainably source materials, some works propose repurposing waste materials to reduce raw material consumption [62, 223]. ReClaym and SCOBY similarly fall within this category as

ReClaym is primarily derived from food waste and SCOBY is often thought of as waste produced during the kombucha brewing process. While ReClaym gives food waste a second life as a raw ingredient for a new material, SCOBY itself is used as a new material.

Other works reduce raw material consumption through unmaking practices that carefully and intentionally take apart an artifact to obtain and reuse the materials [205, 231]. Unmaking doubly acts as a sustainable end-of-life option for artifacts that closely resembles the method of reuse [115], highlighting the importance of “linking invention and disposal” [34]. Along these lines, is the traditional form of recycling, which processes an artifact to break it down to its original material so that it can be re-fabricated into a new artifact. Alganyl perfectly exemplifies recycling via the process of re-cooking, in which I take a used Alganyl artifact and/or unneeded pieces of Alganyl and cook them in boiling water in order to obtain new pieces of Alganyl.

Composting provides another, albeit slower, method of circular disposal [134]. Composting involves disposing of biomaterials in the environment, where they degrade and foster the growth of new living organisms, which in turn can be harvested and used to make new materials. It is important to note that compostable materials differ from biodegradable materials—all compostable materials are biodegradable, but not all biodegradable materials are compostable. The difference is a matter of standards and policies set in place by governing environmental agencies. As defined by ASTM, biodegradable materials are typically defined as anything that breaks down into harmless compounds via naturally occurring microorganisms such as bacteria, fungi, and algae [10]. In contrast, compostable materials must break down into natural elements within 90 days and cause no harm to the environment [12]. For example, Alganyl, ReClaym, and SCOBY all break down in less than 90 days into biomass, carbon dioxide, and water when disposed of in a natural environment qualifying them as ‘compostable’. However, I often use ‘biodegradable’ as a broader term to describe their degradable quality.

Within HCI, biodegradable materials are often used in conjunction with non-degradable electronic components to create more sustainable artifacts and interfaces such as mycelium wearables embedded with LEDs [133] or biofoam pressure sensors embedded with stainless steel conductive

fibers [131]. When it comes to disposal, these electronics must be removed (and ideally reused) before the artifact is disposed of in the environment. However, there is a new push towards making electronic components also biodegradable, resulting in interactive artifacts such as a heater made from leaf skeletons, chitosan, and silver nanowires [204], wearable bend sensors made from bioplastics and carbon [116], and optical fibers made from cellulose [87]. My SCOBY artifact, an interactive breastplate, incorporates both traditional electronics that can be reused (i.e., LEDs and a microcontroller) and biodegradable electronics (i.e., a capacitive touch sensor made from SCOBY coated in activated charcoal).

Sustainable end-of-life has also been approached by *not* ending life at all—some research looking at how to extend the use of artifacts by leveraging personal attachment to the artifact, thus discouraging disposal [78]. This aligns similarly with practices that extend the life of an artifact such as repairing, refurbishing, and upcycling [189]. I similarly hint at how personal attachment to the biomaterial can be built during the making and making-with processes by gaining material understanding. Through this personal understanding and attachment, the maker is more likely to thoughtfully consider how the material is sourced, used, and disposed of.

3.3.3 Do-It-Yourself

While the Life Cycle Analysis is incredibly useful on a large scale to analyze the environmental impact of a company or even an industry, makers and DIY enthusiasts particularly like to use it to reflect on their own making practices. The concept of DIY itself puts the responsibility of a product on a person/people rather than a company/industry. By simply making a product instead of buying a product, the DIY creator immediately gains awareness about the resources (i.e., materials, energy, etc.) used to make the product and about what happens to a product once it has been used and is no longer needed or wanted. This exchange of responsibility and gained awareness then leads to deeper relationships between people and their products, thus fostering more *sustainable* and *intimate* design practices. In this train of thought, making and making-with biomaterials is an act of DIYbio that brings awareness to the sustainability of biomaterial development.

3.3.4 Accessibility

Intertwined with DIY is accessibility. I believe that accessibility plays a role both in the sustainability of making and making-with biomaterials and sustainability on a much larger scale. From the biomaterial perspective utilizing widely available ingredients (e.g., compost, agar, water) and tools (e.g., scissors, fabric irons, cake piping bags) that people already have reduces the need for un-sustainable sourcing practices that must account for pollution caused by manufacturing and transportation. From a grander perspective, accessibility in materials, tools, and methods (e.g., stirring, microwaving, sculpting), can encourage a wider range of people to get involved in making and making with biomaterial. As such, I envision a future where people can make their own sustainable biomaterials and craft corresponding sustainable artifacts, thus gaining personal independence from non-renewable resources, minimizing personal waste streams, and decreasing personal carbon footprint.

3.3.5 Slowness

Lastly, I want to highlight the importance of slowness in sustainability. Slow Design promotes well-being for individuals, society, and the natural environment by encouraging reflection, participation, and evolution in the design process [85, 160, 177, 208, 219]. Accordingly, slow design amplifies the experience of time [89] by inviting people to engage in acts of reflection and “arts of noticing” [32, 164]. In these slow, reflective moments, I see an opportunity to use that time to design more critically and intentionally (i.e., taking the time to consider all steps in the life cycle, planning how specific materials will be utilized). As such, this slow, intentional approach drastically opposes the infamous “move fast and break things” [210] approach, which has led to a making culture of rapid disposal, and consequently environmental damage. By leveraging moments of slowness that are driven by the biomaterial’s agency (e.g., when the biomaterial is growing, drying, cooking, etc.) I promote designing in a more thoughtful and sustainable way.

Chapter 4

Alganyl: Algae-Based Bioplastic



Figure 4.1: *Unnatural BioFLOWERs* is an Alganyl-moss sculpture created by Ella McQuaid and myself. The sculpture questions the “natural” aspects of working with bioplastics, as the Alganyl flowers biodegrade and follow the perennial rhythm of plants, but do not have an inherent life source and are man-made.

Alganyl was the first biomaterial I worked with during my PhD. Motivated by the devastating impact of plastic pollution, especially in the textile industry, I envisioned making a fabric-like, bio-based, biodegradable plastic that could be used as an alternative to vinyl (PVC) fabric or polyethylene (PE) film used in clothing, bags, packaging, upholstery, and more.

Bioplastics are biodegradable (i.e., disintegrate or break down naturally into a mixture of biogases and biomass) [199], bio-based (i.e., made from sustainable materials that consume carbon dioxide while alive) [225], and plastic-like (i.e., have similar properties to synthetic plastics) [176]. The most commonly known bioplastics are polylactic acid (PLA) and polyhydroxyalkanoates (PHA) [128], however, these bioplastics are highly processed, requiring specialized equipment to make. Moreover, they require specific environmental factors to biodegrade (i.e., they cannot be composted or degraded when placed in the natural environment).

Accordingly, I chose to develop a highly *accessible* and *compostable* bioplastic. To do so, I looked at open-source bioplastic recipes from Kwong’s Bio-Plastic Handbook [125], Kretzer’s Bioplastic tutorials [119], Raspanti’s BioFabricating Materials tutorials [181], and Materiom’s Material Library [152].

I specifically chose to base Alganyl off of Margaret Dunne’s Agar Agar Plant Based Bioplastic recipe [70], which utilizes a mixture of three food grade ingredients: agar powder, glycerin, and water. I expanded upon Dunne’s work by first optimizing the ratio of ingredients for *strength* and *flexibility*, which resulted in a bioplastic that resembled vinyl fabric; strong, flexible, slightly stretchy, and feels smooth against the skin. I then explored a set of design parameters to customize the optimized Alganyl via fabrication techniques, color, texture, environmental sensing ability, and electrical conductivity. I correspondingly created a wide range of applications including a floral sculpture 4.1, clothing 4.5, environment sensing accessories (a UV light sensing bracelet and temperature sensing necklace) 4.6, biodegradable circuits 4.7, and a transparent concert bag 4.9.

When Alganyl artifacts are no longer needed, they can be sustainably disposed of in two different ways: linearly via composting or circularly via recycling. When composted, Alganyl takes 60 days to biodegrade 97%, which is about 1000 times faster than vinyl fabric to break down.

Moreover, Alganyl is *fully circular*, meaning that used or unwanted Alganyl can be re-cooked to make a new Alganyl that does not rely on sourcing new ingredients other than water.

4.1 Making Alganyl

To develop Alganyl, I focused on the three qualities that define bioplastics: bio-based, plastic-like, and biodegradable. Accordingly, I began by identifying accessible, bio-based, and nontoxic ingredients, drawing from Dunne’s Bioplastic Cook Book for FabTextiles [70]. I then experimented with various ratios of ingredients as seen in Table 4.1 to arrive at an “optimal” recipe that has plastic-like qualities that resemble vinyl fabric. I further tested Alganyl’s ability to biodegrade in a natural environment, which I describe in Section 4.3.

4.1.1 Ingredients

While there are numerous DIY bioplastic recipes, I specifically took guidance from Dunne’s “Agar Agar Plant Based Bioplastic” recipe to identify three highly accessible, food-grade ingredients for Alganyl: agar, glycerin, and water [70]. I note the role of each ingredient as follows:

- *Agar*, also known as agar-agar, is a gel-like substance that acts as the key binding ingredient of Alganyl. Agar consists of polysaccharides derived from the cell walls of some species of red algae (e.g., Rhodophyceae) [178]. It most often comes dehydrated in form of a white powder that can be bought in grocery stores, as agar is commonly used as an emulsifier, thickener, texturizer, and binder in cooking. To rehydrate agar powder it must be added to water and heated to boiling point (85-90°C), thus causing the agar to ‘bloom’ and gelify. When cooled back down, the activated agar retains its gel-like consistency.
- *Glycerin* is a non-toxic, colorless, odorless, viscous liquid that is derived from soybeans and palms. In cooking, it is often used as a thickener, solvent, sweetener, humectant, and preserver [168]. In material science, it often acts as a plasticizer [192], which is the role it plays in Alganyl (i.e., providing flexibility).

- *Water*, while not a bio-based material, is non-toxic, renewable, and easily available. Within Alganyl, water is used to dissolve and activate the agar when heated. While Alganyl is predominately made up of water, most of Alganyl’s water content evaporates during the drying process.

4.1.2 Recipe Optimization

I optimized the recipe of Alganyl to obtain a bioplastic that was both strong and flexible, ultimately aiming for a bioplastic that both felt and acted like vinyl plastic fabrics used for public seating or polypropylene plastics used for Ziploc bags.

To make each recipe, I began by bringing the mixture of agar, water, and glycerin to a boil by either microwave or stovetop. During the heating process, I intermittently stirred the mixture to ensure that the agar was uniformly distributed in the liquid, as its heavier density makes it sink to the bottom of the cooking container. Once transformed into a uniform, viscous mixture, I poured the heated Alganyl onto a clean, flat, heat-resistive surface, letting it naturally flow into a shape, cooling quickly enough to form its own bounds. Once poured, the Alganyl immediately begins to gelify due to the sudden drop in temperature (boiling to room temperature) and continues to dry for 24-72 hours (dry time depending on airflow and humidity of the surrounding environment). While drying, Alganyl shrinks approximately 46% in volume due to the evaporation of the water. For each recipe, I kept the amount of agar and water the same and adjusted the amount of glycerin to tune the material properties, thus making recipes that range from brittle to flexible.

Early on in this development process, I gained tactile information about Alganyl through material tinkering [170, 186], experience prototyping [38], and kinesthetic-based prototyping [142]. These embodied experiences of touching, moving, stretching, and crumpling Alganyl, helped me understand that there was a correlation between the flexibility and stickiness of Alganyl and the amount of glycerin added to the recipe. As such, I chose to only adjust amount of glycerin added to the recipe when iterating.

To arrive at my “optimal” recipe, I ran tensile tests with a universal testing machine to

determine the flexibility and strength of each recipe. I used formulas dictated by the ASTM D638 type IV standard for testing plastics [11] to arrive at average values for percent elongation at break (i.e. flexibility) and tensile strength for each recipe. The results shown in Table 4.1 indicate the average of five samples for each recipe. As expected, the results indicate that the concentration of glycerin is the main factor in the flexibility and strength of Alganyl, backing up my intuited, felt experiences. I also found that flexibility and strength have an inverse relationship; increasing glycerin leads to an increase in flexibility but a decrease in strength. I decided to use Recipe 3 as the “optimal” ratio of ingredients for Alganyl because it provided the best balance of *strength* and *flexibility*.

Recipe	Water (mL)	Agar (g)	Glycerin (g)	Elongation (%)	Strength (MPa)
1	50	2	0	0.61	56.67
2	50	2	1.5	6.09	31.66
3	50	2	3	13.04	12.53
4	50	2	4.5	16.87	6.45
5	50	2	6	19.65	4.19

Table 4.1: Strength and flexibility, denoted in the table as Elongation %, of five different recipes. Recipe 3 is the “optimal” ratio of ingredients for Alganyl because it provided the best balance of strength and flexibility.

4.1.3 Material Benchmarking

Table 4.2 compares the tensile strength of five algae-based bioplastics to Alganyl. Most recipes use the same ingredients (agar, water, and glycerin) with the addition of some starches or an algae gel instead of agar powder. However, the ratio of ingredients varies greatly between each bioplastic recipe and so do the cooking methods, for example, one recipe was boiled for 30 minutes [206]). I only compare the tensile strength because documentation of other bioplastics rarely included values for percent elongation (i.e., flexibility). Through this comparison, I learned that Alganyl is neither the strongest nor weakest material in Table 4.2, having similar strength to many other agar-based bioplastics. By benchmarking Alganyl against these other bioplastics, I see the potential for further optimizing the recipe and perhaps the cooking methods to obtain a

stronger version of Alganyl.

Recipe	Strength (MPa)	Source
100 mL water, 1 g agar, 63 g glycerin	0.67	[209]
100 mL water, 0.5 agar, 0.83 g glycerin, 2.83 g sago starch	2.43	[97]
100 mL water, 0.5 agar, 0.83 g glycerin, 2.83 g potato starch	8.5	[232]
100 mL water, 4 g agar, 6 g glycerin	12.53	
100 g agar gel, 15 g glycerin	17.25	[148]
100 mL water, 1 g agar, 15 g glycerin	49.9 ± 12	[206]

Table 4.2: Comparing the recipes and strengths of different agar-based bioplastics.

For further comparison, typical thermoplastics used in engineering like polypropylene, polyethylene, and polyvinyl chloride, have tensile strengths ranging from 50-80 MPa [129]. As such, most of the agar-based bioplastics displayed in Table 4.2, including Alganyl, have significantly smaller strength values, making these bioplastics an unrealistic alternative for plastics parts that are heavily and often exposed to high amounts of load. However, most thermoplastics go towards single-use applications such as packaging and can be considered to be over-engineered for their given application. In this light, I found that Alganyl was sufficiently strong enough to create various applications including clothing, bags, decor, and more.

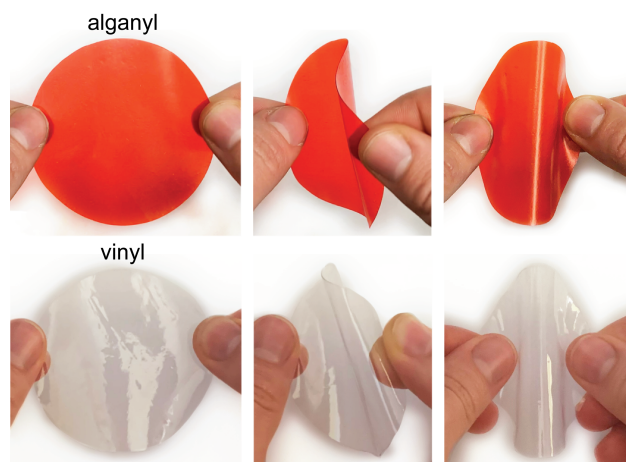


Figure 4.2: Red-colored Alganyl in comparison to clear vinyl.

When comparing the aesthetics of Alganyl to traditional plastics, I found that Alganyl *looks* most similar to the clear, flexible, petroleum-based thermoplastics used for Ziploc bags (i.e.,

polyethylene); however, Alganyl is slightly thicker making it *feel* more sturdy and durable. Therefore, the closest plastic that I could find to Alganyl in terms of look and feel was vinyl fabric (i.e., polyvinyl chloride), which I compare Alganyl to in Figure 4.2. Similarly to vinyl, Alganyl has a shiny sheen to its surface and feels very smooth.

4.2 Making-With Alganyl

To create Alganyl artifacts from my optimized Alganyl recipe, I identified easy-to-use subtractive and additive fabrication techniques and developed a variety of methods to customize Alganyl via color, texture, sensing ability, and electrical conductivity. I exemplify these design explorations through the creation of artifacts such as a sculpture 4.1, a dress 4.5, a UV light-sensing bracelet 4.6, and a biodegradable circuit 4.7.

4.2.1 Fabrication Methods

To subtractively fabricate with Alganyl (Figure 4.3), I most often cut Alganyl with an X-acto knife or scissors in combination with custom stencils. However, I could also cut Alganyl directly with an Epilog Laser Fusion M2 laser cutter using the vector cut function set at 70% speed, 20% power, and 50% frequency. To laser engrave Alganyl, I used the same settings but selected the raster engrave function, resulting in digital designs that were etched onto the surface of the Alganyl.



Figure 4.3: Subtractively fabricating with Alganyl by cutting it with an X-acto knife, scissors, or a laser cutter. The laser cutter was also used to engrave detailed patterns onto the surface of Alganyl.

For additive fabrication (Figure 4.4), I used heat sealing. Similar to industrial thermoplastics that change phase from solid to liquid when heated, Alganyl melts at elevated temperatures and solidifies when cooled. To heat seal overlapping Alganyl pieces together, I used safe and accessible

heating elements found around my home such as a fabric iron and the tip of a hot glue gun (without any glue in it). To avoid melting the Alganyl directly onto the heating element, I typically placed a layer of wax paper or a thin sheet of cotton between the Alganyl and the heater. I used heat sealing to support other additive fabrication techniques found in traditional textile practices such as weaving. To create three-dimensional forms, I pleated, folded, and rolled up pieces of Alganyl, which I then heat-sealed in specific locations to hold the form in place.



Figure 4.4: Additively fabricating with Alganyl by heat sealing pieces together with a fabric iron or the hot tip of a hot glue gun. Heat sealing can be used in conjunction with traditional textile fabrication techniques such as weaving to create composite pieces.

4.2.2 Color and Texture

Alganyl is naturally clear and smooth, which motivated a series of experiments surrounding color and texture. To uniformly color Alganyl, I added 2-3 drops of synthetic food-grade dyes to the original recipe or swapped the water content of the recipe for a water-based natural dye solution such as hibiscus tea. To add colorful patterns to Alganyl, Ella McQuaid experimented with painting food dye directly onto the surface of the Alganyl as it was drying (i.e., when the Alganyl was a gel).

To add texture, I dried the liquid Alganyl mixture on textured surfaces rather than a smooth surface, which resulted in one side taking on the texture of the surface and the other side, which was exposed to air, staying smooth. I also added texture through my fabrication techniques, such as laser engraving the surface of dry Alganyl or heat-sealing pieces of Alganyl together in a pattern.

These explorations of color and texture ultimately led to a small collection of Alganyl garments that were fabricated using the subtractive and additive techniques mentioned in Section 4.2.1.

To make the garments Ella and I prepared several clear and colorful samples. For the dress (Figure 4.5), we began by cutting all the clear Alganyl samples into round sequins that we heat sealed together in an overlapping fish-scale pattern to create a *texturally* interesting base ‘fabric’. We then followed a traditional dress pattern to cut our base fabric into shape and heat seal the seams together. We then added colorful embellishments on top of the base dress to create a more aesthetic garment. The embellishments (coral, fish, and seaweed) paired with the fish-scale pattern of the sequins resulted in a sea-themed dress, meant to emphasize the impact of plastics (and microplastics) on our oceans.

The skirt (Figure 4.5) utilized the same textured base fabric, but was cut into a circle skirt pattern. We dictated the form of the skirt by folding intentional pleats that were held in place by a belt made of colorful Alganyl sequins. The pleats not only added volume to the skirt but made it highly maneuverable and fun to spin around in. We finished the skirt by adding more colorful sequins at the bottom hemline to emphasize the form and movement of the skirt as its worn.

Unlike the dress and skirt, the shirt (Figure 4.5) was predominantly made from large sheets of Alganyl rather than the textured base ‘fabric’. Specifically, we used sheets of Alganyl that were patterned with color during the drying process via painting. The front of the shirt consists of a floral sheet, while the back is made up of a rainbow sheet. The large sheets of the shirt provided a very smooth uniform texture that acts more as a canvas for visual patterns. These two main pieces were held together on the sides by solid red sheets of Alganyl while the shoulder straps were made up of colorful Alganyl sequins.



Figure 4.5: Three articles of Alganyl clothing: a dress, a shirt, and a skirt.

4.2.3 Environmental Sensing

To create environment-sensing Alganyl, I embedded photochromic pigments that changed color when activated by ultraviolet (UV) light and thermochromic pigments that changed color when activated by temperature. Both pigments were non-toxic and biodegradable, having been proposed for on-skin tattoos that indicate exposure to UV solar radiation [39]. These pigments came in the form of powders, which I incorporated into Alganyl once it was done cooking, but before I poured it onto a surface to dry. Through trial and error, I found that adding 0.25g of powder to Recipe 3 in Table 4.1 resulted in a successful environment-sensing Alganyl.

I specifically used UV light sensing (i.e., photochromic) Alganyl to create a bracelet that acts as a sunblock reminder—sunlight having levels of UV light that damage skin. When the wearer is not exposed to UV rays (i.e., indoors) the bracelet is cream, but when the wearer steps into the sun the bracelet changes to dark pink; the saturation of the pink color depends on the amount of UV exposure. Because UV light is invisible, this bracelet helps visualize the amount of UV light the wearer is exposed to, regardless of the season. It is commonly assumed that sunblock only needs to be applied during the summer when it is hot. However, harmful UV light can be present regardless of the temperature, the bracelet shown in Figure 4.6 was worn outside on a cold winter day.

I similarly used temperature sensing (i.e., thermochromic) Alganyl to create a necklace that detects and displays the temperature of the environment and the body. When worn inside, the body’s warmth and the room temperature turn the necklace light blue and orange. When transitioning from a warm (indoor) environment into a cold (outdoor, winter) environment, parts of the necklace close to the skin stay warm while the other parts get cold, leading to a range of color saturation. When worn outside in the cold for longer periods of time, at which point the body also gets cold, the necklace turns dark blue and orange. While the necklace does indicate environmental conditions, its placement on the user’s chest, as shown in Figure 4.6, means that it more accurately indicates the temperature of the user wearing the necklace, thus showing the potential for creating biodegradable thermometers.

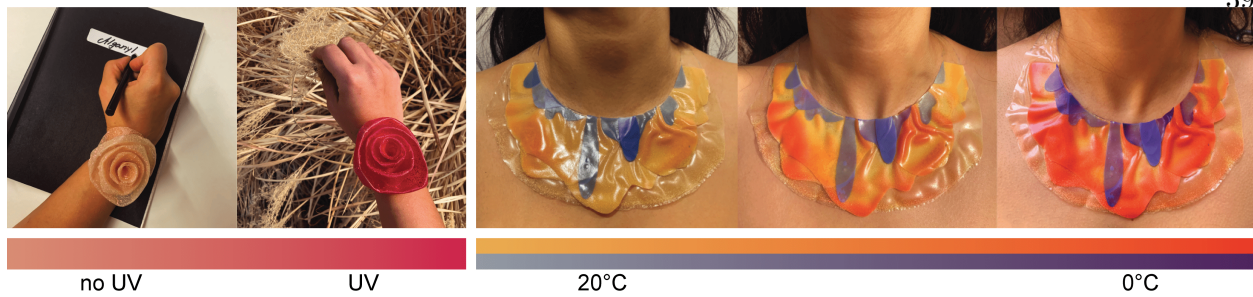


Figure 4.6: Photochromic bracelet that changes from light pink when not exposed to UV light (i.e., when worn inside) to dark pink when exposed to UV light (i.e. when worn outdoors). Thermochromic necklace that changes from light orange and blue when exposed to warm temperatures to dark orange and blue when exposed to cold temperatures.

4.2.4 Electrical Conductivity

Lastly, I explored adding a *biodegradable* conductive paste made up of activated charcoal powder and vinegar [75, 201], to create basic circuits. I used a screen printing technique with a custom laser cut stencil to ‘print’ the activated charcoal paste onto the surface of the Alganyl thus creating a skyline pattern. Figure 4.7 shows a sample in which I embedded small Light Emitting Diodes (LEDs) throughout the skyline which illuminated a red glow when the sample was connected to a power source. While the LEDs and external electronics are not biodegradable, they can be easily removed after use and *reused* while everything else can be composted.

I created an identical sample with the same biodegradable conductive skyline print on it. Rather than embedding LEDs, I added a layer of thermochromic Alganyl on top of the clear

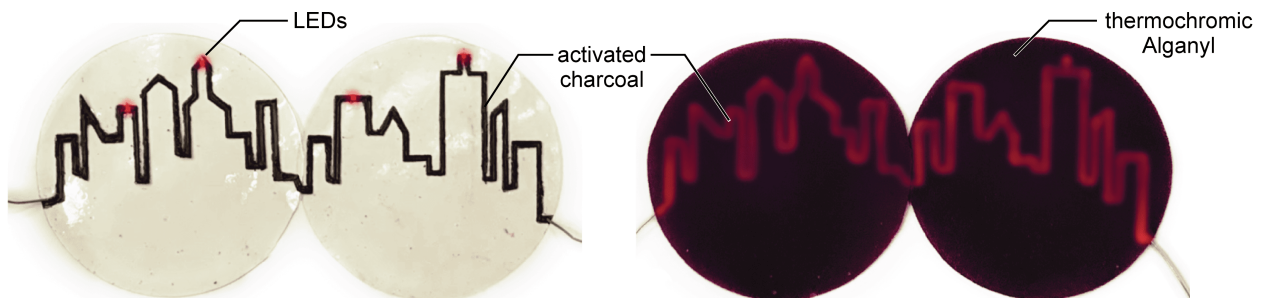


Figure 4.7: Biodegradable Alagnayl circuits made from carbon-based conductive pastes that can power a series of surface-mounted LEDs and change the color of thermochromic Alganyl.

skyline printed samples; the thermochromic Alganyl went from purple when at room temperature to red when exposed to heat. As seen in Figure 4.7, when the circuit is connected to an external power source, the paste begins to heat up and causing the thermochromic Alganyl sitting on top of the paste to selectively change color, thus revealing the city skyline.

4.3 Examining Sustainability of Alganyl

My main motivation behind Alganyl was to create a sustainable plastic alternative. As such I purposely designed Alganyl to be made from renewable, non-toxic, bio-based ingredients that result in a bioplastic that can quickly degrade in the environment or be completely recycled and remade.

4.3.1 Alganyl Life Cycle

To more deeply examine the sustainability of Alganyl I looked at its entire life cycle which is made of 6 steps shown in Figure 4.8: (1) sourcing ingredients, (2) cooking Alganyl, (3) fabricating Alganyl artifacts, (4) using Alganyl artifacts, (5) re-cooking Alganyl, and (6) composting Alganyl. This life cycle accounts for both a linear approach, through composting and a circular approach, through re-cooking.



Figure 4.8: The life cycle of Alganyl accounts for sustainable disposal circularly, through re-cooking, and linearly, through composting.

- (1) *Sourcing Ingredients.* Alganyl is made from only three ingredients agar, glycerin, and water. While I got water from my kitchen faucet, the agar and glycerin had to be purchased from a local grocery store. As such, we must account for the energy required to source, process and distribute these materials, especially agar which is an algae-based material that has to travel a long way to get to the landlocked state of Colorado. I envision Alganyl being more sustainable from an ingredients perspective by deriving agar directly from locally sourced algae [58].
- (2) *Cooking Alganyl.* I brought all three ingredients to a boil using a microwave or stovetop to make Alganyl. These heating elements both require power (gas or electricity). The tools used for cooking Alganyl can be easily varied (e.g., pots, pans, spoons, spatulas), thus allowing people to use whatever equipment they already have around their kitchens to make Alganyl.
- (3) *Fabricating Alganyl Artifacts.* I fabricated Alganyl artifacts via cutting and heat sealing. Laser cutting and heat sealing both require power. I further customized Alganyl by adding colorful dyes, environment-sensing pigments, and conductive pastes, which were all nontoxic and minimally impacted the biodegradability of Alganyl. I then used these explorations to inform the creation of ReClaym artifacts.
- (4) *Using Alganyl Artifacts.* When kept at room temperature, Alganyl does not degrade and keeps its properties and behaviors as it ages. If exposed to cold water, Alganyl artifacts repel the water rather than dissolving. However, after being exposed to cold water they tend to re-dry in a slightly deformed manner. Alganyl samples kept their color and patterns for over two years at indoor temperature (max 25°C) under artificial lighting conditions. When left in direct sunlight for more than a few days, we noticed that the Alganyl's color fades similarly to clothing dyed with organic dyes.
- (5) *Re-cooking Alganyl.* I first explored a circular approach to disposing of Alganyl—recycling

via re-cooking. The first, a circular disposal method, involves re-cooking dry Alganyl scraps in additional water that re-starts the process at the drying stage. To re-cook Alganyl, I placed used, unwanted, or unneeded Alganyl pieces in water (ratio of 3 g Alganyl to 10 g water) and brought the mixture to a boil. I heated and stirred the mixture until all the Alganyl was dissolved (approximately 10 minutes at high heat), leaving a uniform, viscous liquid that looked like the original mixture made from raw ingredients. I then poured the re-cooked Alganyl liquid onto a surface and let it dry, resulting in a new piece of Alganyl that could be fabricated with again. Re-cooking uniformly colored Alganyl samples did not affect the original color intensity, however, re-cooking patterned or multicolored Alganyl resulted, as expected, in a uniform color obtained by mixing all pigments together. Meanwhile, I noticed that re-cooked, photochromic, and thermochromic Alganyl samples lost their sensing abilities. I assume this occurs due to exposure to higher temperatures for a relatively long duration.

By implementing this re-cooking process, I envision a circular economy using Alganyl, where the base ingredients (agar and glycerin) are re-used, eliminating the constant need for new raw materials every time Alganyl is made. I exemplify this concept with a clear bag that can be brought to concerts, sports games, and other live events that commonly require bags to be transparent for safety reasons. Such a requirement often adds the pressure of quickly finding ways to get a transparent bag for the sole purpose of using it during a concert. As seen in Figure 4.9, the transparent concert bag we made from re-cooked Alganyl that was



Figure 4.9: The clear concert bag is made up of re-cooked Alganyl scraps that were given a second life.

cut into sequins and heat sealed into the same base ‘fabric’ used for the dress and skirt. The composite piece was then folded and heat-sealed into the shape of the bag. Two additional sequins were added onto the bag to seal in two small magnets that kept the bag closed.

- (6) *Composting Alganyl*. I quantified the biodegradability of Alganyl by taking mass-loss over time measurements, which is a standard method to determine how long a material takes to biodegrade [72]. This method involved burying a sample 2 cm in soil that contains living microbes (to simulate a natural, outdoor environment). I then dug up the sample, brushed off the soil, and measured its mass every 3 days. I used Equation 4.1 to calculate percent degradation, where M_0 is the mass of the SCOBY on Day 0 and M_x is the mass of the SCOBY on Day X.

$$Degradation(\%) = \frac{|M_x - M_0|}{M_0} * 100 \quad (4.1)$$

I found that Alganyl degraded *97% in 60 days* in a controlled environment kept at 40°C. Figure 4.10 shows qualitatively Alganyl’s degradation over 60 days. I note that Alganyl might degrade at a different rate if disposed of directly in nature, depending on the temperature, humidity, and microbial activity of the soil. The food-grade dyes and activated charcoal paste do not affect the biodegradability of the Alganyl, and the thermochromic and photochromic pigments we used have been shown to be consumed over time by macrophage cells having been used in bio-medical applications [39].

4.3.2 Sustainability Through Accessibility

Beyond its life cycle, Alganyl also approaches the idea of democratizing sustainable biomaterials through accessibility. Because Alganyl is only made up of three, low-cost ingredients and utilizes familiar making and making-with methods, it can be easily made and made-with by people of all ages and backgrounds, allowing everyone (not just expert designers) to make sustainable artifacts. Accordingly, when I ran a user study with Alganyl, in which university students learned

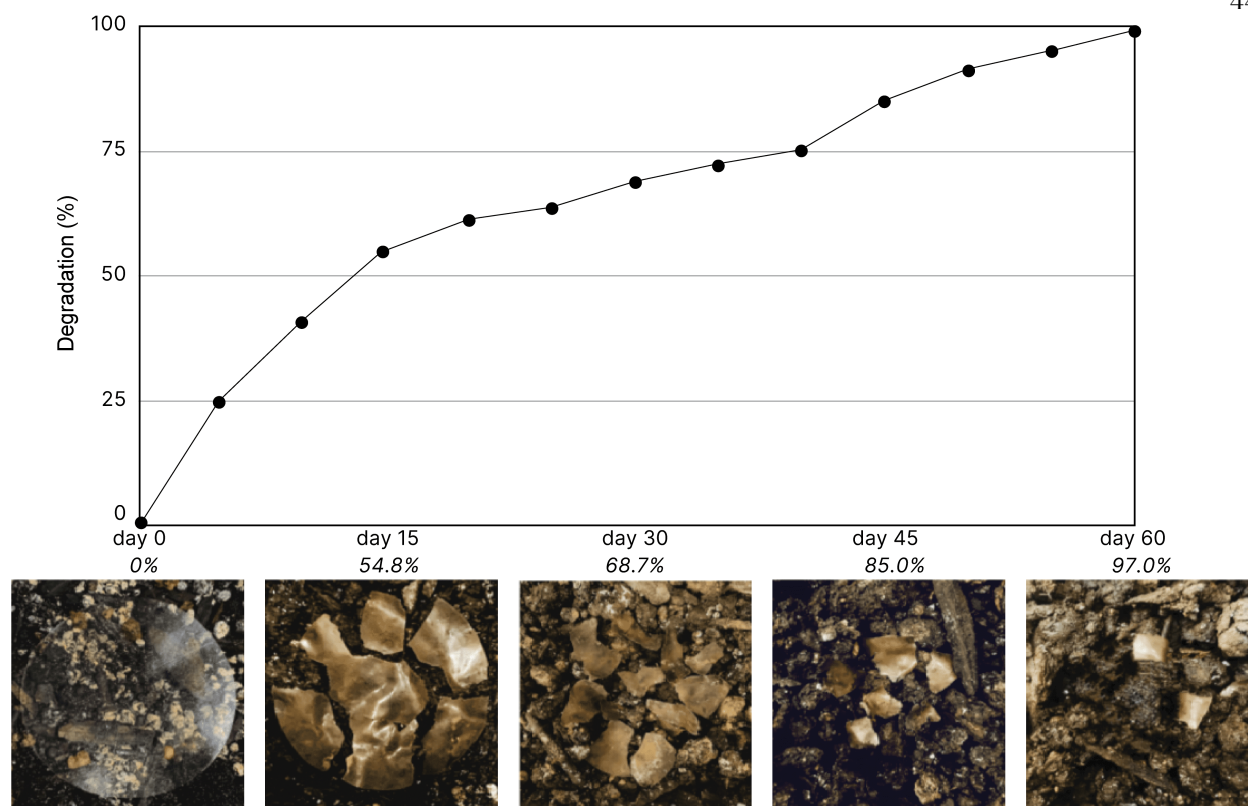


Figure 4.10: Alganyl biodegrades 97% in 60 days when buried in compost.

to make and make-with Alganyl, participants indicated that they appreciated the simplicity of the making process and the biodegradability of the material. Through the accessibility of Alganyl, participants further envisioned a future in which people address sustainability on a personal, at-home level by replacing everyday artifacts made of plastic such as sandwich bags, plastic wrap, dishwasher pods, bandages, jewelry, and facemasks; Figure 4.11 showcases a couple of the artifacts made by participants. Moreover, these artifacts demonstrate a wide application space for Alganyl.



Figure 4.11: Alganyl artifacts made at home by user study participants.

Chapter 5

ReClaym: Compost-Based Bioclay



Figure 5.1: This ReClaym plant pot was one of the first artifacts I created from my food waste once I arrived at my “optimal” recipe. The pot was hand-extruded through a piping bag to create a coil pot shape. I used the pot as a home for my venus fly trap plant.

After working with Alganyl, I was motivated to develop a biomaterial that was primarily made from used, waste materials as opposed to new, raw materials (e.g., agar). By using waste materials, I lower the environmental impact associated with sourcing new materials, while also extending the life cycle of the waste material. Considering the significant environmental issue of food waste being discarded daily in food practices [47], I decided to create a biomaterial from my food waste. By choosing to develop a food waste-based biomaterial, I challenged myself to become just as comfortable working with my food waste as I am working with my food.

When searching for existing food waste-based biomaterials, I discovered that most existing biomaterials made from food waste were used to make clays, pastes, and concretes from one singular type of food waste like olive pomace [13], eggshells [167], oyster shells [80], mussel shells [195], or coffee grounds [6]. In contrast, I wanted to develop a bio-based clay that was made from *all types of composted food waste*. To do so, I leveraged the process of composting, to degrade all types of food waste into a soil-like state that is somewhat uniform.

I combined my compost with various ratios of nontoxic binders to arrive at an optimal recipe for ReClaym, a bio-based and biodegradable clay. Since ReClaym is primarily made from composted food waste, it reveals personal aspects such as food preferences, physical location, cultural identity, cooking techniques, and temporal relationships with food. The *personal* aspect of compost makes ReClaym a dynamic biomaterial that is unique to each household and to each time it is made. Consequently, ReClaym mirrors the ever-changing nature of what we eat. The uniqueness of compost is further captured by ReClaym’s properties (e.g., texture, color, smell, etc.), which are always changing to reflect our current relationship with the food we consume (and don’t consume).

Using hands-on fabrication techniques (sculpting, molding, and hand-held extruding) that supported the inconsistencies and imperfections of ReClaym, I created a collection of applications that explore different ways of customizing ReClaym via sterility, electrical conductivity, environmental sensing ability, color, and texture.

Lastly, I examined the circular nature of ReClaym, which both begins and ends with the act of composting—giving food waste a second life and providing a sustainable end-of-life for ReClaym

artifacts. The circular mindset holds designers accountable for their materials and fabricated artifacts. In this line of thought, I named the biomaterial *ReClaym* (pronounced re-claim) because it affirms that we take responsibility for our food waste by recovering and refurbishing it to make new biodegradable artifacts that can be composted again to make new ReClaym.

5.1 Making ReClaym

My aim was to develop a compost-based biomaterial that engages the body, thus encouraging makers to become just as comfortable working with their food waste as they are working with food. To arrive at ReClaym, I experimented with various ratios of ingredients as shown in Figure 5.2. For each recipe, I examined the properties and reflected on my sensorial experiences with the biomaterial. ReClaym is the resulting “optimal” recipe, which is made from the ratio of ingredients that could be extruded and hold three-dimensional forms.

5.1.1 Ingredients

Unlike other bio-based clays that are made of a singular type of food waste, ReClaym is made from all types of composted food waste (primarily plant-based food waste). The flexibility of food waste that can be converted into ReClaym makes ReClaym a highly accessible biomaterial, not relying on many specific ingredients. While I took initial ingredient inspiration from Sauerwein’s 3D printable mussel shell clay [195], I relied heavily on my knowledge of material science and food chemistry to identify exact ingredients, ratios, and methods. I began by narrowing down the recipe to four ingredients—compost, water, sodium alginate, and calcium carbonate—to make ReClaym, which I describe the importance of as follows:

- *Compost* is the primary ingredient of ReClaym, which is a living mixture containing microbes that break down organic matter into CO_2 and a soil-like biomaterial (humus) [72]. I used my own personal compost to give my kitchen food waste a second life as ReClaym. When composted, food waste and other organic matter are broken down by naturally occur-

ring microorganisms, bacteria, and insects; thus, we consider compost a *living* biomaterial. The resulting compost is mostly uniform, however physical and chemical properties such as color, texture, and pH are highly variable based on the types of organic matter composted. Consequently, each mixture of ReClaym made is dependent on the compost and reflects the food both disposed of and consumed by one specific person or household, at one specific point in time. Therefore, ReClaym is unique to each maker, given that compost is a reflection of a person's cultural identity, physical location, food preferences, cooking techniques, and current relationship with food.

- *Sodium Alginate* is a brown seaweed extract that forms a gel when dissolved in water of any temperature. Similarly to agar, sodium alginate is commonly used in the kitchen as a vegan gelatin substitute, thickener, emulsifier, and texture improver [169], making it easy to find at the grocery store. Sodium Alginate mixed with water thus acts as the key binder and stabilizer in ReClaym.
- *Calcium Carbonate* is a highly versatile mineral that makes up about 4% of the Earth's crust [9]. Despite being a mineral, calcium carbonate is a bio-based and renewable biomaterial that is produced by living organisms, being found in eggshells, seashells, and coral [9]. Moreover, it is non-toxic and easily degrades into carbon dioxide and lime when placed in the environment [9]. Due to its ubiquitous nature, calcium carbonate can be easily purchased in powder form at most grocery stores and pharmacies as it is also a common health supplement. The purpose of adding calcium carbonate to ReClaym is to help stabilize the gel formed by the water and sodium alginate [9] that gives the ReClaym mixture a clay-like consistency when wet and a ceramic-like hardness when dry.
- *Water* is a widely available and renewable resource that acts as a key binding ingredient for many types of clay and concrete mixtures. We use water to dissolve the sodium alginate thus forming a gel to hold the compost together, giving the ReClaym mixture a clay-like consistency.

5.1.2 Recipe Optimization

I defined “optimal” as a recipe that felt and behaved somewhat similarly to traditional crafting clays, meaning that it could (1) easily hold 3-dimensional forms, (2) be extruded through a piping bag with minimal effort, and (3) feels good for sculpting.

To make each recipe, I began by mixing together the same ratio of water and sodium alginate, which was then left to sit for one hour. Over the course of the hour, the sodium alginate bloomed in the water resulting in a gel similar to the consistency of aloe vera gel that acted as the base. I then added calcium carbonate to stabilize the gel creating a thick white mixture that we mixed into the compost to create a homogeneous ball of ReClaym. Once combined, I sculpted round samples and attempted to extrude small coil pots for each ReClaym recipe as shown in Figure 5.2.

I then utilized material tinkering [170] and experience prototyping [38] to arrive at my “optimal” ratio of ingredients to make ReClaym—these methods encouraging me to gain sensory feedback from each iteration to inform future iterations [187]. Accordingly, through the creation of each recipe (round sample and pot), I got a feel for the resulting biomaterial, examined its look, and judged its ability to hold three-dimensional form. Based on the performance of the recipe I iterated on the amount of calcium carbonate and compost added to the base gel. For example, looser mixtures (i.e., recipes with higher water content) resulted in ReClaym that would lose its form dictated by the extruder, thus spurring a new recipe with more compost.

Recipe 6 provided the “optimal” version of ReClaym, which holds three-dimensional forms well, is easy to extrude through a piping bag, and feels good to sculpt on a sensory level. To further improve upon Recipe 6, I ran the compost through a strainer to remove larger pieces of organic matter, resulting in a smoother (less lumpy) clay-like biomaterial.

I noticed that while I always used Recipe 6, each batch of ReClaym I made was slightly different. This was because my compost, the primary ingredient, was different each time, changing with the types of food waste I was producing. Accordingly, I noticed that ReClaym’s color, texture, and even smell reflected the types of food I had composted for each batch. This slight variation

<i>Recipe</i>	<i>Ingredients</i>	<i>Sample</i>	<i>Coil Pot</i>	<i>Properties</i>
1	60 mL water 1.6 g sodium alginate 0 calcium carbonate 50 g compost			Feel: brittle and delicate due to the rough and incongruent texture, but feels like one solid piece of compost Extrudability: cannot be extruded, the coil pot was sculpted Shapeability: holds shape well from sculpting
2	60 mL water 1.6 g sodium alginate 105 g calcium carbonate 0 compost			Feel: smooth and consistent texture that makes it feel like a traditional ceramic Extrudability: can easily be extruded Shapeability: cannot hold 3 dimensional forms well (we see a slight build up of extruded layers)
3	60 mL water 1.6 g sodium alginate 52.5 g calcium carbonate 25 g compost			Feel: slightly lumpier than recipe 2 Extrudability: easy to extruded, but requires no force making extrusion difficult to control Shapeability: cannot hold 2 or 3 dimensional shapes well, the circular sample spreading significantly and the layers of the coil pot immediately collapsing
4	60 mL water 1.6 g sodium alginate 65 g calcium carbonate 30 g compost			Feel: inconsistent texture where there are spots that are rough and spots that are smooth Extrudability: can be extruded Shapeability: can almost hold 3 dimensional forms (the coil pot has a tilt to it), and does not hold the shape dictated by the nozzle
5	60 mL water 1.6 g sodium alginate 80 g calcium carbonate 25 g compost			Feel: lumpy texture that feels very dense Extrudability: can be extruded, but requires lots of force Shapeability: can hold 2 and 3 dimensional shape, but does not hold the shape dictated by the nozzle of the hand-held extruder
6	60 mL water 1.6 g sodium alginate 25 g calcium carbonate 50 g compost			Feel: rough and slightly lumpy, but not as inconsistent as recipe 4 Extrudability: can be extruded with minimal effort Shapeability: holds 2 and 3 dimensional shapes dictated by the hands of the sculptor and the nozzle of the hand-held extruder

Figure 5.2: Recipe iterations for ReClaym. Recipe 6 indicates the “optimal” recipe.

in material properties led me to add more water-alginate gel or compost to precisely adjust the consistency of ReClaym each time I made a batch. I would also adjust the consistency to aid specific fabrication methods, for example, creating slightly wetter versions for extruding and dryer versions for sculpting.

Along these lines, I also realized that other makers of ReClaym might want to optimize the

recipe for alternative properties and behaviors. For example, a maker might not need to extrude ReClaym and might not have access to calcium carbonate, therefore they could choose to use Recipe 1. As such, I provided detailed notes about the properties of each recipe developed to help guide future ReClaym makers.

5.1.3 Material Benchmarking

The goal with benchmarking ReClaym is not to see how to turn ReClaym into a biodegradable version of traditional sculpting clays, but to instead gain a better understanding of how ReClaym can be implemented and what sets it apart from other, similar materials. I specifically compared the primary ingredient, density, and biodegradability of a variety of commonly used clay-like products in Table 5.1. As seen in the table, ReClaym is the only material that is primarily made of a waste product (i.e., compost) *and* biodegradable, making it the most *sustainable* option. For example, the Bio-based Clay is made from waste mussel shells, but cannot biodegrade [195], while the DIY Dough Clay can biodegrade, but is made from highly manufactured, store-bought ingredients [35]. This benchmarking activity also drew my attention to the fact that the density of ReClaym aligns most closely with Sculpey Clay [52] and DIY Dough Clay [35], giving me further insight into how it behaves and feels.

Material	Primary Ingredient	Density (g/cm ³)	Biodegradable	Source
Advanced Ceramics	Clay Minerals	2.5-6	no	[161]
Sculpey Clay	PVC	1.23	no	[52]
Bio-based Clay	Mussel Shells	1.7	no	[195]
Play-Doh	Flour	1.45	no	[95]
DIY Dough Clay	Flour	1.32	yes	[35]
ReClaym	Compost	1.26	yes	

Table 5.1: Comparison of ReClaym to similar clay-like materials used for artistic and making practices.

5.2 Making-With ReClaym

As I began to make-with ReClaym, I realized that each batch of the biomaterial was different due to my ever-changing personal compost used for each iteration. Thus, to support the inconsistencies between each batch when making ReClaym artifacts, I chose to use *familiar, hands-on fabrications techniques* that encourage *communication between maker and biomaterial* through the sense of touch. The constant physical communication with ReClaym led to gaining embodied knowledge of the biomaterial and, eventually, to a deep *understanding of the biomaterial*. By doing so, I supported ReClaym as a unique and inconsistent biomaterial, ultimately resulting in personally meaningful and wholly unique artifacts that reflect both the agency of the maker and the batch of ReClaym.

Following this approach to making-with ReClaym, I and several other members of the Living Matter Lab, created a collection of experimental artifacts that demonstrated the wide range of ways to customize ReClaym. These explorations revolve around tuning the sterility, electrical conductivity, environmental sensing, color, and texture of ReClaym.

5.2.1 Fabrication Methods

The hands-on fabrication techniques that I utilized to *communicatively* and *supportively* make ReClaym artifacts included sculpting, molding, and hand-held extruding (Figure 5.3). Sculpting relied purely on instinctual movements that were directed by the maker's envisioned design and the batch of ReClaym—exemplifying a direct, real-time feedback loop due to the lack of tools separating biomaterial and maker. To aid in sculpting ReClaym, I used manual tools used in traditional sculpting practices for scoring (joining pieces of clay together) and shaping precise forms. Molding involved a variety of molds, ranging from hard, solid molds to soft, flexible molds. For hard molds (like the plastic tear-drop mold), the mold had to be lined with vegetable oil so that the dry ReClaym could easily be removed. For soft molds (like a nitrile glove), the mold could simply be peeled off the dry ReClaym. Hand-held extruding was executed with a piping bag used

in baking practices instead of a syringe, to give the maker more control. While circular-shaped nozzles were most often used, I also found that ReClaym held the shape dictated by star and ribbon-shaped nozzles.

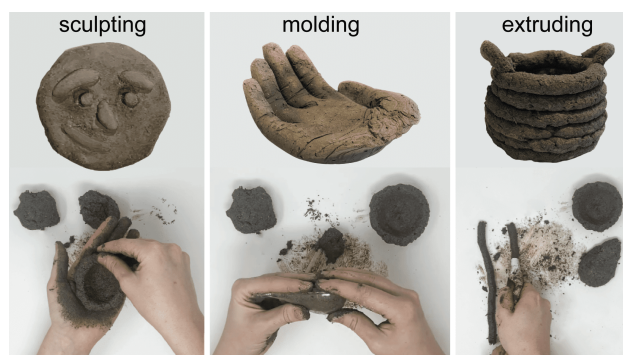


Figure 5.3: Manual fabrication techniques—sculpting, molding, and hand-held extruding—for making ReClaym artifacts.

5.2.2 Sterility

I was first inspired to take advantage of ReClaym’s naturally non-sterile nature, using its origin as compost, which contains many living microbes, to create a living sculpture. For the sculpture, Netta Ofer shaped the wet ReClaym and then selectively embedded grass seeds. Instead of letting the sculpture completely dry out at room temperature, I kept the sculpture in a slightly humid location (i.e., under a plastic bag that acted as a greenhouse). After a few days, the grass began to sprout from our ReClaym, providing a proof of concept for using ReClaym as a scaffold to encourage the plants to grow into a desired form.

This experiment led to an inquiry about sterility and thus a method for sterilizing ReClaym by baking it in the oven at 200°C for one hour, which effectively killed all the microbes. With the assistance of Mirela Alistar, we ran a microbial growth test in which two tiles were prepared: one that was sterilized and one that was left unsterilized. Each tile was then gently pressed into a petri dish containing Luria Broth (LB) agar medium that is commonly used to culture bacteria. The petri dishes were incubated at 37°C for 24 hours. The results in Figure 5.4 show bacterial

growth from the unsterilized tile and no bacterial growth from the sterilized tile indicating that the sterilization method was successful.

The sterility test showed us the potential for creating food-safe objects like bowls and plates. I chose to create tableware from ReClaym because I liked the circular aspect of eating a meal off of food waste that has been given a second life. While the plate and bowl can be re-used, I mainly see ReClaym tableware acting more as single-use plates that can be immediately composted rather than traditional ceramic tableware that is washed and re-used. ReClaym plates and bowls can of course be also used to hold non-food-related items such as keys, jewelry, and other household knick-knacks.



Figure 5.4: Sterility test results show the bacterial growth on LB agar plates from an unsterilized ReClaym tile and a sterilized ReClaym tile. The unsterilized ReClaym proved to work for living sculpture applications, while sterilized ReClaym was used for tableware applications.

5.2.3 Electrical Conductivity

To make ReClaym electrically conductive, I coated its surface either with activated carbon powder or graphite powder, both of which are both electrically conductive and considered non-toxic and biodegradable [201]. To coat the ReClaym, I would either submerge wet ReClaym in the powder, the dry powders naturally sticking to the wet ReClaym, or paint dry ReClaym with a ‘glaze’ made from 2g alginate-water gel to 0.1g of either activated carbon or graphite powder.

In Figure 5.5, I showcase electrical resistance measurements of five values (i.e., m values) on two tiles with the dimensions of 5cm x 5cm x 1cm. One was coated with ~ 0.2 g activated carbon

powder and the other was coated with $\sim 0.2\text{g}$ of graphite powder. Using a multimeter, I placed the electrodes on the respective pairs of circles connected by the grey lines to measure each m value. I found that the graphite tile had consistently higher resistance values compared to the activated carbon tile.

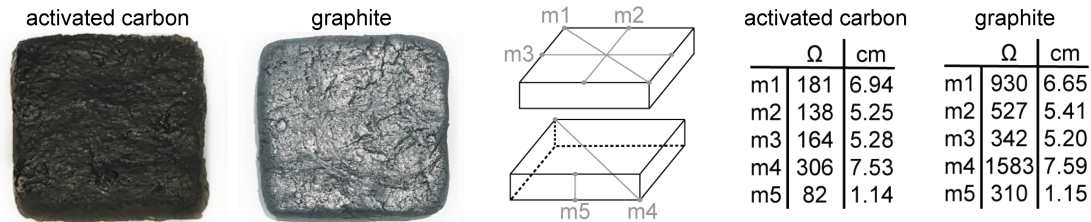


Figure 5.5: Resistance measurements of ReClaym tiles that were coated with activated carbon powder and graphite powder.

I then sculpted another conductive ReClaym tile coated with activated carbon (i.e., the less resistive material) to create a musical instrument with the help of Chris Hill. For the instrument, each tile acts as a capacitive touch sensor. Instead of attaching or embedding electronics directly into the tiles, which would impact the biodegradability of the tiles, I created copper tape beds for each tile to sit on, connecting them to an Arduino Uno. When the player touches the tile, a tone dictated by Chris' code is produced through our speaker. As the player moves their finger around the tile, different tones are produced based on how the capacitance changes on the surface of the tile. Listen to the ReClaym instrument by scanning the QR code in Figure 5.6 or by going to <https://youtu.be/9WGMJz0abrg>.

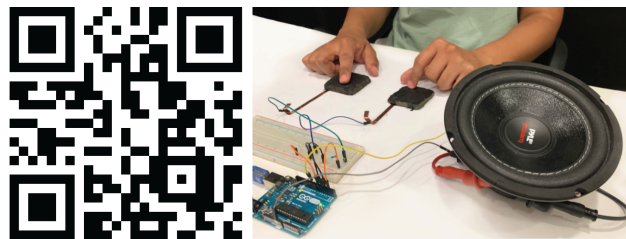


Figure 5.6: ReClaym instrument made from activated charcoal tiles that act as capacitive touch sensors. Scan the QR code to take a listen.

5.2.4 Environmental Sensing

Similar to the conductive tiles, I added photochromic, photoluminescent, and thermochromic powders to the surface of ReClaym tiles through coating, in which approximately $\sim 0.3\text{g}$ of powder adhered to the surface of a wet $5\text{cm} \times 5\text{cm} \times 1\text{cm}$ tile. Meanwhile, the glaze, which was painted onto dry ReClaym, was made up of a ratio of 2g alginate-water gel to 1.5g powder. The photochromic tile (Figure 5.7a) transitioned from white to dark pink when exposed to ultraviolet (UV) light. The photoluminescent tile (Figure 5.7b) glows in the dark when charged with UV light. The thermochromic tile (Figure 5.7c) transitioned from white to dark blue when cooled. These three pigments are also non-toxic, and biodegradable, having been priorly proposed for on-skin tattoos that indicate over-exposure to UV solar radiation [39].

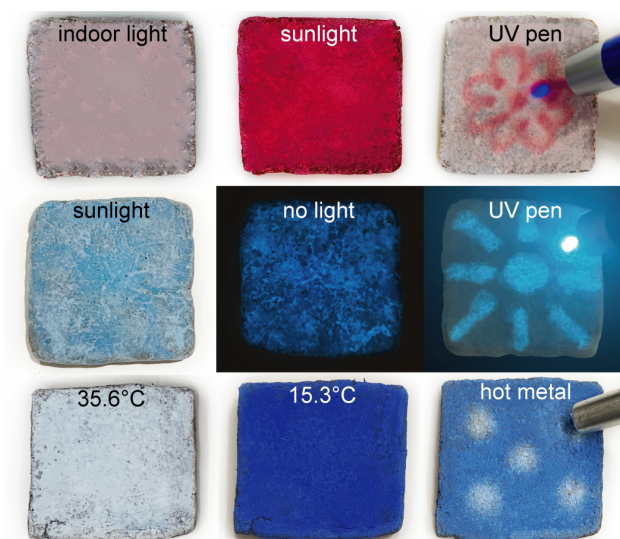


Figure 5.7: Photochromic ReClaym tile that turns dark pink while exposed to UV radiation. Photoluminescent ReClaym tile that charges with UV light and then glows in the dark. Thermochromic ReClaym tile that goes from white when hot to dark blue when cold.

I expanded on the idea of photoluminescent ReClaym, by sculpting mushroom figurines that could be placed in a garden and glow in the dark. As shown in Figure 5.8, I placed the mushrooms in some of my indoor potted plants by a window. Throughout the day, the mushrooms were charged with UV light, which provided them energy to fluoresce for the first couple hours at night, the mushrooms slowly losing their glow over time. I envision a variety of fluorescent sculptures placed

throughout an outdoor garden, similar to solar garden lights. These sculptures could lengthen the time of visual enjoyment of a garden and act as physical location indicators throughout the garden environment at night when it is difficult to see.

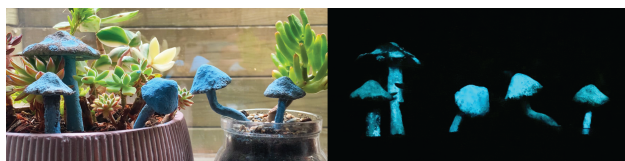


Figure 5.8: ReClaym photoluminescent mushroom sculptures that charge in the sunlight during the day and then glow at night.

5.2.5 Color and Texture

The final ReClaym exploration revolved around customizing its color and texture. To add color to ReClaym, I painted it with either plain food dye or a glaze. When painted with plain food dye, ReClaym took on a muted colorful tint that still showcased the natural colors and textures of ReClaym. When painted with the biodegradable glaze, which consisted of a ratio of 3g alginate-water gel to 0.5g of cornstarch and 1 drop of food dye, the ReClaym took on vibrant colors, while its natural colors and textures were completely covered up. To demonstrate the colorful glazes, I and other members of the Living Matter Lab molded several Carcassonne game tiles that were painted to aesthetically emulate the classic version of Carcassonne (Figure 5.9), however, we envisioned the glazes providing makers the ability to customize tile-placement games made from ReClaym however they want. Further showcasing how ReClaym can be used in the context of games, I sculpted a collection of accessories for a sorcerer character in a tabletop role-playing game, such as Dungeons & Dragons (D&D), which encourages character physicalization and personalization. I used a magenta biodegradable glaze to color the hat, purple food dye mixed with the biodegradable glitter gel to color the crystal ball, and graphite powder to color the wand (Figure 5.9).

Because ReClaym carries a natural texture that reflects the compost, additional textures must be more prominent (e.i., must be large textural patterns that vary greatly in height). To

create such patterns, I utilized traditional sculpting tools and kitchen utensils. Textures can also be added through stamping. While stamps with small textural details often got lost, successful stamps had a large, distinct overall shape. For example, I stamped a ReClaym sample with Gaia the puppy’s paw, which I further colored with plain blue and purple food dye (Figure 5.9). The purpose of such a keepsake is to remind people of an exact moment in time. The physical artifact can transport the maker back to their memories—the food they were eating, making ReClaym, and fabricating the ReClaym artifact with their loved one. While I created a keepsake for a pet, I also see ReClaym potentially being used to capture a baby’s handprint made from compost that contains the baby’s food.



Figure 5.9: Colorful and textured ReClaym applications include Carcassonne tiles, accessories for a sorcerer character in D&D, and a memory keepsake for a puppy.

5.3 Examining Sustainability of ReClaym

ReClaym was intentionally designed from the beginning to be completely *circular*. I break down the ReClaym life cycle into four main steps, where the fourth step feeds into the first step to complete the cycle as depicted in Figure 5.10: (1) composting food waste, (2) making ReClaym, (3) fabricating, (4) using ReClaym artifacts, and (5) composting ReClaym artifacts.

- (1) *Composting Food Waste.* ReClaym is made from food waste, giving a second life to biomaterials that have already been used and are not thought of as useful anymore. Thus the first step of the ReClaym life cycle is also the last step—sourcing biomaterials that have already been used and are ready to be disposed of. By purchasing compost instead of using personal compost, the maker must recognize that they introduce another energy



Figure 5.10: The life cycle of ReClaym is entirely circular, beginning and ending with the act of composting.

requirement into the making process. Therefore, I recommend using a non-electric home composter as a more sustainable and low-cost way to create personal compost.

(2) *Making ReClaym*. I made ReClaym from a mixture of compost, water, sodium alginate, and calcium carbonate. All of these ingredients can be degraded in the natural environment, with compost, water, and sodium alginate all being bio-based, and calcium carbonate being a non-toxic mineral. While the compost and water were sourced from my kitchen, the sodium alginate and calcium carbonate had to be purchased from a local grocery store, therefore we must account for the energy required to source and distribute these biomaterials. The optimized recipe created a clay-like biomaterial that could hold three-dimensional forms.

(3) *Fabricating ReClaym Artifacts*. I fabricated ReClaym artifacts using hands-on fabrication techniques rather than digital fabrication techniques that require a power input. I further customized ReClaym via color, texture, sensing, conductivity, and sterility. For these experiments, I utilized biodegradable dyes and glitter, and non-toxic sensing and conductive

pigments, all of which minimally impact the biodegradability of ReClaym. I then used these explorations to inform the creation of ReClaym artifacts.

- (4) *Using ReClaym Artifacts.* During use, all the ReClaym artifacts were sturdy, lightweight, and biodegradable; including the tableware which was sterilized through a baking method that other artifacts did not go through. Moreover, the imperfections found in each artifact serve as a reminder of their hand-made quality and their origins from our personal food waste.
- (5) *Composting ReClaym.* ReClaym breaks down into biomass, carbon dioxide, and water when disposed of in an environment with microorganisms, fungi, and bacteria and leaves behind no toxic residue. Once used, ReClaym artifacts can be composted in the same composter used for the food scraps—making ReClaym a truly circular biomaterial—or can be directly disposed of in the environment. As showcased in Figure 5.11, ReClaym takes little to no time to biodegrade (~ 3 days) because it is primarily made up of compost; moisture and organisms within the natural, soil environment easily break down the structure of ReClaym artifacts. Moreover, we encourage ReClaym to be placed in the natural environment or in a home garden after use, as compost replenishes the nutrients within soil.

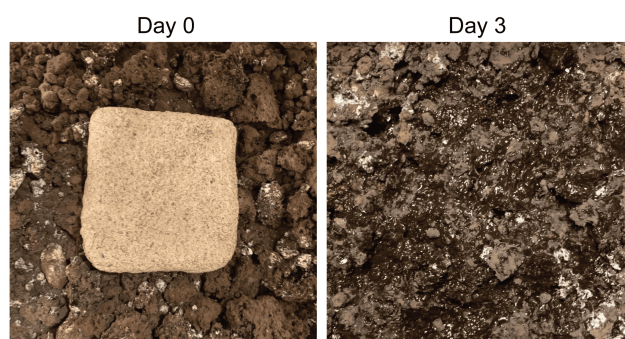


Figure 5.11: ReClaym breaks down in only ~ 3 days when composted due to the fact that it is predominantly made of compost.

Chapter 6

SCOBY: Cellulose-Based Bioleather



Figure 6.1: The SCOBY Breastplate is an interactive wearable created by myself, Derrek Chow, and Hyelin Choi. It is made from SCOBY and took 13 weeks to design, grow, and fabricate. When the biodegradable SCOBY touch sensor at the core of the breastplate is touched, the embedded LEDs display a corresponding light response at the top of the breastplate.

Inspired by ReClaym’s qualities of ‘livingness’, I wanted to experience *growing* a biomaterial rather than *assembling* a biomaterial from a recipe. This prompted me to look at a variety of different living organisms often used in Bio-HCI and biodesign, including mycelium, slime mold, spirulina algae, bacteria, and SCOBY—SCOBY being the organism I chose to work with.

SCOBY (Symbiotic Culture Of Bacteria and Yeast) is a three-dimensional cellulosic zoogveal mat that forms at the “air-liquid interface” of a traditional sweet tea called kombucha [127]. The SCOBY eats the sugar present in the kombucha tea, thus fermenting it [212]. During the fermentation process, a floating cellulose biofilm (i.e., the SCOBY) grows due to the symbiosis between acetic acid bacteria (e.g., *Acetobacter* and *Gluconobacter*) and osmophilic yeast species (e.g., *Saccharomyces*, *Zygosaccharomyces*, *Schizosaccharomyces*) [212].

In comparison to the other organisms I looked at, SCOBY grows at a considerably slower rate: slime mold grows in a couple of hours [145], bacteria grows in a day [114], and mycelium grows in a few days [133]. In contrast, a healthy layer of SCOBY takes about 2-4 weeks to grow depending on environmental factors such as temperature, UV light exposure, and contamination.

Once a healthy SCOBY formed, I harvested it from the kombucha culture and dried it out. When dry, and thus no longer living, the SCOBY has similar properties and behaviors to traditional animal-based and plastic-based leathers—an affordance biodesigners have priorly leveraged to position SCOBY as a sustainable fabric [51, 136, 158, 196]. Due to the slowness of SCOBY’s growth, my approach to making-with SCOBY was significantly more intentional and reflective than it was with Alganyl and ReClaym. Accordingly, my design space exploration was much more pointed—identifying methods to tune and customize SCOBY through shaping, coloring, and incorporating electrical conductivity. These explorations then purposefully informed the creation of an interactive SCOBY breastplate that senses various touch interactions (e.g., squeezing, tapping, brushing) and displays corresponding light responses via embedded LEDs.

Like Alganyl and ReClaym, SCOBY is sustainably disposed of through composting, where it biodegrades in just 30 days. SCOBY can also be re-grown from the same, initial kombucha culture indefinitely (i.e., once a SCOBY is harvested, a new SCOBY begins to grow).

6.1 Making SCOBY

Unlike Alganyl and ReClaym, which were *assembled* from an optimized ratio of ingredients, SCOBY was *grown*. As such, instead of tuning recipes to obtain an “optimal” biomaterial, I experimented with SCOBY’s growing times and methods of drying to obtain a biomaterial that had similar properties and behaviors to traditional animal-based and plastic-based leathers.

6.1.1 Growing SCOBY

To grow SCOBY I followed a three-step cyclical process outlined by kombucha brewing recipes [7, 37] and DIY SCOBY bioleather resources [48, 152]: (1) preparing, (2) growing, and (3) refreshing.

- (1) *Preparing*. While there are many recipes for preparing a kombucha culture, I used a ratio of 3.3 L water, 200 g of sugar, and 3 tea bags. To make the sweet tea, I boiled the water and poured it over the sugar and tea bags. Over time, the tea brewed and the sugar dissolved. I then let the sweet tea cool to 30°C, removed the tea bags, and then inoculated the sweet tea with 500 mL of starter culture containing live bacteria and yeast. I specifically used a bottle of GT’s Raw Kombucha as the starter culture. I then kept the kombucha SCOBY culture in a bioreactor, which was a plastic or glass container (of an appropriate size) that was loosely covered to allow for air exchange but to avoid contamination.
- (2) *Growing*. Over time, the sweet tea fermented due to the bacteria and yeast, and a layer of biofilm (i.e., the SCOBY) formed at the top of the liquid due to the increased presence of oxygen. The amount of time SCOBY took to form depended on the sugar concentration of the kombucha tea, the strength of the starter culture, and the external environment (e.g., light exposure and temperature). In my case, SCOBY formation occurred between 2 and 4 weeks.
- (3) *Refreshing*. Once the SCOBY developed (i.e., after 2-4 weeks), I replaced approximately

30% of the liquid culture with new sweet tea. When I refreshed the culture, I harvested the SCOBY, which I dried out and used as a sustainable, leather-like biomaterial. The refreshed culture essentially restarted the cycle, causing the tea to ferment again, and a new SCOBY to grow at the top of the liquid.

6.1.2 Characterizing Living SCOBY

To learn more about the SCOBY formation and growth process, I set up a bioreactor with timelapse photography, as seen in Figure 6.2. Through this timelapse, I learned to identify the subtle daily changes that occurred throughout the entire culture during growth. Over the course of 16 days, I determined three primary visual cues that indicated growth: (1) at the top of the culture, the SCOBY grew to cover the surface of the liquid, and then, each day, it grew thicker and more opaque; (2) at the middle of the culture the color of the liquid grew lighter and more yellow; and (3) at the bottom of the culture, dark sediments (yeast cells) settled.

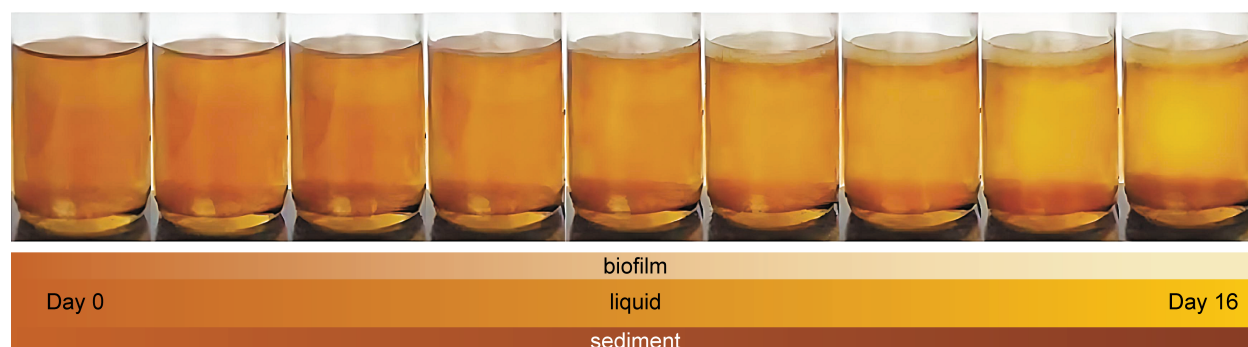


Figure 6.2: Visual cues that indicate that the culture is growing include the formation and thickening of the SCOBY biofilm at the top of the culture, the color of the liquid getting lighter, and the dark sediments settling at the bottom of the bioreactor.

I found the growth of the SCOBY to be the most prominent change in the kombucha culture over time. Consequently, I set up another, larger bioreactor to further analyze the SCOBY. For this analysis, I removed the growing SCOBY from its bioreactor once a week to measure its thickness and mass. I then carefully placed the SCOBY back in the bioreactor to allow it to keep growing, the larger bioreactor mouth allowing me to more easily remove and replace the SCOBY

for measurements.

As shown in Figure 6.3, I found that it took 7 days for the SCOBY to form a lacey transparent layer of 1.22 mm in thickness and 9.53 g in mass. After 28 days of growth, the SCOBY was opaque and reached a thickness of 7.33 mm with a mass of 69.78 g. I noticed that both thickness and mass increased somewhat linearly, highlighting that SCOBY has a surprisingly consistent growth rate for an unpredictable living organism.

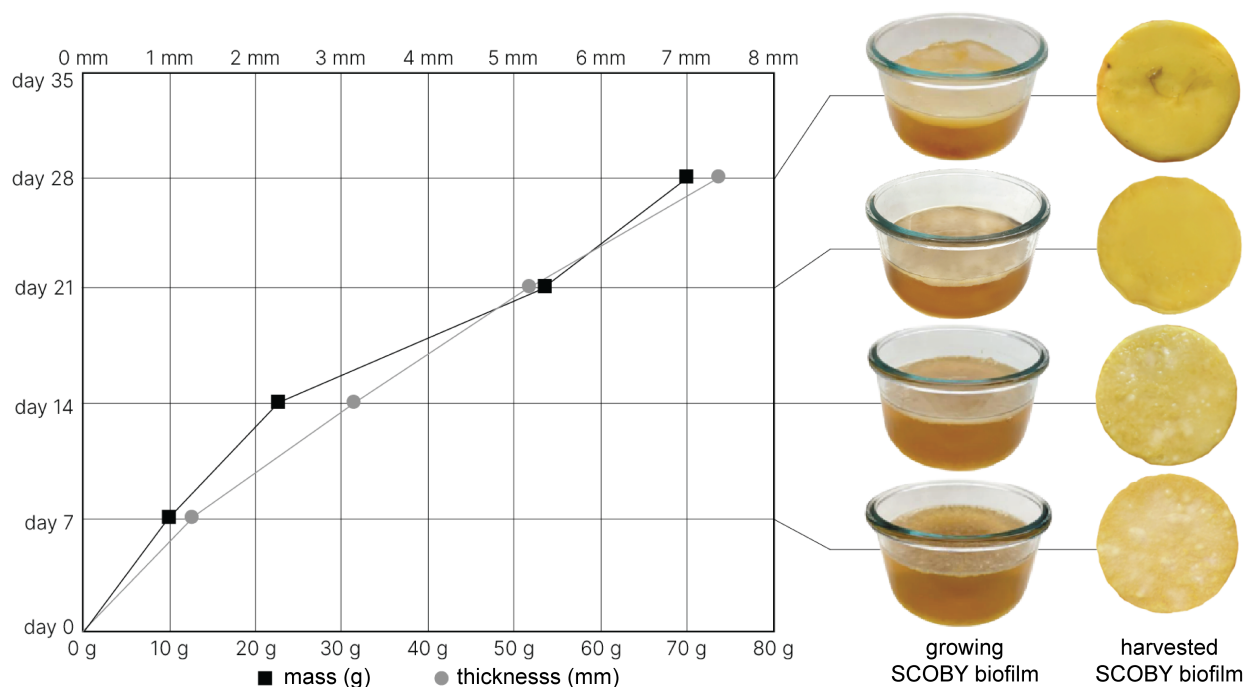


Figure 6.3: The SCOBY grows thicker and more opaque over time.

6.1.3 Characterizing Non-Living SCOBY

I then characterized the properties of non-living SCOBY (i.e., SCOBY that was removed from its culture and dried out) as a leather-like biomaterial. To do so, I set up more bioreactors, grew the SCOBY for approximately 3 weeks, harvested the SCOBY from the culture, and then dried it at room temperature. Using an equation for shrinkage [224] I calculated that SCOBY averagely shrunk 93.42% in mass and 89.88% in thickness when dried out—often growing to a thickness of 5 mm and then drying to a thickness of 0.5 mm.

I experimented with adding oil (e.g., olive or coconut) while the SCOBY was drying and noticed significant changes in drying times and the biomaterial's flexibility. When dried without oil, the SCOBY biofilm took 2-3 days to dry and felt brittle. When dried with oil, the SCOBY biofilm took 4-5 days to dry and felt more flexible; the oil slowed down the rate of evaporation and held some of the moisture in, keeping the SCOBY flexible.

I followed my initial observations with a thorough analysis of the strength and flexibility of the two types of SCOBY shown in Figure 6.4: (1) brittle SCOBY dried without oil and (2) flexible SCOBY dried with a layer of oil. I cut the SCOBY samples into the shape prescribed by the ASTM D638 Type IV standard [11] and then measured and calculated the maximum tensile strength and percent elongation (i.e., flexibility) of 5 different samples for each type of SCOBY using a universal testing machine set up with a 50 N load cell that moved at a rate of 0.05 mm/min. I note that the color difference between the brittle SCOBY and flexible SCOBY samples in Figure 6.4 is not caused by the drying method. The different colors of the SCOBY are caused by different types of tea used for each culture, which I found has minimal effects on the SCOBY's mechanical properties.

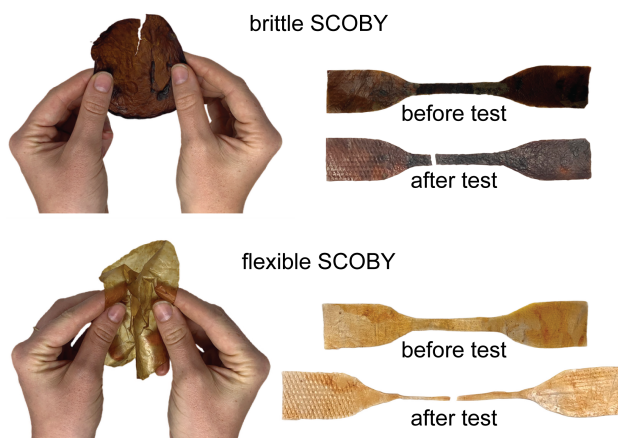


Figure 6.4: Brittle SCOBY dried without oil in comparison to flexible SCOBY dried with oil.

In Table 6.1, I compared the strength and flexibility of both the brittle and flexible SCOBY samples to commercial leathers. I found that the flexible SCOBY had an average maximum tensile strength of 8.06 MPa and an average percent elongation of 27.13%, placing stronger than the other

bio-based leathers, which include the brittle SCOBY, mycelium leather, and fruit leather. However, the flexible SCOBY was not quite as strong as polyurethane (PU) leather and cowhide leather (napa leather). The brittle SCOBY had an average maximum tensile strength of 6.84 MPa and an average percent elongation of 3.83%, making it the weakest and significantly the least flexible.

Material	Strength (MPa)	Elongation (%)	Source
Brittle SCOBY	6.84	3.83	
Reishi Mycelium Leather	7.4	36	[182]
Fruitleather Rotterdam	7.74	49.2	[190]
Flexible SCOBY	8.06	27.13	
Polyurethane Leather	10.2	N/A	[156]
Napa Cowhide Leather	11.9	41	[103]

Table 6.1: Comparison of brittle and flexible SCOBY to commercial leathers.

6.2 Making-With SCOBY

Because SCOBY was grown, my pace of making-with SCOBY was dependent on the growth of the biomaterial. This heavily impacted how I explored the design space of SCOBY and created SCOBY artifacts. Because of its *slowness*, I learned that I had to be more conscientious with how each SCOBY was used. For example, while a new SCOBY was growing, I spent that time planning *exactly* how I would use it (e.g., how I would fabricate it, which way(s) would I customize it, what experiments would I run on it, etc.), so as to not waste the newly grown SCOBY and correspondingly my time. This *intentionality* not only taught me to waste less biomaterial but to also respect SCOBY as a living organism with agency in the design process.

In light of SCOBY’s slowness and my corresponding focus on intentionally making-with SCOBY, I limited my design space explorations to just the factors that held the biggest impact on the design of one artifact—an interactive SCOBY wearable. Therefore, I focused my efforts on developing methods to tune the shape, color, and electrical conductivity of SCOBY.

6.2.1 Fabrication Methods

To create artifacts from SCOBY, fabrication occurred at three stages of the SCOBY's life: when the biofilm was growing, when it was drying, and when it was dry (i.e., dead).

During the growing stage, I leveraged the fact that SCOBY grows to cover the entire surface of the container to control the size and shape of the SCOBY. For example, I experimented with growing as large of a SCOBY as I could by using an inflatable pool as a bioreactor. I also designed smaller, custom bioreactors to respectively control the outer and the inner shape by building obstacles for the SCOBY to grow around as shown in Figure 6.5.

During the drying stage, I used molds to obtain three-dimensional shapes from the SCOBY. Specifically, I placed wet SCOBY over existing three-dimensional objects and let it dry. To preserve the object molds, I typically covered them in plastic wrap that I then coated in oil to help with SCOBY removal from the mold. However, I avoided applying too much oil such that the SCOBY would dry more brittle and hold shape, as opposed to the flexible SCOBY dried with lots of oil that acted more like traditional leather. Drying pieces of SCOBY on top of each other further provided a way to shape and create larger, stronger SCOBY structures. This layering method was effective because as a freshly harvested, wet layer of SCOBY dries, it self-adheres to other pieces of SCOBY. I also used layering to embed other objects, such as LEDs, within the SCOBY.

Once dry, I was easily able to cut the SCOBY with scissors, an X-acto knife, and a laser cutter. I used an Epilog Laser Fusion M2 laser to cut and engrave the SCOBY with digitally created designs as shown in Figure 6.5. I laser cut the SCOBY using the vector cut function with a setting of 30% power, 70% speed, and 50% frequency. I also experimented with laser engraving the SCOBY using the raster function with a setting of 20% power, 90% speed, and 50% frequency. While engraving doesn't shape the SCOBY in an obvious way like cutting, engraving changes the thickness of SCOBY and impacts the textural experience of the biomaterial—the engraved areas being rough in texture and the non-engraved areas being smooth in texture.

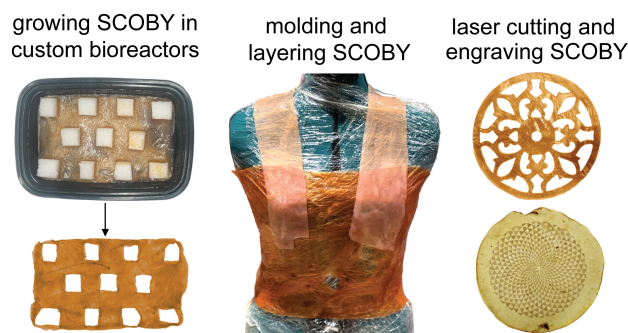


Figure 6.5: Fabricating with SCOBY at three different stages of its life: growing SCOBY in custom bioreactors to dictate shape; drying SCOBY on top of itself and on molds to adhere pieces of SCOBY together and create three-dimensional forms; and laser cutting and engraving dry SCOBY to create patterns.

6.2.2 Color

With the help of Hyelin Choi, we explored how to tune the color of SCOBY. The first way we adjusted the overall SCOBY color was through the type of tea used for the culture and the length of growing time. For example, a liquid culture consisting of only black tea resulted in a darker, more brown SCOBY while a green tea culture resulted in a lighter, more yellow SCOBY as shown in the first two SCOBY samples in Figure 6.6. Moreover, the longer the SCOBY was grown for, the thicker and more opaque it became, thus resulting in a more vibrant color when the SCOBY was dried. We also found that adding non-toxic food dyes to the culture would also change the color of the SCOBY without impacting its health.

While we preferred to keep the color of the SCOBY natural (i.e., yellow, tan, brown), we experimented with selectively painting food dyes onto the surface of SCOBY to create colorful patterns. The two middle samples in Figure 6.6 show a SCOBY that was painted on while the SCOBY was wet (i.e., still alive) and a SCOBY that was painted on once the SCOBY was dry (i.e., dead). As seen, the dyes diffused across the SCOBY that was painted on while wet, resulting in the drawing losing its initial definition, while the drawing on the SCOBY that was painted on while dry kept its definition.

We also selectively colored SCOBY via transfer printing, exemplified by the last two SCOBY

samples in Figure 6.6. To transfer print, we printed a digital design onto a sheet of wax paper using a standard printer and ink printer. We then pressed the printed wax paper onto semi-dry SCOBY and gently rubbed it with the back of a metal spoon. Once the print was transferred, we let the SCOBY fully dry. We noticed that the process of transferring distorted the designs. No matter how much pressure we applied, we could rarely transfer all of the printed design onto the SCOBY. The rubbing motions of the spoon also led to some of the ink smudging on the SCOBY, producing a lower-resolution version of the digital design. As such, more detailed patterns almost become incomprehensible via transfer printing.



Figure 6.6: Colorful SCOBY samples grown in different types of tea, painted on with food dye, and patterned via transfer printing.

6.2.3 Electrical Conductivity

To make the SCOBY electrically conductive, I initially experimented with adding activated charcoal powder directly to the kombucha with the intention of growing conductive sheets of SCOBY. However, the amount of activated charcoal required to make the SCOBY electrically conductive impeded its growth. Thus, I coated semi-dry SCOBY with an activated charcoal paint, which is conductive and non-toxic, allowing the electrically conductive SCOBY to degrade in the environment with minimal impact [201].

I then recorded the resistance over the length of electrically conductive SCOBY sheets. For these measurements, I cut three 11cm by 4cm strips of SCOBY and used a digital multimeter to measure resistance between two points as shown in Figure 6.7. While I observed a somewhat linear trend (i.e., resistance increasing with distance), the resistance values varied between each

of the three electrically conductive SCOBY samples. I theorize that this inconsistency came from imperfections in the activated charcoal paint and how well the SCOBY absorbed it.

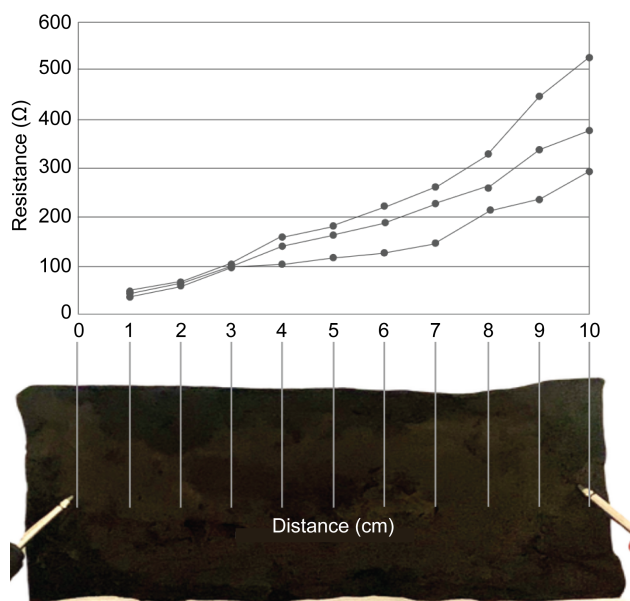


Figure 6.7: Analyzing the resistance values of SCOBY coated in electrically conductive activated charcoal.

6.2.4 SCOBY Breastplate

I applied the fabrication techniques and methods of tuning color and electrical conductivity described above to create an interactive SCOBY breastplate. The breastplate is made up of four SCOBYs that were each *slowly* grown, customized, layered, and dried on top of each (Figure 6.8). I grew each layer of SCOBY within a rectangular bioreactor (56 cm by 40 cm) for 3 weeks resulting in a SCOBY of ~ 5 mm in thickness. I then harvested the SCOBY and cut it into my desired shape and dried it around a mannequin to give it the breastplate form. Through layering, I embedded LEDs around the top of the breastplate. Through transfer printing, I patterned the straps. Through painting with activated charcoal, I transformed a final layer of SCOBY into a biodegradable, conductive touch sensor, which I laser cut into shape and placed around the core of the breastplate.

The resulting SCOBY breastplate senses touch interactions via the SCOBY coated in activated charcoal and displays corresponding light responses via the embedded LEDs. Using an

Adafruit Feather microcontroller, programmed by Derrek Chow, we made the brightness and duration of the LED illumination change proportionally to the pressure of the touch. As demonstrated in Figure 6.9, a short light touch results in a brief dim glow, while a long intense touch results in a bright lingering glow).

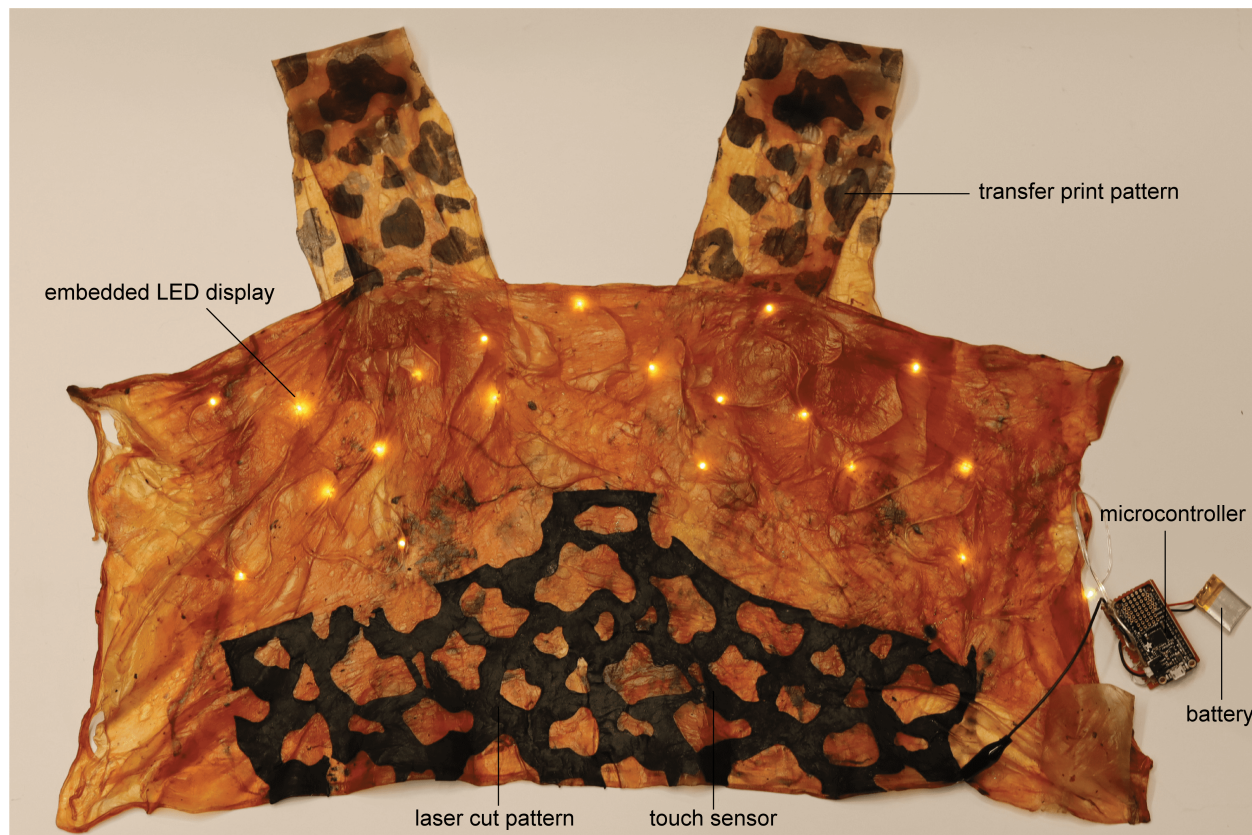


Figure 6.8: SCOBY breastplate assembly.

6.3 Examining Sustainability of SCOBY

SCOBY biofilm has gained recent popularity as a potentially sustainable alternative to leather-like materials made from animal hides or plastics. When compared to these more traditional materials, growing SCOBY requires significantly less processing to become a usable biomaterial, reducing pollution in the sourcing and manufacturing steps. Moreover, the slowness of SCOBY's growth encourages makers to be more intentional about what they design, leading to less SCOBY waste.



Figure 6.9: The SCOBY breastplate senses various touch interactions and displays corresponding light responses via the embedded LEDs.

6.3.1 SCOBY Life Cycle

The life cycle of SCOBY is made up of five steps shown in Figure 4.8: (1) sourcing ingredients, (2) growing SCOBY, (3) fabricating SCOBY artifacts, (4) using SCOBY artifacts, and (5) composting SCOBY. The growing stage of SCOBY is circular in the way that the same culture can be kept alive and refreshed. However, once the SCOBY is harvested from the culture, it breaks out of the cycle once and must be disposed of through composting.

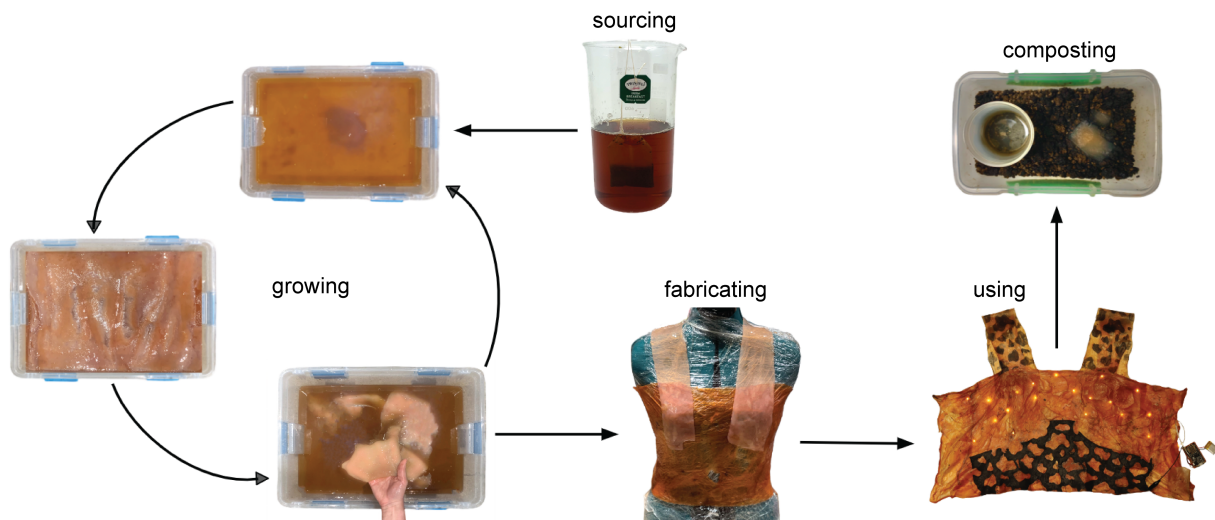


Figure 6.10: The life cycle of SCOBY begins with a cyclical growing process, however, once the SCOBY is removed from the culture its life becomes linear.

- (1) *Sourcing Ingredients.* SCOBY only requires four ingredients to prepare the kombucha culture—tea, sugar, water, and starter culture—all of which are bio-based, non-toxic, and edible, speaking to the fact that kombucha is widely consumed as a drink. I sourced the tea, sugar, and starter culture (GT’s Raw Kombucha) from my grocery store. Alternatively, I could source starter culture from already existing cultures that I had growing in the lab, thus reducing the need to buy kombucha from the store.
- (2) *Growing SCOBY.* Once I prepared a culture, I would keep it alive by refreshing it with some new sweet tea every month while harvesting the SCOBY for use. Once the culture was refreshed and the SCOBY was removed, a new SCOBY would begin to form at the liquid-air interface. I noticed that the act of growing rather than making (e.g., Alganyl and ReClaym), encourages me to be more thoughtful about my experimentation with it because of my emotional attachment to the organism that I essentially had to kill to further design with it. Moreover, the SCOBY itself is often viewed as a waste product of the kombucha brewing process. In this light, I give SCOBY a second life as a bioleather.
- (3) *Fabricating SCOBY Artifacts.* I used a variety of fabrication techniques throughout the growing and drying process to shape and form SCOBY. Other than laser cutting, these methods were entirely hands-on and had no additional power requirements. I further experimented with tuning and patterning the color of SCOBY by changing the type of tea, adding non-toxic food dyes, and printer ink. Lastly, I analyzed SCOBY coated in activated charcoal, which is electrically conductive and biodegradable. Instead of creating a collection of artifacts like Alganyl and ReClaym, I intentionally only made one wearable interface from SCOBY—an interactive breastplate—that was thoughtfully and carefully created using a combination of these fabrication techniques.
- (4) *Using SCOBY Artifacts.* When worn, the SCOBY breastplate warmed up against the skin causing the SCOBY to mold to the body. This led Derrek Chow, who wore the breastplate during a photo shoot, to use words like “hugging” and “second skin” to describe the intimate

coupling of the human body and nonhuman organism that occurred during the wearing experience. While SCOBY has similar properties and behaviors to traditional leathers, it is not entirely waterproof, however, adding a layer of oil or beeswax helps seal it to make SCOBY more suitable for real-life applications.

- (5) *Composting SCOBY*. I quantified the biodegradability of SCOBY biofilm by following the same mass-loss over time method I used for Alganyl (Equation 4.1). I found that a 5 cm by 5 cm square SCOBY sample of 0.36 mm thickness degraded 96% in 30 days and a 5 cm by 5 cm square conductive SCOBY sample of 0.42 mm thickness degraded 84% in 30 days. I note these values are specific to the designed experiment, the slowness at which other SCOBY samples degrade might differ depending on their size (i.e., area and thickness) and the environment in which they are disposed of (i.e., the soil's temperature, humidity, and

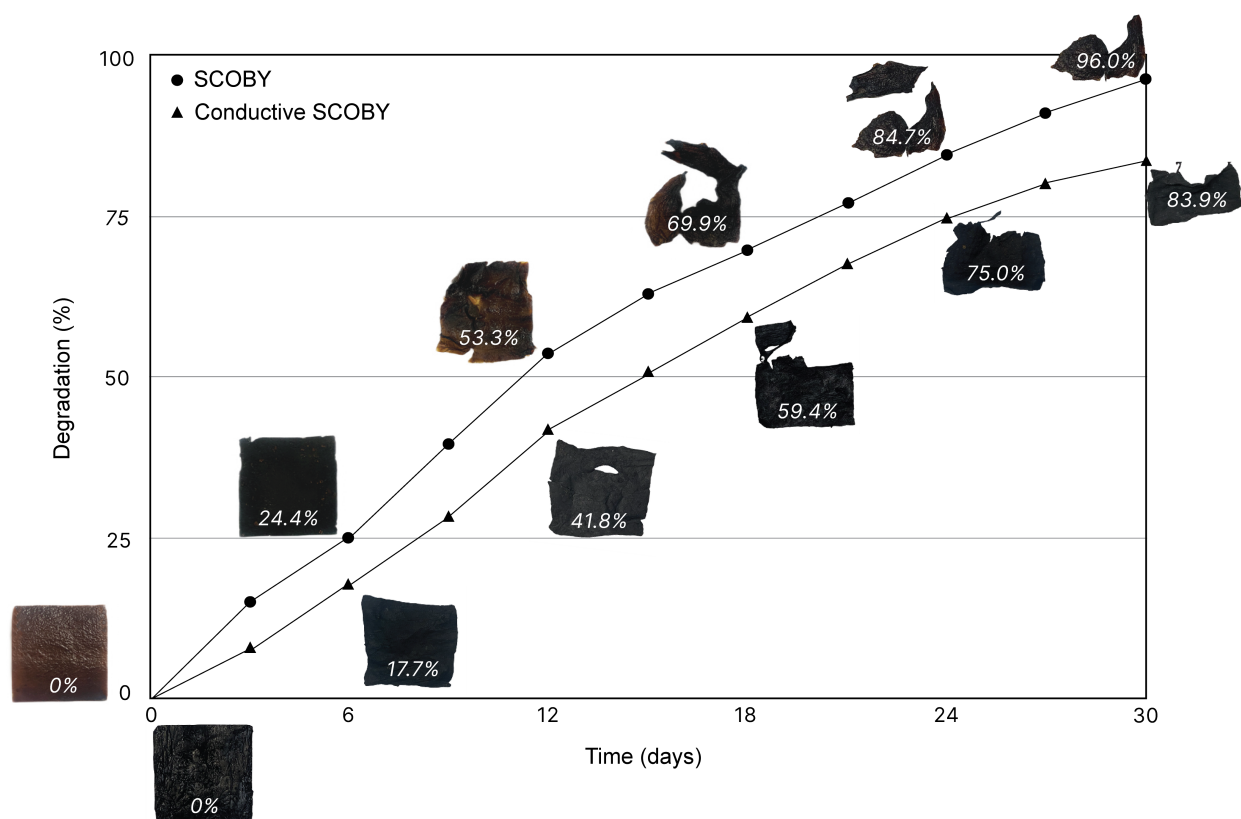


Figure 6.11: When composted, plain SCOBY degrades 96% in 30 days and conductive SCOBY, which was coated in activated charcoal, degrades 84% in 30 days.

microbial activity). Figure 6.11 shows the measured biodegradation of both samples in a controlled soil environment kept at 40°C. The corresponding photos show the degradation of the plain SCOBY (top) and conductive SCOBY (bottom) samples every 6 days.

When disposing of the SCOBY breastplate, all the electronics can be removed and reused. The microcontroller, battery, and alligator clip can be easily detached, while the embedded string of LEDs can be firmly pulled through the SCOBY layers. The rest of the wearable (including the touch sensor) can then degrade in soil.

6.3.2 Sustainability Through Slowness

Quick iterations, resulting in numerous prototypes before finalizing any given product, is a highly encouraged practice in design as it enables immediate insight and feedback. This practice is not at all uncommon in HCI research, reminding us of the fail-fast approach in design thinking [143, 144], rapid prototyping in digital fabrication [20, 194], and trial-and-error in business and engineering [151]. That being said, working with SCOBY, challenged my trained *modus operandi* to its core. Because a new SCOBY took approximately 3 weeks to grow and multiple days to dry the pace of the usual iteration felt tremendously slow.

When I began growing kombucha SCOBY for the purpose of the breastplate, I tried to fight the slowness, and optimize the process through workarounds. For example, setting up multiple bioreactors for growing SCOBY biofilms in parallel and using heating mats to encourage the cells to multiply faster. However, because my attention was diluted by being distributed over multiple cultures, some of the bioreactors got contaminated and never grew SCOBY, while other bioreactors on heating mats failed because of too much evaporation, condensation, and ethanol buildup.

While I initially resisted fully embracing the slowness of SCOBY's growth and the lack of control I had in the process, I found much more success in embracing its slowness and thus its agency as a living organism. I did so by proceeding from a position of patience, kindness, and humility—drawing from my reflections on kombucha SCOBY's slow growth to recognize its livingness. By viewing the kombucha SCOBY as another active designer in my process rather than a biomaterial

for me to control, I learned to give the SCOBY the space to grow on its own time instead of trying to insert myself into its growing process.

By recognizing SCOBY's slowness and synchronizing with its speed, I learned to be more conscientious with how each SCOBY was used to build the breastplate. While a new SCOBY was growing, I would plan how to cut it, pattern it, and lay it on the mannequin (Figure 6.12). By incorporating this intentionality and reflection during each step of the design process, as opposed to a fast, iterative design process, I wasted less of the SCOBY, resulting in a more sustainable design practice that aligned with the temporality of the SCOBY.

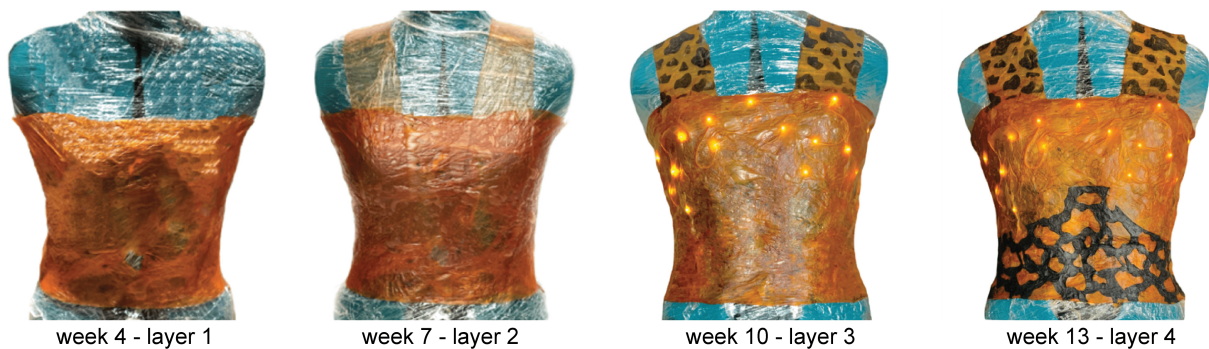


Figure 6.12: The SCOBY breastplate was slowly and intentionally designed, grown, and fabricated over the course of 13 weeks.

Chapter 7

Reflections and Aspirations

To conclude, I reflect on the tensions in creating biomaterials that are both sustainable and usable; the nature of biomaterials and how they might differ from conventional materials used in design and engineering; and aspirations for more-than-human practices that I want to further explore and incorporate into my research with biomaterials.

7.1 Reflections on Sustainable Biomaterial Development

In this dissertation, I unpack three biomaterials that I worked with during my PhD: Alganyl, ReClaym, and SCOBY. When developing the recipes for Alganyl and ReClaym, I noticed that I relied heavily on my knowledge of material science and food chemistry to identify ingredients that would bind, plasticize, gelify, and stabilize the recipe. With SCOBY, I similarly relied on my past experiences with food science to gain insight into the SCOBY growth and fermentation process. I further used methods such as material tinkering [170], tensile testing [11], and experience prototyping [38] to “optimize” recipes and benchmark each new biomaterial against more familiar, traditional materials. Moving forward, I envision material science, chemistry, and biology being invaluable resources for HCI researchers who want to develop new sustainable and expressive materials for tangible interfaces.

Coming from a mechanical engineering background, I initially felt the desire to create new sustainable biomaterials that could be a *direct replacement* of their conventional counterpart. In this pursuit, the emphasis is on recreating the same physical and mechanical properties as the

existing material. Accordingly, the first biomaterial I developed, Alganyl, was designed to directly emulate petroleum-based plastics like vinyl fabric. In turn, I “optimized” the ratio of ingredients to make the flexibility, strength, and feel of Alganyl as similar as possible to its traditional counterpart.

However, as I continued to develop and work with new biomaterials, I made a conscious effort to detach from this trend and not overlook the unique properties that a sustainable biomaterial might have when it is not confined to replacing its counterpart. Thus, when developing ReClaym, I purposely used ingredients that were biodegradable and non-toxic, even though adding ingredients such as cement or earthen metals could have resulted in a clay-like material that would have felt more like conventional ceramics and would have acted in more predictable ways. As a result, I developed a clay-like biomaterial that was both *sustainable* and *deeply personal*, instead of an exact replacement for ceramics.

Along these lines, my view of ‘material limitation’ shifted towards ‘material affordance’. For example, Alganyl is not waterproof; interaction with cold water deforms Alganyl when it dries, and boiling water completely dissolves it. While this is a limitation in the context of some applications, such as clothing that are often exposed to moisture (e.g., rain, snow, and sweat), I instead view Alganyl’s water-solubility as an affordance that leads to its sustainability. Because Alganyl is not waterproof it degrades quickly in the environment and can be easily re-cooked.

I further explored the implications of Alganyl’s water-solubility by creating an edible ramen packaging and various other speculative instant foods that are transformed with boiling water (Figure 7.1). I made the ramen packaging by incorporating a ramen flavoring pack with the other Alganyl ingredients during the cooking process (e.g., similar to how I embedded the environment-sensing pigments into Alganyl). I then wrapped and heat-sealed the dried, flavorful sheet of Alganyl around a block of ramen noodles to create a package. When the packaged noodles are dropped into boiling water, the Alganyl packaging dissolves and flavors the water while the noodles re-animate. With Netta Ofer, we expanded on this idea of dissolvable instant foods by formulating a whole collection of speculative instant foods like mac and cheese and oatmeal that dissolve in boiling water to create the meal. These food-based applications take advantage of some of the

core properties that make Alganyl unique, such as its ability to dissolve in boiling water and its derivation from bio-based, non-toxic, edible ingredients.



Figure 7.1: Alganyl instant foods that dissolve in boiling water.

As sustainability is becoming increasingly more important in both design and HCI, I encourage makers to consider the unique materialities of sustainable biomaterials instead of just looking to directly replace traditional materials. For *assembled* biomaterials, such as Alganyl and ReClaym, this may look like choosing ingredients that ensure sustainability rather than specific mechanical properties. For *grown* biomaterials, such as SCOBY, this may look like embracing and working around the imperfections that naturally occur within all living beings. In either case, makers will have to look beyond just the development of the biomaterial and correspondingly think about the ecosystem of methods, tools, and applications that surround the biomaterial.

7.2 Qualities of Biomaterials for More-Than-Human Futures

In line with recognizing and celebrating the unique affordances of biomaterials, I specifically highlight the *temporalities* and *aesthetics* of biomaterials. While the slower temporalities and aesthetic unpredictabilities of biomaterials might be viewed as less than ideal from a human-centered perspective that endorses speed and perfection, I believe these qualities invite humans to de-center themselves and cultivate humility in the design process. As such, I exemplify and reflect on ways I shift my inherently human-centered perspectives towards more-than-human perspectives of biomaterials through these two qualities.

7.2.1 Temporalities of Biomaterials

Living organisms grow at a pace that is considerably slower than the digital artifacts commonly used in HCI. For example, the yeast cells in SCOBY take 90 minutes to replicate under optimal laboratory conditions [67], which is hundreds of millions of times slower than current microprocessors that can provide feedback in milliseconds.

The slow, temporal aspect of living organisms, and biomaterials at large, have mostly been explored inadvertently, with researchers seeing the slowness of a biomaterial as an inherent part of the design process that they just have to deal with. For example, mycelium takes multiple days to grow before it can be used to encase electronics [79, 133], while slime mold takes a few hours to grow a “living wire” [145]. Alternatively, other works use biological temporalities as a driving force for interaction. For example, the slow rate of mould growth determines the rate of gameplay in Mould Rush [114], while the slow movement of houseplants towards sunlight controls the rate an IoT enabled curtain moves [228]. In contrast to these works, I view *slowness as a key reminder of the biomaterial’s agency in the design process*, which, when listened to and synchronized with, can lead to less wasteful and more sustainable design practices.

I first identified slowness as an aspect of a biomaterial’s agency when working with ReClaym and Alganyl. While both biomaterials are derived from living organisms, neither is living and therefore neither grows. However, *slowness* was a part of the making process for both; Alganyl taking time to cook (approximately 10 minutes on a stove) and dry (24-72 hours) and ReClaym taking time to obtain ingredients (1-12 months for food waste to degrade into compost depending on the composting system) and make (2 hours to make the sodium alginate gel used to bind the dry ingredients). However, these slow moments during the making process provided me with much-needed time to meaningfully reflect on my past experiences with the biomaterial (i.e., identify what I liked and didn’t like about past recipes, samples, and experiments) and consider future design decisions.

I then chose to more deeply examine slowness as an aspect of more-than-human design

with SCOBY—a living biomaterial that I *grew* rather than a non-living biomaterial that I *assembled*. SCOBY took approximately 2-4 weeks to grow, which was considerably longer than the few hours/days needed to assemble Alganyl and ReClaym. However, by embracing the slowness of SCOBY I was able to engage in acts of noticing and reflection which led to a deeper understanding of the organism’s temporality and natural rhythms of growth. By doing so I built a deeper awareness of SCOBY’s *livingness* and thus its agency in the design process, which further fostered acts of care and respect toward the organism.

While the inherent slowness of biomaterials can be a source of frustration, doubt, and worry when for the human maker. I believe that designing at the slow, nonhuman rates of biomaterials “challenges perceptions of design’s appropriate pace” [62]. By embracing the slowness of biomaterials—thus adjusting our human/digital-centered pace to a nonhuman/organism-centered pace—we as humans can begin to design from a position that is more reflective, intentional, and sustainable.

7.2.2 Aesthetics of Biomaterials

Unlike standardized materials typically used in engineering and design practices like plastic or metal, biomaterials, especially the biomaterials I present in this dissertation, are imperfect varying in their properties and aesthetics each time they are used. Rather than fighting against these material imperfections, I embrace them as both a tool that boosts creativity [149] and as an intimate aesthetic quality that is grounded in *Wabi-Sabi*. Wabi-Sabi is the aesthetic philosophy that considers beauty in that which is imperfect, transient, or incomplete [215]. According to Wabi-Sabi aesthetics, artifacts are beautiful for bearing marks of imperfection (e.g., cracks, unevenness, asymmetry) that indicate individuality, the randomness of nature, and the nobility of aging.

ReClaym particularly embodies this imperfect aesthetic. ReClaym reflects the non-uniformity of the food waste composted, resulting in a different material every time it is made, which is unique to each person and reflects their current relationships with food. ReClaym does not mimic the clean and smooth qualities of automation and mechanical perfection—its messiness and irreproducibility

conveys a more honest, closer-to-human aesthetic that the maker can connect with.

Meanwhile, SCOBY's imperfections stem from the fact that it is a grown material. Throughout my experimentation with SCOBY, although following the same growing process every single time, I could not exactly replicate the material's color, thickness, or texture. For example, the color of the SCOBY would vary each time we made a new batch depending on the type of tea chosen (green or black) for the sweet tea and the color of the starter culture. Moreover, the thickness of the SCOBY also often impacted the opacity and, in turn, the intensity of the color. Slight unevenness in the color of SCOBY was often caused by yeast flocculation, which resulted in dark brown stringy structures that attached to the biofilm. Meanwhile, lots of yeast flocculation and trapped bubbles of air could also impact the texture.

Even my most "perfect" biomaterial, Alganyl, would naturally flow into imperfect shapes when poured onto a table to dry. Alganyl also would rarely cook all the way down during the re-cooking process, resulting in small dense, clumps in the re-cooked sheets.

I recognize that some of these aesthetic imperfections and unpredictabilities can be limited in my biomaterials. For example, I could have selected specific food waste items to compost and further ground up my ingredients to make ReClaym more consistent. However, I purposely designed the recipe of ReClaym to reflect my eating habits, and as such I *wanted* to see its inconsistencies. For SCOBY I could have grown the cultures in a more controlled and/or automated environment to ensure more uniformity. However, taking care of the SCOBY cultures myself and growing them in the same environment that I live and work in brought me closer to the SCOBY and made my design practice even more personal and rewarding. For Alganyl, I could have completely dissolved the existing pieces of Alganyl during the re-cooking process to obtain more "perfect" re-cooked Alganyl sheets. However, the undissolved clumps added a unique aesthetic quality and added mechanical strength to the re-cooked Alganyl sheet.

I ultimately view the imperfections of each biomaterial as unique personality traits—marks of the biomaterial's individuality as a being with agency. Imperfections can also visually indicate the personal touch of the human maker or other meaningful experiences that the artifact has gone

through. Accordingly, some of my favorite aspects of my biomaterials are their imperfections as displayed in Figure 7.2. I love that the re-cooked Alganyl has a stained glass-like aesthetic; that ReClaym has clumps that show that I ate an egg several weeks ago; and that the SCOBY has dark spots of yeast flocculation that reflect the microbial makeup of the kombucha culture it grew in.

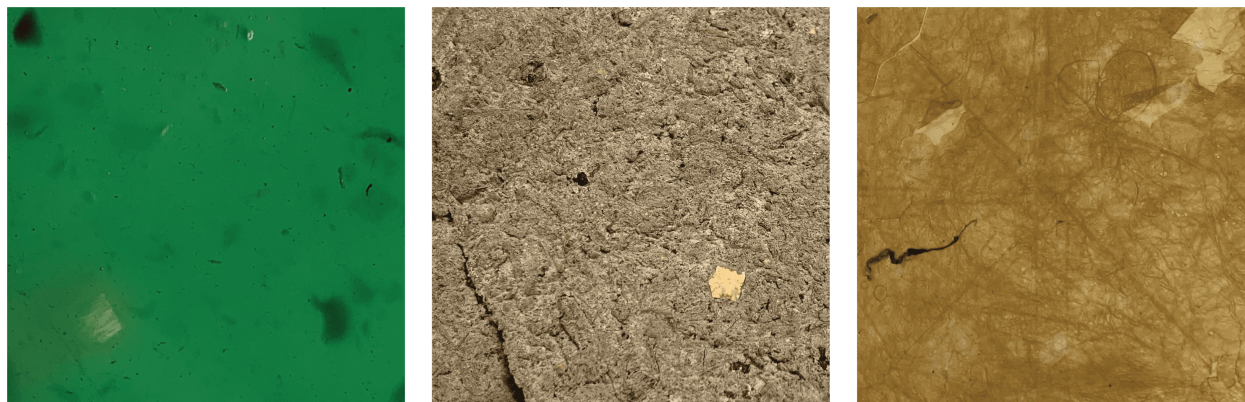


Figure 7.2: Material imperfections in re-cooked Alganyl, ReClaym, and SCOBY.

7.3 Accessible Making and Making-With Biomaterials

One of my long-term aims is to raise people’s awareness and eventually direct attitudes towards using sustainable, biomaterials such as Alganyl, ReClaym, and SCOBY in an everyday context. To do so, I promote *accessibility* in making and making-with biomaterials.

The kitchen has always been a place of science despite the fact that, from a societal perspective, food and science have been mostly compartmentalized up until 30 years ago [153]. Nowadays, food and science have merged, food being created in labs [42, 69] and science being created in kitchens [2, 65]. For example, supported by research that shows equivalent results [118], DIYBio spaces use a pressure cooker (min 2 bars) as an autoclave, or a microwave to sterilize small volumes [65]. This equipment is not only easily accessible, but it is also familiar (i.e., people often use these items for cooking). The combination of familiar tools and techniques encourages greater creativity and comfort with a biomaterial that is otherwise unfamiliar and daunting.

While Alganyl, ReClaym, and SCOBY can be made in a variety of environments, I found

that my making practice benefited from taking place in the kitchen, the experimental hub of the home—a *place of creativity, community, and conscious making*. The kitchen as a familiar and comfortable place of fabrication is singular in the fact that it is inextricably tied to the act of cooking. I specifically leveraged the tacit knowledge I gained from years of experience cooking to support the creation of all my biomaterials. For example, most people are familiar with measuring out and mixing ingredients, actions I used to prepare all my biomaterials, further which are made up of ingredients that can easily be found at grocery stores at relatively low cost. In the case of ReClaym, measuring and mixing its four ingredients is the only step needed to make the bio-clay. Alganyl had the added step of heating its three ingredients to a boil, which can be done using either a microwave or stovetop, whichever one the maker feels most comfortable with. To prepare a SCOBY culture, the process is the same as making tea for any other purpose, with the addition of mixing in a starter culture (i.e., store-bought kombucha).

By positioning the kitchen as a makerspace, the maker is already put at ease, the familiarity of the space being comfortable rather than intimidating. This familiarity then puts the maker at ease when it comes to working with an unfamiliar biomaterial, providing a safe place for creative making to occur. For example with ReClaym, I used objects found around the home as molds and plastic sandwich bags found in the kitchen for extrusion. With Alganyl I similarly used common crafting equipment found in the home such as a fabric iron for heat-sealing and scissors for cutting. Moreover, by engaging in making practices in the kitchen, the maker can easily adopt a kitchen mindset—since the kitchen is used to prepare food, it is a place of experimentation and nurturing.

I envision people beyond the design and HCI communities engaging with making and making-with sustainable biomaterials by leveraging the familiarity of cooking and the comfortable environment of the kitchen as well as other unintimidating, communal spaces such as libraries, DIY makerspaces, and even classrooms. To aid in this effort, I ran a variety of workshops with Alganyl, ReClaym, and SCOBY in different locations, with different groups of people (e.g., different ages and expertise) throughout my PhD. For example, during the COVID-19 pandemic, I ran virtual Alganyl workshops for college design students, the results from these workshops being published

at the TEI'22 conference [21], where I also ran a corresponding Alganyl studio for HCI practitioners [22]. I also have taught elementary to high school students how to make and make with Alganyl by hosting workshops at local public libraries and classroom visits. With ReClaym I similarly have run workshops for elementary through university level students in classrooms and even in public parks outside, where we utilized compost from a nearby urban garden. Most recently, I brought a collection of dried SCOBY samples all the way to Warsaw, Poland for HCI practitioners at the TEI'23 conference to participate in a hands-on studio [24].

Through these workshops I engaged makers (e.g., designers, artists, HCI researchers, DIY enthusiasts, tinkerers, etc.) of all ages and expertise in making and making-with biomaterials that they were unfamiliar with as shown in Figure 7.3. As such, my primary goal for each workshop was to guide makers in gaining knowledge, comfort, and confidence in the biomaterial so that they could incorporate the sustainable biomaterials into their own creative practices. In return, these workshops provided a space for me to openly discuss and collaborate with community members, thus broadening my own situated perspectives of each biomaterial. By emphasizing open sharing and learning (e.g., values championed by DIY communities [123]) via communal workshops, we can begin to speculate on a future where not just expert biodesigners, but everyone can make and make-with biomaterials—leading to more wide-spread awareness regarding sustainability and materials.



Figure 7.3: Virtual Alganyl workshop with undergraduate students during the COVID-19 pandemic; Alganyl workshop with middle school students at a local public library; ReClaym workshop with elementary school students outside at a local public park; SCOBY studio with HCI practitioners at the TEI'23 conference in Warsaw, Poland.

7.4 Future More-Than-Human Practices for Biomaterials

In the future, I aspire to dig deeper into the more-than-human practices used to support making and making-with biomaterials. Accordingly, I plan to continue unpacking the nuances of engaging the body to support material correspondence [28] and embracing slowness to prompt reflection and intentionality [23]. Furthermore, I propose two more practices—encouraging care-based interactions and extending multispecies collaborations—to provide new ways of centering the design process around nonhuman biomaterials. Through these more-than-human practices, I envision building more thoughtful, supportive, ethical, and sustainable relationships with the biomaterials we design with, which, in the long term, may be the foundation for a more sustainable future.

7.4.1 Encouraging Care-Based Interactions

When designing with any biomaterial that is grown (i.e., a living organism), caretaking is an inevitability, as the maker needs to keep the organism alive. As such, the maker is required to nurture, assess health, and facilitate appropriate environments for the organism—ultimately taking responsibility for the health of the organism as an ethical duty. However, caretaking is often relegated to the background when working with living organisms and has only recently been highlighted as a primary interaction between users and organism-centered artifacts in HCI. Most notably, Lu and Lopes developed a slime mold smartwatch that links the functionality of the watch to the care of the slime mold; with care, the slime mold forms a living wire that completes the circuit [145]. Meanwhile, Chen et al. showcased care-based interactions with Nukabot, a culture of lactic acid and bacteria that lives in a wooden bucket bioreactor embedded sensors that communicate the health of the culture [45].

Along these lines, I am beginning to explore what it means to bring caretaking interactions to the forefront of a design process with SCOBY. Recently, I designed, with the help of Mirela Alistar and Joshua Coffie, a digitally enhanced bioreactor for a kombucha culture to live in, as

shown in Figure 7.4. The digital components of the bioreactor non-invasively track (via sensors) and enhance (via sound) the health and growth of the culture. The bioreactor utilizes three sensors, a photoresistor, a temperature sensor, and a UV light sensor. The temperature sensor and UV light sensor, placed in the top of the bioreactor help track the SCOBY's health—temperature and UV light posing the biggest threat to the SCOBY. I tracked these values on a daily basis to ensure the environmental conditions were appropriate for the SCOBY to grow. The photoresistor, which is placed beneath the culture, measures the amount of light that filters through the culture. As the SCOBY grows, less light reaches the sensor. To communicate growth the sensor values are mapped to different pitches of sound. Accordingly, even if the caretaker cannot *see* growth happening on a day-to-day basis, they can *hear* growth.

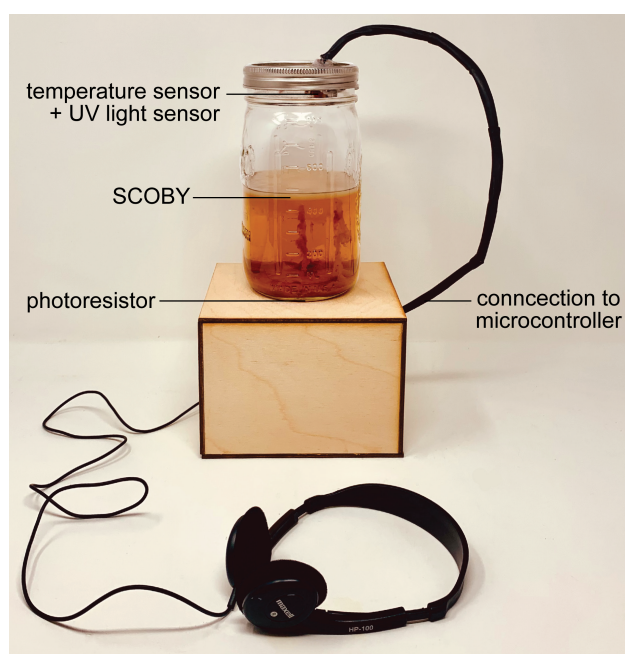


Figure 7.4: Encouraging care-based interactions with digitally enhanced bioreactors that help humans track the growth and health of SCOBY.

I actively engaged with the kombucha SCOBY on a daily basis by listening to the pitch determined by the SCOBY's growth, tracking potentially harmful environmental facts (i.e., temperature and UV light), and observing the organism (i.e., identifying visual signs of growth and checking for contaminants). As I got into a habit of caring for the SCOBY, the experience went

beyond just checking on the growth and health of the culture. My caretaking interactions became a meditative practice that allowed me to slow down and connect with another organism for a few moments each day. I used these slow moments for introspection and mindfulness, many slow technologies being purposely designed to enhance reflection [85, 89, 160]. Through this reflection, I found myself gaining a deeper *understanding* of SCOBY’s livingness, thus fostering feelings of “shared vitality” [86, 107, 155].

In the future, I want to bring more attention to care ethics [110] and care-based interactions when designing with biomaterials. I believe that by prioritizing care between the human maker/user and the nonhuman biomaterial we can begin to imagine more sustainable, post-anthropocentric relationships between humans, nonhumans, and technology. While caretaking most obviously applies to living biomaterials, I also envision recognizing and emphasizing caretaking interactions with non-living biomaterials. For example, developing Alganyl and ReClaym was a highly time-consuming process that involved daily interaction with the recipes. Once I arrived at a recipe I used hands-on fabrication techniques that relied heavily on input from the material, making the fabrication process feel like I was *nurturing* the material rather than forcing the material into a desired form. This aspect of caring for and nurturing the biomaterial led to more thoughtful uses of the biomaterial and artifacts that I was more emotionally tied to.

7.4.2 Extending Multispecies Collaborations

Multispecies collaborations have been widely explored in HCI and interaction design [137, 138, 139, 140, 203]. Researchers typically *notice* that these collaborations are happening and design to support/further the collaboration through observation and embodied experience (e.g., hunting for mushrooms, watering slime mold). However, researchers often overlook the unseen multispecies collaborations that occur on a daily basis (e.g., the collaborations that occur between humans and microorganisms). Accordingly, I envision expanding how researchers recognize and think about daily multispecies collaborations that go unnoticed due to their invisible nature.

One example is to radically shift our perceptions of the human body, from the human body as

a singular organism (i.e., a person) to the human body as a “*multispecies assembly*” [94, 96]. Even though we cannot see them, the human body is home to an ecosystem of microorganisms (microbes), most of which are bacteria and fungi, that live in harmony with us. The totality of these microbes that live on and within the body is commonly known as the microbiome. While the microbiome is *nonhuman*, it lives in *symbiosis with the human body*, enabling the synthesis of nutrients during digestion, protecting the skin from harmful microbes, and more [56]. Accordingly, the microbiome challenges the *human* | *nonhuman* binary because these microbes support the function of the human body, but are not human (i.e., microbes are orders of magnitude simpler—from a biological perspective—than the multicellular human organism). Moreover, the microbiome is entirely unique to each person, the microbial makeup depending both on the body’s natural environment (e.g., the body’s natural pH and salinity) and the body’s interactions with the surrounding world (e.g., food consumed, objects touched, people hugged). As such, when the body interacts with the world on a macro level, the microbes that exist on the body also experience that interaction on a micro level. One such way to recognize human-microbiome interactions and further facilitate specific human-microbiome collaborations is by growing microbiome samples to a visible level as seen in Figure 7.5.

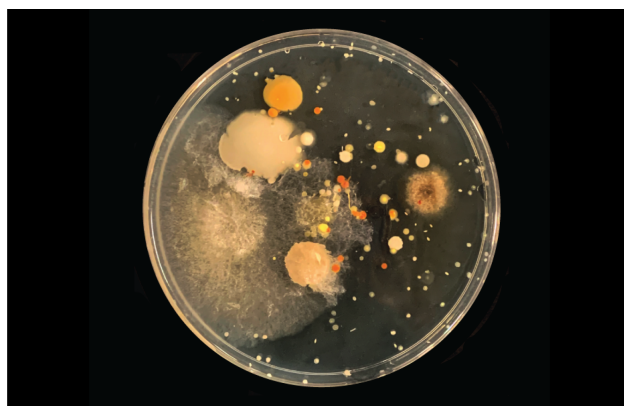


Figure 7.5: Expanding notions of multispecies collaboration via the microbiome. This petri dish shows a grown microbiome sample taken from my shoulder.

By recognizing that we as humans are constantly, *unconsciously* collaborating with our mi-

crobiome, we can then begin to *consciously* collaborate with our microbiome. Through human-microbiome collaborations, we can gain deeper insight into our health and reflect on our bodies and as exemplified by Boer’s gut microbiome cultivation and tracking kit [36], Campo Woytuk’s menstruation kit [41] and Helms’ breastfeeding artifacts [96]. Through such multispecies collaborations, we can begin to disassemble notions of dualism that separate humans from nonhumans.

We can also extend our examination of the microbiome to other animals, plants, and even biomaterials, as every being, thing, and environment engages and collaborates with microbes. For example, biomaterial-microbe collaborations most notably occur during biodegradation. While all three of the biomaterial I discuss in this dissertation biodegrade in the natural environment, ReClaym best exemplifies the multispecies collaborations that can occur. ReClaym, which was derived from compost, engaged microbes to break down food waste into compost. In this case, the microbes (fungi and bacteria) act as another maker in the ReClaym making process. As such, this shifts the perspective from biodegradation as end-of-life towards biodegradation as a site for *multispecies making*. When the biodegraded food waste (i.e., compost) is then ultimately transformed into ReClaym, all the living microbes that participated in the biodegradation processes are still present, meaning that ReClaym is teeming with life even though it doesn’t look alive. The living, nutrient-dense nature of ReClaym further provides an environment for non-microbial organisms, like plants, to also thrive, as exemplified by the growing sculpture in Figure 5.4.

Ultimately, I envision bringing further awareness to unseen microbial interactions and collaborations that occur, thus extending the perception of multispecies collaborations. By doing so, I hope to highlight how humans, nonhumans, and the natural environment are all entangled and reliant on each other and should thus respect and support each other.

7.5 Outlook: A Case for Biomaterials

In this dissertation, I present a process for making and making-with *biomaterials*, materials that are both bio-based and biodegradable. This process consists of biomaterial development and characterization, identification of supportive fabrication techniques, exploration of design pos-

sibilities, and analysis of sustainability from beginning to end of life. I specifically demonstrate this process with three biomaterials: Alganyl, an algae-based bioplastic; ReClaym, a compost-based bioclay; and SCOBY, a cellulose-based bioleather. Through these biomaterials, I speculate on *more-than-human futures* in which biomaterials not only provide a sustainable alternative to conventional materials, but prompt corresponding making practices that prioritize the ‘voice’ and well-being of nonhuman actors in the design process. Through this work, I hope to offer a pathway towards more sustainable, diverse, and inclusive relationships with the natural world.



Figure 7.6: Biomaterials for More-Than-Human Futures

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