Integrating Biomaterials and Interactive Technologies: Practice-based Perspectives on the Growth of Biodesign within Human-Computer Interaction

Keywords:
human-computer interaction, biodesign, biomaterials, interactive technology, sustainability

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Abstract

Biodesign has grown significantly in the last decade as an approach focused on designing with biological materials, processes, and systems. The inherent transdisciplinarity of biodesign enables it to cut across multiple fields. In this work, we look at how biodesign has recently been applied within Human-Computer Interaction (HCI), a disciplinary field that focuses on the design, development, and study of interactive technologies. Subsequently, Biological-HCI (Bio-HCI) has emerged as a rapidly growing and evolving area of research at the intersection of biodesign and HCI. To highlight the nascence of Bio-HCI, we examine three of our own Bio-HCI projects—SCOBY Breastplate, B10-PR1NT, and µMe—as case studies that exemplify how biodesign is being explored through specific, situated practices with a variety of interactive technologies. Through these cases, we identify potential themes and opportunities for Bio-HCI as it continues to push current understandings of computational interaction and promote more sustainable technological futures.

This peer-reviewed article has been accepted for publication but not yet copyedited or typeset, and so may be subject to change during the production process. The article is considered published and may be cited using its DOI.10.1017/S2977905725100036

Introduction

Biodesign has arisen as a transdisciplinary approach that harnesses biological materials, processes, and systems to design innovative applications across diverse fields, including (but not limited to) healthcare, architecture, material science, art, manufacturing, and fashion. Biodesign goes beyond existing principles of biomimicry and sustainability in design by incorporating *biomaterials* (e.g., living and once-living organisms) as essential design components (Myers and Antonelli 2012). In doing so, biodesign carries a unique ethos that revolves around the importance of designing *with* the biological world to combat current ecological challenges brought about by climate change.

In contrast, Human-Computer Interaction (HCI) is a disciplinary field rooted in computer science that focuses on the development of computational technologies and the interactions humans have with these technologies (e.g., user interfaces, virtual reality, artificial intelligence, robots, and more). Although HCI primarily deals with the digital, there have been efforts to recognize the physical *materiality* of computational technologies and how materials shape our interactions when designing and using such technologies (Wiberg et al. 2013; Ishii et al. 2012). This expanding exploration of materials in HCI, paired with the rise of synthetic biology (Benner and Sismour 2005), Do-It-Yourself biology (Delgado 2013; Kuznetsov et al. 2012), sustainable design (Blevis 2007; Williams 2007), and posthuman design (Forlano 2017; Wakkary 2021) has led to increasing interest in biomaterials as vital components for the design of user interfaces and other interactive technologies.

Facilitated by this utilization of biomaterials and the corresponding processes, practices, and perspectives biomaterials carry, HCI is beginning to employ biodesign as a broad approach to the design of interactive technologies—resulting in an emerging area of research referred to as Biological-HCI (Bio-HCI). Bio-HCI speaks to a rapidly growing and evolving body of work that bridges humans, technology, and the biological world. These works are broad in scope, ranging from biodegradable tangible user interfaces (Guridi, Iannacchero, and Pouta 2024; Koelle et al. 2022; Bell et al. 2024), to digital information encoded in DNA (Pataranutaporn, Ingalls, and Finn 2018; Alistar and Pevere 2020; Kim, Linehan, and Pschetz 2022), to care interactions with living displays

Figure 1. Three Bio-HCI projects used as case studies. (Left) Biomaterials for ubiquitous computing as exemplified by the SCOBY Breastplate, an interactive wearable grown from microbial cellulose that is embedded with LEDs and controlled by a custom, biodegradable touch sensor. (Middle) Biomaterials for digital fabrication as exemplified by B10-PR1NT, a project focused on developing a new circular eggshell-based biopaste for 3D printing. (Right) Biomaterials for dynamic interfaces as exemplified by the µMe project, an exploration of using the microbes found on the human skin to create a collection of personalized, color-changing, living textile dyes.

(Kim et al. 2023; Lu and Lopes 2022; Oktay et al. 2024; Chen et al. 2021). While the diversity of projects demonstrates the rich potential of Bio-HCI, there remains a need for further reflection on situated methods and mindsets that emerge more broadly when biodesign is applied across various HCI contexts.

In this work, we specifically contribute three of our own Bio-HCI projects, shown in Figure 1: SCOBY Breastplate, B10-PR1NT, and µMe. Through these design case studies, we provide personal, practice-based perspectives on how we utilized biodesign as an approach to integrate biomaterials (i.e., scoby, eggshell paste, and the microbiome) with existing HCI research contexts (i.e., ubiquitous computing, digital fabrication, and dynamic interfaces). We further reflect on how our situated practices in the context of these design cases surfaced thematic tensions and opportunities such as agency, temporality, circularity, and care, that arose from combining the biological and digital. In doing so, this work aims to provide reflective and generative insights to support the continued growth of biodesign within HCI via Bio-HCI. By embracing current practices and fostering more work at this intersection, we hope to see the biological and digital worlds converge and evolve in ways that build more responsive and eco-conscious technological futures.

The Emergence of Bio-HCI

Several epistemologies, frameworks, and methodologies have primed the field of HCI to embrace the approach of biodesign, leading to the emergence of Bio-HCI (the combination of the two). Conceptually speaking, Bio-HCI is foregrounded by frameworks related to posthuman and more-than-human design (Wakkary 2021; Forlano 2017), feminist design (Bardzell 2010), sustainable design (Blevis 2007; Lazaro Vasquez, Wang, and Vega 2020), and speculative design (Dunne and Raby 2024). The philosophical and ethical perspectives of these design frameworks ground and guide much of Bio-HCI, encouraging researchers to design interactive technologies from more non-hierarchical, embodied, situated, and ecologically-aware positionalities.

Technically speaking, Bio-HCI builds upon the "material-turn" in HCI (Robles and Wiberg 2010), a shift that acknowledges how interactions are not solely defined by what is displayed on a screen, instead recognizing the inherent materiality of interfaces (Wiberg et al. 2013). This has led to a surge in new computational materials (Vallgårda and Redström 2007), tangible user interfaces (Ishii et al. 2012), and implementations of material-centered design methods (Karana et al. 2015; Giaccardi and Karana 2015). With this increasing focus on materials, paired with advancements in synthetic biology (Benner and Sismour 2005), biotechnology (Ratledge and Kristiansen 2006), and Do-It-Yourself biology (Delgado 2013; Kuznetsov et al. 2012), Bio-HCI has readily begun to embrace the integration of *biomaterials* within interactive technologies.

Common biomaterials (i.e., living and once-living organisms) utilized in the context of Bio-HCI include, but are not limited to, plants (Holstius et al. 2004; Sareen and Maes 2019; Chang et al. 2022; Janicki et al. 2024; Hu et al. 2024; Luo et al. 2020), algae (Koelle et al. 2022; Bell et al. 2022; Zhu, Winagle, and Kao 2024; Ofer, Bell, and Alistar 2021; Breed, Putten, and Barati 2024; Søndergaard and Campo Woytuk 2023; Soares da Costa et al. 2025), mycelium (Weiler et al. 2019; Genç, Launne, and Häkkilä 2022; Lazaro Vasquez 2019; Gough et al. 2023; Hamidi, Baljko, and Gómez 2017), slime mold (Lu and Lopes 2022), bacteria (Groutars et al. 2022; Zhou et al. 2023; Yao et al. 2015; Boer et al. 2020; Riggs, Nitsche, and Howell 2025; Kim et al. 2018), microbial cellulose (Bell, Coffie, and Alistar 2024; Ng 2017; Nicolae et al. 2023; Ofer and Alistar 2023), gelatin (Lazaro Vasquez et al. 2024; Lazaro Vasquez et al. 2022), and chitosan (Song et al. 2022; Den Teuling, Winters, and Bruns 2024). These biomaterials then take on various forms as bioplastics, biocomposites, biofoams, biodyes, biopastes, and bioleathers that can be combined with other interactive technologies to create unique, and often sustainable, displays, games, wearables, packaging, controllers, data physicalizations, sensors, instruments, and more.

While there are many ways in which biomaterials (and the broader biodesign approach that biomaterials encourage) are utilized within Bio-HCI, we focus on three existing spaces of HCI where biomaterials have been widely applied and hold significant promise for further research and development: ubiquitous computing, digital fabrication, and dynamic interfaces.

https://doi.org/10.1017/S2977905725100036 Published online by Cambridge University Press

Biomaterials in Ubiquitous Computing

The space of ubiquitous computing in HCI aims to embed computing capabilities into everyday materials and objects, making technology invisible and accessible in the background. This often looks like smart home devices (e.g., speakers, refrigerators), wearable technologies (e.g., watches, glasses), and smartphones. Bio-HCI has, in turn, been exploring how biomaterials can integrate within these interactive everyday objects.

Current research has primarily revolved around how biomaterials can seamlessly integrate with traditional electronic components (Genç, Launne, and Häkkilä 2022; Alistar et al. 2024; Luo et al. 2020), as well as how biomaterials can be used to make new biodegradable electronic components (Lu and Lopes 2022; Katherine Wei Song and Paulos 2023; Zhu, Winagle, and Kao 2024). Some notable examples include a video game controller that was grown from microbial cellulose, and embedded with LEDs, touch sensors, buttons, and a microcontroller (Nicolae et al. 2023), a heater that was made from leaf skeletons coated in chitosan and silver nanowires (Song et al. 2022), and a breadboard that was grown from mycelium and laser cut to allow the connection of LEDs, batteries, wires, and a potentiometer (Lazaro Vasquez 2019). More exploratory work has developed new biomaterials like algae-based bioplastics (Koelle et al. 2022; Bell et al. 2022) and gelatin-based biofoams (Lazaro Vasquez et al. 2022) to integrate with conductive materials like activated charcoal powder and stainless steel fibers, thus enabling these biomaterials to act as sensors that can become a part of a larger interactive system.

These works begin to demonstrate a future of *sustainable* smart devices, interactive everyday objects that are grown from renewable biological sources and biodegrade naturally in the environment when disposed of. While the ultimate goal is to create entirely circular interactive technologies, current efforts that integrate non-biodegradable components (e.g., electronics) focus on harvesting and reusing these components, while the rest of the object biodegrades. The inherent *growth* and *decay* of these sustainable biomaterials challenge existing assumptions regarding the durability, scalability, temporality, and invisibility of ubiquitous computing, opening new relations, interactions, and aesthetic appreciations of technology.

Biomaterials in Digital Fabrication

The space of digital fabrication within HCI addresses the workflow of transforming digital data into tangible objects. In digital fabrication, a digital model is created and translated into code that directly controls manufacturing machines. For example, laser cutting and computer numerical control (CNC) routing subtractively removes material to achieve a given form, while laminated object manufacturing and 3D printing additively build up layers of material to achieve the given form.

3D printing has notably risen as a popular method for digital fabrication given its accessibility, affordability, versatility, and capabilities (Mellis et al. 2013). However, many 3D printing workflows suffer from a reliance on plastics and their corresponding production of renewable print waste. As such, recent Bio-HCI efforts have focused on developing new biomaterials for 3D printing. One of the most widely used biomaterials for 3D printing, Polylactic acid (PLA), is a thermoplastic polyester derived from fermented plant starches, such as corn and cassava. While considered sustainable in comparison to petroleum-based plastic filaments, PLA cannot readily biodegrade in the natural environment, instead requiring industrial composting systems (Kolstad et al. 2012). PLA has further been mixed with other ingredients like wood (Yubo Tao et al. 2017) and cocoa shells (Tran et al. 2017); however, the biodegradability of these hybrid PLA filaments has not been tested.

To ameliorate this issue, recent research proposed switching from 3D printing biomaterial filaments (like PLA) to biomaterial pastes instead of filaments. This is because biomaterial pastes can be more easily designed to readily biodegrade in the environment and require less energy to be extruded from a 3D printer (Faludi et al. 2019). The paste extrusion method for 3D printing—also known as Direct-Write printing or Robocasting (Peng, Zhang, and Ding 2018)—has led to the development of radically sustainable biomaterials made from spent coffee grounds (Rivera, Bae, and Hudson 2023), mussel shells (Sauerwein and Doubrovski 2018), oyster shells (Monsieur and Andersen 2024), corn and wheat flour (Buechley and Ta 2023), and bamboo fibers inoculated with mycelium (Soh et al. 2020). These new biomaterials introduce new constraints regarding their unique properties and behaviors that contrast traditional digital fabrication processes and materials like plastic or metal. Accordingly, this shift towards biomaterials not only enables the digital fabrication of more circular objects, but also encourages a convergence of biological and digital workflows, opening up new practices of fabrication that revolve around different *temporalities* and *agencies* of machines and materials.

Biomaterials in Dynamic Interfaces

Lastly, the space of dynamic interfaces within HCI broadly refers to user interfaces that can adjust in real-time in response to user input and context. Inherently responsive, reactive, or otherwise expressive materials are key to enabling dynamic interfaces. Such materials can change color or shape in response to stimuli like temperature, ultraviolet light, moisture, and movement. In terms of Bio-HCI, biomaterials such as algae-based bioplastics and gelatin-based biofoams have been integrated with color-changing pigments to respond to changes in temperature, ultraviolet light, and pH (Bell et al. 2022; Lazaro Vasquez et al. 2022; Søndergaard and Campo Woytuk 2023), while flour-based doughs and wood-based composites have been designed to change shape in response to water exposure (Ye Tao et al. 2019; Luo et al. 2020; Q. Lu et al. 2024).

Alternatively, living organisms used as biomaterials have the ability to naturally react to such stimuli. These dynamic *living interfaces* (Merritt et al. 2020) essentially leverage organisms as "computers" to naturally process input information and display a response in return. For example, Infotropism leverages plants' natural tendency to move to face light to display information (Holstius et al. 2004), while the Plant-Driven Actuators utilize plants to literally make robots grow, age, and decay

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(Hu et al. 2024). Microorganisms particularly present many possibilities in this space, with Flavorium demonstrating how flavobacteria shifts color in response to changes in temperature (Groutars et al. 2022), Algae Alight showcasing dinoflagellates releasing a bright blue bioluminescence in response physical movements (Breed, Putten, and Barati 2024), and BioLogic utilizing bacterial natto cells embedded within textiles to change shape in response to humidity (Yao et al. 2015).

Unlike biomaterials for ubiquitous computing, biomaterials for dynamic interfaces use the inherent responsiveness or *livingness* of biomaterials to create interactive technologies. In this space, we can envision future interfaces that are not actuated by traditional electronics, but instead by biomaterials that naturally respond to biological inputs. While this presents a more sustainable alternative, it also raises ethical questions about what it might mean to *care* for the biomaterials embedded within our technologies.

Case Studies

We selected three of our own previously published Bio-HCI design projects (Figure 1) as case studies to represent the potential for biodesign in three different spaces within HCI (e.g., ubiquitous computing, digital fabrication, and dynamic interfaces). These projects are notably biomaterial-centric, exemplifying our personal practice with biomaterials as we designed them to integrate with varying interactive technologies. We describe each project, highlighting conceptual and technical aspects of our situated design process that relate to both biodesign and HCI and their intersection. We then reflect on the implications of each project and hint towards themes that present tensions and opportunities for future Bio-HCI research.

SCOBY Breastplate

The SCOBY Breastplate project follows the design of an interactive wearable grown from scoby (Bell, Chow, et al. 2023). Scoby is a symbiotic culture of bacteria and yeast that grows in a liquid kombucha culture. Over time, the bacteria and yeast form a layer of cellulose-based biofilm at the top of the liquid. It takes approximately 1 month for a scoby biofilm to grow to a thickness of approximately 1 cm, as can be seen in Figure 2.

Figure 2. Scoby is a symbiotic culture of bacteria and yeast that grows a cellulose-based biofilm at the air-liquid interface of kombucha over the course of several weeks.

To create the breastplate, we grew scoby in a large container, then harvested the biofilm, cut it to our desired size and shape, and dried it around a mannequin. We took advantage of the scoby biofilm's ability to adhere to itself—when we added a new layer of biofilm to the mannequin, it adhered to the layer of biofilm beneath it—allowing us to build up layers to create the breastplate. We utilized a total of 4 biofilms, each one being harvested after about 3 weeks of growth, as shown in Figure 3. This meant that the breastplate was *slowly* designed and fabricated at the rate of the scoby biofilm's growth.

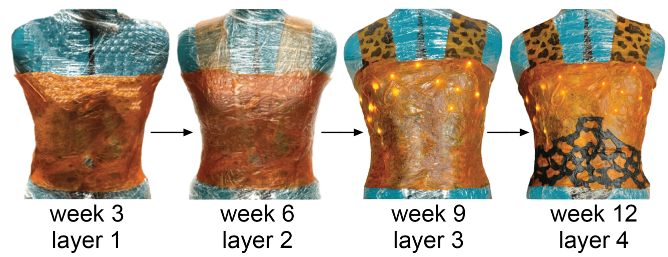

Figure 3. The SCOBY Breastplate was slowly designed and fabricated in layers at the rate of the scoby biofilm's growth.

The layering technique was used to seamlessly embed a strand of LEDs and a custom capacitive touch sensor, which were connected to a microcontroller and battery as annotated in Figure 4. The capacitive touch sensor is particularly notable as it was made from a layer of scoby biofilm coated in activated charcoal. When the sensor is touched, the programmed microcontroller activates the LEDs. The brightness and length of LED illumination correspond to the length and pressure of touch: a short, light touch results in a brief, dim glow, while a long, firm touch results in a lingering, bright glow.

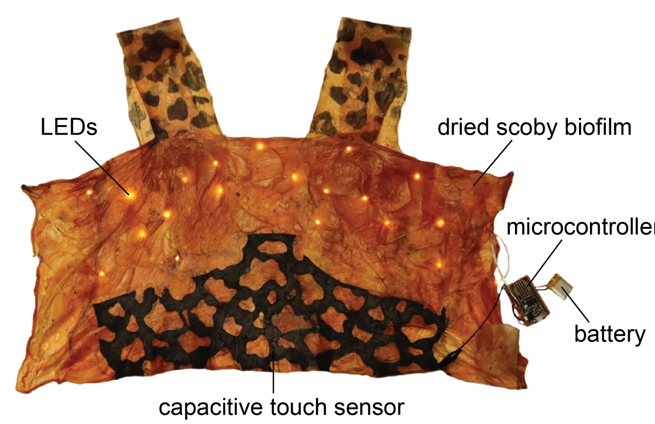

Figure 4. The SCOBY Breastplate leverages scoby's ability to self-adhere to seamlessly embedded LEDs and a custom capacitive touch sensor made from scoby biofilm coated in activated charcoal.

When the SCOBY Breastplate is no longer wanted or needed, it can be disposed of in the environment. The test in Figure 5 shows that the scoby biofilm takes 30 days to biodegrade approximately 96% in a microbial-rich soil, while our custom scoby capacitive touch sensor (i.e., the scoby biofilm coated in activated charcoal) biodegrades approximately 84%. While the custom scoby sensor can biodegrade, the other tradi-

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tional electronic components embedded within the breastplate—the LEDs, microcontroller, and battery—must be removed before disposal. We encourage these components to be reused for other projects.

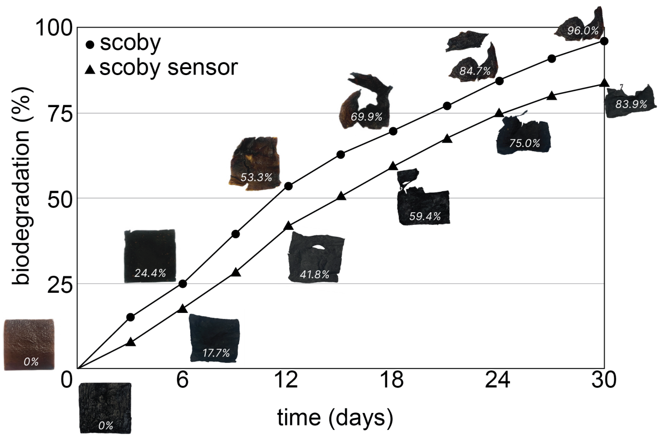

Figure 5. Biodegradation based on the mass-loss of scoby and the scoby sensor over time in a soil environment.

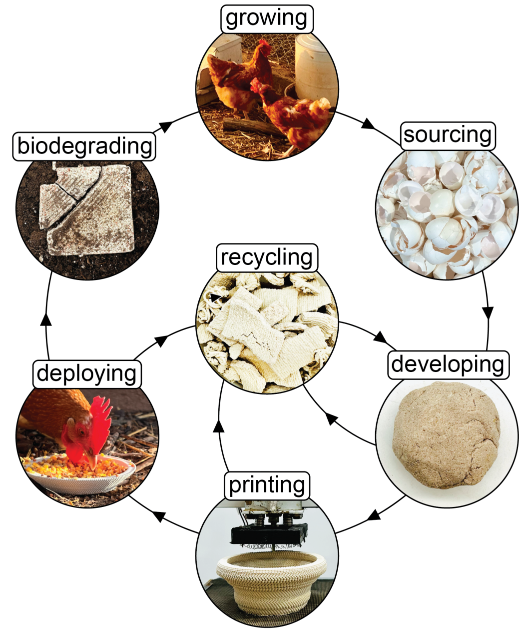

Figure 6. A circular design process for the eggshell biomaterial.

The SCOBY Breastplate showcases how biomaterials and electronics can be seamlessly integrated to create an aesthetic, interactive, and sustainable wearable. It not only exemplifies how traditional electronics such as LEDs and microcontrollers can be embedded within the scoby biofilm, but it also highlights how the scoby biofilm itself can be used to make a new biodegradable electronic component (e.g., the capacitive touch sensor). In contrast to typical electronic prototyping practices in HCI that trend toward a "move fast and break things" mentality, the SCOBY Breastplate demonstrates carefully *designing a computational system at the rate of another living organism*. The relative slowness of the scoby biofilm's growth encouraged a more thoughtful and intentional practice of embedding and assembling the electrical system. In this way, the SCOBY Breastplate evokes new possibilities for designing future sustainable ubiquitous computational devices and systems, where we grow electronic components that can then biodegrade in the environment.

B10-PR1NT

The B10-PR1NT project revolves around the development of an eggshell-based biomaterial for paste extrusion 3D printing (Bell et al. 2025). We intentionally designed the eggshell biomaterial to be circular, considering the entire life cycle—as shown in Figure 6—from sourcing eggshells in our local community through developing a recipe, 3D printing objects, deploying the objects back in our community, and then recycling the biomaterial for immediate reuse or biodegrading objects to return nutrients to the environment.

We began by collecting eggshells from our personal food waste, from friends and family who own chickens, and from local restaurant waste. To make a paste, we ground the eggshells into a fine powder that we combined with xanthan gum, methylcellulose, and water. We iterated through several different ratios of these four ingredients to identify a recipe that could successfully extrude through our printer and build up in stable layers. Figure 7 includes only four of 10+ iterations, where we kept the amount of eggshells and water the same, but varied the amount of xanthan gum and methylcellulose to produce a recipe that had the appropriate rheological material properties for printing resulting in functional and aesthetic objects. This required significant testing, taking into account how the machine applied force to the biomaterial for extrusion and how the rheological properties of the biomaterial responded to the applied force. Iteration 4 indicates our final recipe suited to our printer.

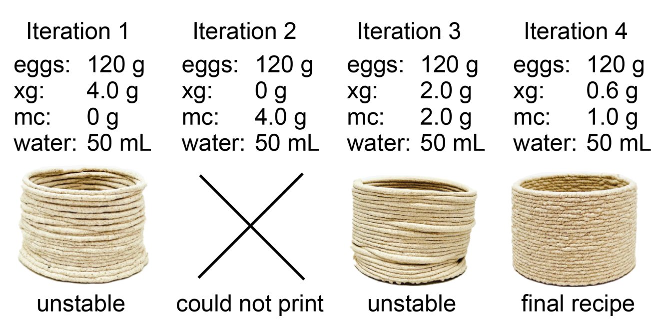

Figure 7. Several recipes made from eggshell powder (eggs), xanthan gum (xg), methylcellulose (mc), and water were tested to identify a biomaterial that could easily extrude through our printer and build up in stable layers.

To print objects from our eggshell biomaterial, we first modeled our desired object in Rhino and Grasshopper. We then used WeaveSlicer, an open-source software designed for 3D printing in paste-like materials (Friedman-Gerlicz et al. 2024), to slice our model and produce a .gcode file for the printer to read. We uploaded the .gcode to our printer—the Eazao Zero. The Eazao Zero is a low-cost, desktop printer

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that extrudes paste-like materials (instead of filament) in layers to build up objects. Annotated in Figure 8, the printer uses a motor to push the eggshell biomaterial through the print tube and flexible hose into the extruder head and nozzle. We also employed a custom heater that sits around the extruder nozzle, made from two fans and nichrome heating wire, to further improve layer stability during printing. We print objects onto a board that can be easily removed from the print bed. Once removed from the print bed, objects are dried fully before being deployed.

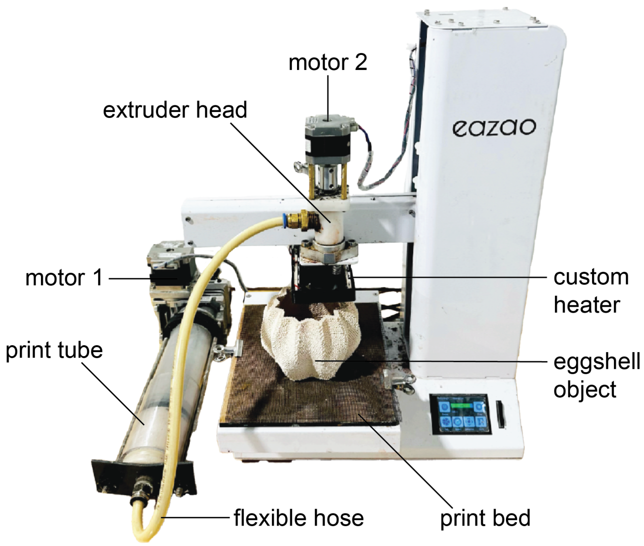

Figure 8. Paste extrusion 3D printer used for the eggshell biomaterial.

We specifically designed and deployed eggshell objects that encourage *circularity*. For example, we created a hen feeder, a shallow bowl printed from eggshells for hens to eat from. Hens often suffer from calcium deficiency caused by laying eggs. As eggshells are often used as a DIY calcium supplement for hens, the feeder is intended to be consumed. We envision the hens slowly consuming the feeder as they peck away at the rest of their food, as demonstrated in Figure 9. If not consumed by the hens, the feeder can assimilate into the surrounding environment through biodegradation—which we found takes about 25 days in soil. Biodegradation of the nutrient-rich feeder, in turn, promotes the growth of plants such as alfalfa, oats, or millet, which the hens can then eventually eat.

B10-PR1NT demonstrates how new biomaterials can be developed with both biological and digital processes in mind. It highlights how to intentionally design a circular biomaterial from a locally available waste stream (eggshells) and other bio-based ingredients to transform the eggshells into a paste. The selection of ingredients ensures that the biomaterial can ultimately biodegrade in the environment when disposed of. The eggshell biomaterial is also designed to be recycled—print waste or unwanted objects can be ground into a powder and rehydrated with water to be re-printed. In this way, the eggshell biomaterial presents *a circular digital workflow that drastically contrasts linear workflows designed for traditionally "technological" materials*, such as plastics, metals, and glass, which are not readily biodegradable nor easily recyclable. Beyond circularity, the properties of the eggshell biomaterial were designed to suit the behavior of the 3D printer, while also inspiring the design of new software and hardware tools for 3D printing. As such, the eggshell biomaterial exemplifies how digital fabrication can inform and support biomaterial development and how biomaterials can extend the creative capabilities of digital fabrication in return. This opens up several new opportunities for designing new digital fabrication workflows that align with the circularity and other unique properties of biomaterials.

Figure 9. Hen feeder 3D printed from the eggshell biomaterial. We envision the feeder being consumed by the hens as a calcium supplement or biodegrading in the environment.

μ*Me*

The μMe project explores using the personal microbiome to create living, dynamic interfaces (Bell, Ramsahoye, et al. 2023). The microbiome refers to a community of microorganisms—microscopic bacteria and yeast—that grow in any given environment. μMe specifically focuses on the human skin microbiome as a living biomaterial that can reveal information about the body and the body's interactions with the surrounding environment. We began this exploration by growing skin microbiome samples in petri dishes that contain an agar-based growth media. As shown in Figure 10, it takes approximately

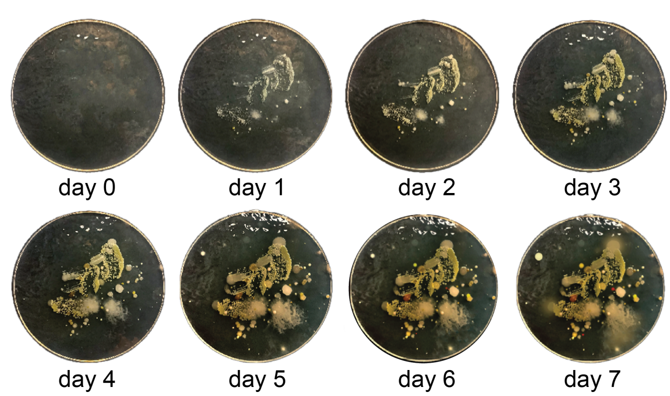

Figure 10. Microbiome sample growing on a petri dish. Over the course of a week, it becomes visible and expresses its full range of colors.

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a week of growth for the microorganisms present in a microbiome sample to become visible to the naked eye and express their full range of colors.

The types of microorganisms present in each microbiome sample are unique to each body (e.g., each person has a different microbiome), while also reflecting external environmental factors that the body engages with (e.g., temperatures, surfaces, and other people can impact the microbiome). To begin to visualize these microbial interactions, we transformed our microbiome samples into a palette of responsive, living dyes that reflect the body, as shown in Figure 11. To create this palette, we isolated specific colorful bacterial colonies from our microbiome samples and subcultured them in new petri dishes. We then collected the isolated bacteria in centrifuge tubes, added distilled water, and then used a vortex mixer to obtain a homogeneous bacterial dye. We used this method to obtain a variety of colors that reflect author 1's skin microbiome. We used this personal palette to dye textiles, thus enabling the creation of wearable interfaces that utilize the microbiome as a material that can sense and display information regarding our body and our bodily interactions in real-time. These living microbial interfaces contrast typical digital displays in that the rate of response and display is inherently *ephemeral* as the microbes continue to grow and die.

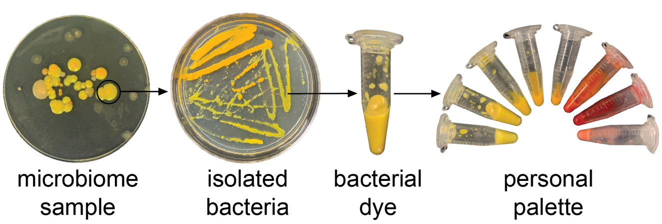

Figure 11. A palette of living bacterial dyes was derived from microbiome samples by isolating and subculturing bacterial colonies, harvesting the bacteria, and mixing the bacteria with water to reach a homogeneous dye.

One of our resulting μMe interfaces was a wearable pendant that changes color in response to temperature. The pendant consists of a layered system that sits against the body, schematically shown in Figure 12. The bottom layer is a textile-based heater made from felt and heating wire that is connected to a battery. On top of the heater sits a custom petri dish made for 6 circular pools that are filled with the agar-based growth media. On top of the agar, sits 6 corresponding circles of cotton textile. The textile was then coated in differing amounts of one of our bacterial dyes derived from *Serratia marcescens*, a bacteria present in our microbiome. The system is designed to provide the living bacteria with an appropriate environment (e.g., warmth and nutrients) to grow, and thus dynamically react to inputs like temperature change.

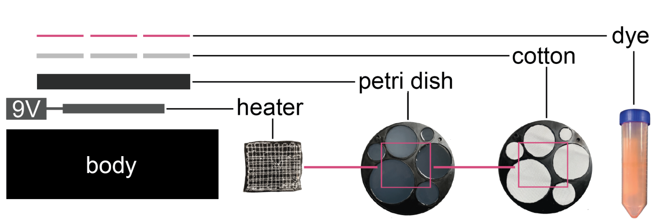

Figure 12. Schematic of the layered pendant system that consists of a textile heater situated beneath a custom petri dish filled with agar and topped with cotton dyed with bacteria.

After one day of growth at room temperature (22°C), the bacteria dyed the cotton a light pink color. On the second day, we turned on the textile heater positioned beneath the dish (30°C), resulting in the bacteria expressing a darker pink color in response to the raised temperature. Because the heater and custom petri dish are different sizes and geometries, only select areas of the pendant changed color, reflecting where the heater was placed underneath the petri dish. By controlling the heater, we showcase how the pendant can react in real-time to changes in temperature by leveraging the inherent responsiveness of the living *Serratia marcescens* dye.

Figure 13. The interactive pendant changes color from light pink to dark pink as the bacterial dye responds to the rising temperature of the heater.

μMe demonstrates the power of leveraging living microorganisms as natural "computers" to create dynamic interfaces. In contrast to a digital system—for example, LEDs that change color in response to temperature sensor data—the bacteria both senses temperature change and displays a different color in response. While current digital interfaces reveal information seemingly instantaneously, the μMe interface functions at the temporal rate of the microbiome, responding at a comparatively slow rate. The information revealed is also ephemeral, as the bacteria continue to grow, change, and die. As such, the functionality of μMe interfaces depends on the health of the growing microbiome samples, which must be kept alive. These *living dynamic interfaces call for new care-taking measures that traditional electronic systems do not require*, such as integrating nutrients (like the agar-based growth media) and maintaining appropriate environmental conditions (like temperature) within a system. By leveraging living organisms within dynamic interfaces, we see an opportunity for developing more caring and conscious modes of engaging with technology.

Thematic Findings for Growing Bio-HCI Further

We look across all three of our Bio-HCI design case studies to identify key thematic findings rooted in technical and conceptual moments of tension that arose in our practice of combining biodesign and HCI. We further reflect on how these tensions might present new opportunities for the combined area of Bio-HCI to grow in the future. While these self-reflective, generative findings are grounded in our personal, situated practices, we connect them to other external works in Bio-HCI

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to highlight broader patterns and trends that could potentially stretch across the emergent field of Bio-HCI.

Control and Agency

Within the field of HCI, as well as across broader design and engineering disciplines, there is an assumption that the human maker has ultimate control over the material to achieve a given design objective. For example, controlling fabric through cutting and sewing to make an item of clothing, or controlling code through programming to build a website.

When working with biomaterials, however, control is not entirely in the hands of the human maker. This is most noticeable in the SCOBY Breastplate and μMe projects, when working directly with living biomaterials that have agency through their *livingness* (Karana, Barati, and Giaccardi 2020). For example, we controlled the temperature of the interactive pendant system, but it was the bacterial dye itself that responded to this environmental change and expressed a different color. Similarly, while we controlled the size and shape of scoby to make the breastplate, the scoby naturally had uneven color and inconsistent thickness. These unpredictabilities inherently call attention to the agency of the non-human organism that is being utilized as a biomaterial. This recognition of non-human living organisms as active agents in the design process echoes other Bio-HCI works that build interfaces around dinoflagellates (Ofer, Bell, and Alistar 2021; Barati et al. 2021), flavobacteria (Groutars et al. 2022; Kim et al. 2023), and mold (Kim et al. 2018; Riggs, Nitsche, and Howell 2025). The shared sense of agency is evident in these cases, where unpredictable and uncontrollable living biomaterials necessitate direct correspondence with the human designer, thereby challenging the typically controlled and expected interactions with technology.

In contrast, the eggshell biomaterial was the relatively controllable, especially given that we intentionally developed a recipe that could be reliably 3D printed with our machine. However, this case introduces the agency of the machine (Devendorf and Ryokai 2015). While we controlled the material through the recipe and controlled the printer through code, unpredictable outcomes still upended our notion of control—printer hiccups, code blips, and biomaterial inconsistencies caused unexpected imperfections in our digitally fabricated objects that showcase the agency of both biological and digital factors in the design process. The entangled agencies of biomaterials and machines has been explored in other projects, such as Weaving Stories, where the creative capacity of wool and a digital jacquard loom are brought to the forefront of the design process as agentic constituents, demonstrating a more-than-human approach to design (Oogjes and Wakkary 2022). We note that the complex agentic relationships between humans, biomaterials, machines, and code in these contexts pose a unique set of challenges and questions that require further exploration.

By taking a biodesign approach that is rooted in a more-than-human design philosophy (Wakkary 2021) to these HCI projects, we recognize that the biomaterial itself, as well as our digital materials and tools, have a distinct agency in the design process. The resulting artifacts (e.g., the breastplate, the hen feeder, the pendant) reflect shared control and agency. Given current hierarchical perspectives of agency and control in design and engineering, we believe the emerging area of Bio-HCI is well-positioned to opens up new opportunities and possibilities for (re)negotiating the relationships between humans, materials, and tools in the design process by introducing biological systems.

Temporal Rates and Rhythms

One of the most notable impacts of biomaterials' agency on the design process is the unique temporalities that they carry. Unlike conventional materials that are often used and fabricated at a human-dictated pace, biomaterials require designers to work in alignment with their natural growth cycles (Lazaro Vasquez, Wang, and Vega 2020). For example, the SCOBY Breastplate was gradually designed at the pace of the scoby biofilm's growth. This biodesign approach, dictated by biological processes like the growth of an organism, challenges typical human-centered temporalities of design in HCI, which often prioritize speed and efficiency. By respecting the inherent temporal rates and rhythms of biomaterials, designers can shift their perspective, treating biomaterials like scoby as a valuable and precious resource that should be used with intentionality. This slow intentionality caused by biomaterials can then potentially extend to other materials used in the design process, like electronic components, which we carefully considered when integrating with the scoby biomaterial.

Temporalities also go beyond fabrication, influencing the rate of interaction. Digital user interfaces that are pervasive in our everyday lives, respond seemingly immediately, feeding into interactions that provide instant gratification. However, a living user interface like μMe disrupts this expectation by operating at the temporal rate of the live microorganisms. μMe instead changes color in response to a new temperature input relatively slowly (e.g., 24 hours). This interaction is shaped by the biological rates of the living biomaterials. Accordingly, μMe interfaces are always changing, and thus *ephemeral* (Döring, Sylvester, and Schmidt 2013). The ephemerality of living biomaterials has been of particular interest in other Bio-HCI works such as Mold Sounds, an artifact that produces sounds that change over time as mold grows and interacts with the embedded conductive components (Riggs, Nitsche, and Howell 2025), Mould Rush, a game that is played at the growth rate of various microorganisms (Kim et al. 2018), the Cyanochromic Interface, a monochromatic display that changes color gradually to indicate that cyanobacterial photosynthesis is occurring, thus bringing deeper awareness to the organisms livingness (Zhou et al. 2023). These works challenge the dominant paradigm of technological temporalities and encourages users to engage with interfaces that constantly evolve over time.

On top of the temporal rates dictated by growth, biomaterials also introduce new considerations regarding their temporality of use and decomposition. The eggshell biomaterial

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especially demonstrates this, as it was intentionally designed to biodegrade rapidly in the environment to return nutrients to the Earth. Beyond biodegradation (Song et al. 2022; Søndergaard and Campo Woytuk 2023), other modes of degradation such as dissolving (Lazaro Vasquez et al. 2023; Rivera, Bae, and Hudson 2023) and disassembling (Katherine W Song and Paulos 2021) highlight the temporality of degradation in Bio-HCI. The inherently transitory quality of biomaterials is essential for the development of fully circular systems that align with larger ecological cycles that distribute nutrients. By embracing the rhythmic temporality of decay and renewal, there is an opportunity to work towards a more ecologically conscious approach to materiality, one that acknowledges the impermanence of objects and the necessity of their reintegration into the ecosystem.

Circularity and Sustainability

Stemming from the natural temporalities of biomaterials, a biodesign approach requires thinking in terms of biological life cycles—acknowledging the interconnected processes of growth, decay, and renewal. This mindset contradicts the linear model of production and disposal often associated with modern design and engineering in capitalist contexts. The shift towards designing with biomaterials and biological processes presents an opportunity to develop technologies that align with natural life cycles, fostering circularity (Pollini and Jimenez 2022).

While the eggshell biomaterial used in B10-PR1NT clearly demonstrates this circularity through both its biodegradability and recyclability, the SCOBY Breastplate is a more complex case. The scoby biofilm rapidly biodegrades in soil, but the traditional electronic components embedded within it (e.g., the LEDs, microcontroller, and battery) cannot. The integration of such components within biomaterials demands further consideration (Lazaro Vasquez 2019; Genç, Launne, and Häkkilä 2022), not only in terms of how these electronic components can be harvested and reused to prolong the disposal of e-waste (J. Lu et al. 2023), but also how these electronic components can ultimately be redesigned so that they can biodegrade. This direction of biomaterial-based electronics highlights an exciting path for Bio-HCI, which has developed biodegradable heaters (Song et al. 2022), sensors (Koelle et al. 2022; Lazaro Vasquez et al. 2022), optical fiber (Guridi et al. 2023), electrical energy storage (Katherine Wei Song and Paulos 2023), wires (Lu and Lopes 2022), actuators (Luo et al. 2020; Yao et al. 2015), and breadboards Lazaro Vasquez 2019.

Beyond the circular methods of disposal that are encouraged in Bio-HCI prototyping processes (Lazaro Vasquez, Wang, and Vega 2020), factors such as energy consumption, the sourcing and shipment of materials and tools, and the social, economic, and cultural impacts of materials and technologies are critical for a more holistically sustainable design practice (Blevis 2007). For example, in the B10-PR1NT project, we recognize the power consumption of 3D printing as a digital fabrication method, but also understand that 3D printing with a sustainable paste-like biomaterial can significantly reduces power consumption (Faludi et al. 2019). We also consider the locality of sourcing eggshells from our immediate, socioculturally situated community, and print objects that can be deployed back in our community. These socio-culutural aspects of Bio-HCI are also explored in the context of community-oriented Bio-HCI projects such as Biomenstrual, which brought attention to the environmental sustainability of menstrual products by designing biodegradable alternatives (Søndergaard and Campo Woytuk 2023) and SeaFoam, which drew from the cultural significance of local seaweed ecologies when developing an algae-based bioplastic (Soares da Costa et al. 2025).

While circularity and sustainability is broadly embraced as a key motivator and contribution of many Bio-HCI works, we hope to see deeper and more nuanced understandings of sustainability in the future. By designing with material, technological, and biological life cycles in mind, as well as with an understanding of how these cycles impact broader communities and ecologies, we can move toward a more regenerative practice that aligns interactive technology innovation with the principles of environmental and social sustainability.

Ethics and Care

Rethinking our relationship with technology through the lens of care, for both the specific biomaterials used in design and the broader environment, offers a shift away from the conventional disposable mindset that dominates digital technologies, towards a more sustainable mindset. Part of this is due to the unique agencies and temporalities of biomaterials, which demand new relationships of understanding, respect, and care from users.

This is most clear with living biomaterials, which carry ethical requirements in terms of ensuring the health of the organism—for example, growing, feeding, and maintaining the health of the scoby biofilm culture or the microbiome samples. While this relationship between the human user and the living biomaterial may be viewed as mere maintenance, many prolonged interactions of ensuring health (e.g., feeding and facilitating ideal growing conditions) can develop deeper relationships of care. These interactions of care are noted in several Bio-HCI works. For example, LivingLoom (Zhu et al. 2025) and FloraWear (Nam et al. 2023) embed plants into wearables, encouraging a more embodied care-taking practice with the plants. Care is also emphasized when designing interactions with dinoflagellates, bioluminescent algae that require kinetic movement from humans (Ofer, Bell, and Alistar 2021) or machines (Breed, Putten, and Barati 2024) to oxygenate the water in non-natural environments (i.e., indoor lab or studio spaces), resulting in a reciprocal blue glow from the dinoflagellates.

When biomaterials are combined with interactive technologies, we envision this ethos of care extending to the entangled digital components. Many electronics are designed for obsolescence, with little consideration for their longevity or ethical implications. By treating these technologies as something to be cared for rather than discarded, we could cultivate more sustainable interactions, designing systems that encourage repair, adaptation, and long-term stewardship (Gegen-

https://doi.org/10.1017/S2977905725100036 Published online by Cambridge University Press

bauer and Huang 2012). This idea is taken a step further in the Slime Mold Smartwatch, where the digital functionality of the watch is dependent on the continued well-being of a living slime mold "wire", resulting in care being a daily interaction the user has with the slime mold and the digital system the slime mold is integrated within (Lu and Lopes 2022). Similarly, caring for the Plant-Driven Actuators is leveraged to develop relationships of care towards the robots the plants are embedded within (Hu et al. 2024).

By embracing care-based practices, we can foster more intimate, reciprocal relationships with both biological and digital technologies, creating systems that are not only functional, but also responsible. These relationships of care extend beyond ethical interactions, facilitating an attunement to the well-being of other living beings and a broader mindset of care for the broader environment.

Conclusion and Impact Statement

The rising growth of biodesign within HCI represents an evolving paradigm that challenges traditional assumptions about technology, fabrication, and interaction. By reflecting on three of our own Bio-HCI projects—SCOBY Breastplate, B10-PR1NT, and µMe–across the existing HCI spaces of ubiquitous computing, digital fabrication, and dynamic interfaces, we highlight the diverse ways in which biomaterials can be used to advance current interactive technologies in a sustainable manner. These case studies illustrate how biomaterials can serve as dynamic, responsive, and computational elements within interactive systems. Beyond these technical capabilities, however, each project highlights ways in which biomaterials also introduce new considerations such as agency, temporality, circularity, and care within our situated practice. While we primarily focus on our own projects, we find that they correspond to a greater shift happening in HCI towards material, ecological, and more-than-human sensibilities carried by the biodesign appraoch—sensibilities that encourage designers to work alongside biological processes and systems rather than impose rigid constraints upon them.

We hope the impact of this work extends beyond our specific case studies and the practice-specific findings we pulled from them, acting as stepping stones towards broader opportunities for HCI and biodesign to co-evolve and the potential formalization of Bio-HCI in the future. By embracing biomaterials within interactive technologies, we believe we can begin to foster new forms of interaction that are more ecologically and ethically mindful. Taking a biodesign approach to the field of HCI not only encourages innovation in sustainable computing, but also invites a deeper reconsideration of our relationship with technology in general—relationships in which we nurture, grow, and care for our interactive technologies as we would for living systems. As the field of Bio-HCI continues to develop, we envision a future where the biological and digital harmonize to create a new class of radically sustainable interactive technologies that benefit both humans and our surrounding environments.

Acknowledgements Special thanks to Derrek Chow, Hyelin Choi, Camila Friedman-Gerlicz, Lauren Urenda, Michelle Ramsahoye, Joshua Coffie, and Julia Tung for their valuable contributions during the investigation stages of the SCOBY Breastplate, µMe, and 3D Printing Eggshells projects.

Author Contribution Statement Fiona Bell: Conceptualization, Methodology, Investigation, Writing - Original Draft. Mirela Alistar: Supervision, Funding acquisition, Writing - Review & Editing. Leah Buechley: Supervision, Funding acquisition, Writing - Review & Editing.

Funding Statement This research was supported by the National Science Foundation (NSF) IIS Future of Work Grant at the Human-Technology Frontier Program (Award: 2026218).

Conflicts of Interest Statement The authors have no conflicts of interest to declare for this publication.

Ethics Statement The authors have no conflicts of interest to declare for this publication.

Data Availability Statement Data availability does not apply to this article.

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