

Biodesign for Interactive Textiles: Dissolution as a Design Strategy for Interaction and Sustainability

by

Eldy S. LÁZARO VÁSQUEZ

B.Arch., San Pedro University, Peru, 2012

M.F.A. in Design, University of California, Davis, USA, 2020

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado Boulder in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

Creative Technology and Design

ATLAS Institute

2025

Committee Members:

Laura Devendorf, Co-chair

Mirela Alistar, Co-chair

Michael Rivera

Katia Vega

Martyn Dade-Robertson

Eldy S. LÁZARO VÁSQUEZ (Ph.D. in Creative Technology and Design)

Biodesign for Interactive Textiles:

Dissolution as a Design Strategy for Interaction and Sustainability

Thesis co-advised by Laura Devendorf and Mirela Alistar

Abstract

This dissertation explores how sustainability can be approached not only as an environmental concern but as a design opportunity, particularly through the lens of material-led design. Working across biodesign, interactive textiles, and Sustainable Human-Computer Interaction (SHCI), this work investigates how biomaterials can expand the design space of interactivity by enabling new ways to think, make, and engage with materials, including dissolution as a strategy that foregrounds temporality, transformation, and material decay as part of interaction.

While interactive textiles have traditionally relied on electronics and conductive materials, this research asks what becomes possible when interactivity is shaped instead by the inherent properties of biomaterials. To explore these possibilities, the dissertation is structured around three projects: (1) *Biofoam*, a soft material responsive to pressure and water; (2) *Dissolving Wearables*, garments that shape-change through material decomposition; and (3) *Open-source Biofiber Spinning Machine* that fabricates customized biomaterial fibers for interactive textiles.

Together, these projects serve as proof-of-concept explorations, showing how biodesign for interactive textiles can support sustainable design practices that attend to material lifecycles, temporality in interaction design, and the values embedded in

the process of making. The dissertation also reflects on challenges in working with biomaterials, emphasizing the importance of tacit knowledge and access to fabrication tools. It argues that open-source biomaterials require not only technical openness but also cross-domain knowledge sharing and inclusivity of skill levels.

By attuning to biomaterials' agency and affordances, this dissertation contributes to sustainability discourse in HCI by moving beyond material substitution. It offers conceptual and practical approaches for engaging biomaterials as a dynamic participant that shapes interactions, values, and possibilities for future textile-based interfaces.

*Dedicated to my parents, Gloria and Esteban.
And to the growing community of biodesigners and sustainability
advocates striving for a more sustainable future.*

Acknowledgements

I'm deeply grateful to my PhD co-advisors at the University of Colorado Boulder, Laura Devendorf and Mirela Alistar, for supporting me throughout my doctoral journey and believing in my research ideas. Thank you for answering my endless questions and nurturing critical thinking in my work. Laura, I especially appreciate your guidance in writing and conceptual framing, and your mentorship in distilling complex ideas clearly. I have learned so much from observing how you balance focus in the lab, family time, and planning ahead, as well as from your encouragement, emotional intelligence, and constructive feedback. Mirela, I am thankful for your hands-on approach and for trusting in my design skills. Working with you at the ATLAS Institute has taught me how to navigate experimental challenges, collaborate effectively, and apply technical knowledge in practice. Both of you gave me the freedom to explore my own ideas, and your mentoring styles have shaped how I think about broader impacts, interdisciplinary research, and building supportive research communities.

I am also deeply thankful to the members of my Ph.D. dissertation committee, Michael Rivera, Katia Vega, and Martyn Dade-Robertson, for their guidance and feedback throughout my research. Michael, I have greatly enjoyed collaborating with you on the Biofiber Spinning Machine project and learning from your expertise in Technical HCI, machine development, and project management. Thank you for welcoming me into your Utility Research Lab, which gave me the opportunity to engage with lab activities, mentor students, collaborate on projects, and observe how a research lab evolves and develops practices. Katia, thank you for your ongoing encouragement and for always believing in my work. I am grateful for the informal conversations that provided clarity and thoughtful feedback as I developed my PhD proposal, as well as your valuable insights on my dissertation. Martyn, I am grateful for your insightful questions and advice from my thesis proposal through to my defense, which helped me

clarify definitions and communicate effectively across interdisciplinary communities. I also want to thank Elvin Karana, who was part of my Comprehensive Exam committee. Your thoughtful questions and critical feedback during the proposal phase helped me refine my methodology and provided a strong foundation for the research presented in this dissertation. Your work has been an inspiration for my material-led design approach.

I would like to thank my incredible research collaborators: Gabby, Etta, Lily, Deanna, Steven, Shanel, Mikhaila, Sasha, Hannah, Nikita, Katerina, Fiona, Latifa, Viola, Sepideh, Shira, Julia, Srujana, Mary Etta, Netta, Xin, Michael, Mirela, and Laura. Thank you for believing in the work we did together, for the collaborative spirit you brought to every project, and for the invaluable opportunity to learn from your unique perspectives and ways of knowing. Collaborating with each of you has been one of the most rewarding parts of my PhD journey.

My path toward doctoral research was shaped by the mentorship I received during my MFA in Design at the University of California, Davis. I'm sincerely grateful to Katia, Christina, and Beth for nurturing my curiosity, trusting my ideas, and guiding me through moments of uncertainty as I began to see research as a form of design inquiry. Katia, thank you for believing in me, for welcoming me into your research lab, and for introducing me to the Human-Computer Interaction community, where I first discovered how design and technology could intersect in very unexpected ways. Christina, I appreciate your mentorship while I developed my first Sustainable Design course as a PhD student and the thoughtful feedback you offered as I learned to translate research into teaching practice. Beth, thank you for the open conversations we had about navigating personal and professional paths and for generously sharing your time, resources, and network. The three of you encouraged me to pursue this PhD and have profoundly shaped my perspective on design, research, and the communities that make such work possible.

I also want to thank my husband and dearest love, Alex. Your patience and endless care over the years have brought so much ease to my days as a PhD student. I can't thank you enough for making me feel "at home" whenever we are together, whether near or far. I don't think I've ever had such a cheerleader and uplifting presence by my side. Your trust and belief in me, and in the things I do, make me feel so blessed and loved. I'm thankful for the countless hours you spent listening to me when I was excited, happy, sad, disappointed, frustrated, or confused as I navigated this rollercoaster called a PhD journey. You've learned to provide exactly the support I need through all my emotions, and that's invaluable. I love you dearly and deeply.

I'm deeply thankful to my parents, Gloria and Esteban. Without the sacrifices you made to give my brothers and me access to higher education, pursuing this degree would have been much harder. Your long hours of work and short hours of sleep created opportunities for me to be where I am today. You have all my respect, love, and admiration. Thank you for supporting my life and academic choices unconditionally, always with trust and encouragement. You are the perfect example of perseverance, fearlessness, and selflessness. From my earliest memories, you instilled in me a sense of self-worth, confidence, and love, and I thank God every day for having you as my parents.

To my brothers, James and Ronald, thank you for showing your excitement and pride in my achievements as your only sister far from home. Thank you for the laughs and good times we share when we're together, for treating me with love, care, and respect, and for supporting our parents when needed, which brings me peace of mind.

I would also like to thank my extended family in Chimbote, Peru, for their constant warmth and support from afar. A special thank you to Ronald's family: Alexandra, Alec, and Aitana, for the joy and laughter you bring whenever I visit. Your pride in my achievements and your loving encouragement mean a great deal to me. To my extended family in Germany: Chantal, Volker[†], Nadine, Werner[†], Celine, and their children,

Lukas, Klara, and Erik, thank you for how warmly you have welcomed me into your family since the first time Alex introduced me to you all. I am so grateful for how you've made me feel at home when Alex and I visit, and for the ways you've supported both of us as we navigate life together. I'm also very thankful for how genuinely happy you are for me as I complete this important chapter. I love you all.

I am also grateful to my friends from the ATLAS Institute across labs, including both those who have already graduated and those still in the program: Netta, Fiona, Latifa, Viola, Xin, Deanna, Casey, Etta, Sandra, Krithik, Rishi, Suibi, Torin, David, and Ruhan. I have had the chance to collaborate with some of you on research projects, practice talks and presentations, receive feedback, and share accountability during my PhD journey. I'm thankful to each of you for the role you played in shaping my experience at CU Boulder. I would also like to thank the wider ATLAS community: Sophie, Dave, Thiago, Mimi, Ronnie, Celeste, Ada, Anika, Emma, Sapna, Michelle, and Josh, for creating a welcoming and vibrant research environment. Thank you for the long discussions about supporting one another during PhD lunches and for the laughs in our social gatherings. I am also appreciative of the ATLAS faculty who offered guidance and inspiration throughout my time in the program, including Carson, whose insights were especially important in the gelatin biofibers research project. I continue to be inspired by the creativity and care embodied by the faculty across our research institute. I would also like to thank Ellen Do for her career advice, Mark Gross for his leadership of the ATLAS Institute, and all of the staff who supported me throughout my PhD time at CU Boulder, including Gabe and Bridget for administrative assistance, Ruscha for supporting PhD student wellbeing, and Stephanie, Hillary, Anne, Randi, and Sara for managing logistics, Human Resources, and accounting.

I am deeply grateful to the friends I made during my time at UC Davis: Tracy, Elyse, Jonathan, Jean, Elle, Margot, Kitan, Jesse, and Pablo. Growing these friendships over the course of my PhD has made my years of study so much more enjoyable. Thank you

for the great times we shared, for making me feel special and loved, and for being there during important life events, both big and small.

I'm also thankful to my friends back home in Peru, from architecture school and related networks: Anabel, German, Estuardo, Katty, Evelyn, and Roxana; my FabLab friends: Roxana, Delia, Benito, Vaneza, Tío Geny, Lefo, Carlos Enrique, Johnny, Naldi, Jorge Valerio, Tony, and Yeison; my Rotaract friends: Noelia, Mady, Nelly, and Felipe; and my life-advice friends: Gledy, Roxana, Carlos, Patty, and Huayruro. You all have made sure I feel welcomed and connected every time I visit, no matter the distance.

Finally, I would like to acknowledge the communities, research groups, and initiatives that have inspired my work across biodesign, interactive textiles, and sustainable HCI. Within academia, I am grateful to the Unstable Design Lab, the Living Matter Lab, and the Utility Research Lab, all at CU Boulder; Morphing Matter Lab at UC Berkeley; the Material Design for Transition group at Politecnico di Milano; CHEM Arts at Aalto University; the Material Experience Lab at TU Delft; the Hub for Biotechnology in the Built Environment (HBBE) at Northumbria University; the Healthy Materials Library; the Biodesign Challenge; and the Experimental Textiles Talk Series. Their scholarship and creative practices have broadened my perspective on systemic thinking, interdisciplinary collaboration, experimental approaches, creative technology, hands-on prototyping, and material interaction, helping me situate my research in a wider context of biodesign, sustainability, and design practice.

Outside academia, I am inspired by Fabricademy and the broader FabLab community, Materiom, the Open Source Hardware Association (OSHWA), Sketching in Hardware, and the global network of makers and designers advancing biomaterials and open-source practices. I am also grateful for the many people exploring biomaterials across disciplines and for the designers, engineers, and makers contributing to community-driven innovations. The work of researchers and practitioners at the intersection of design, HCI, material science, biodesign, textiles, and e-textiles has

further shaped my thinking. Events such as Biofabricate, the Biodesign Symposium, and Electronic Textile Camp, which push the boundaries of craft, design, and technology, have provided perspectives that continue to inform and inspire my research, teaching, and material-led design approach.

Preface

Elements of the research comprising this thesis have been published in several peer-reviewed conference proceedings as referenced. As this dissertation is presented in manuscript format, there is some unavoidable repetition in the introductory and methodological material across the component manuscripts. Efforts have been made to reduce redundancy where possible and reference relevant descriptions in other sections rather than reproducing content verbatim. Some duplication remains necessary to ensure that each manuscript constitutes a self-contained body of work.

I have been careful not to reproduce any copyrighted material. The content of this Ph.D. thesis was authored solely by myself. I used AI-assisted tools, such as ChatGPT [150], only to improve readability and clarity through grammar correction, wording refinement, and stylistic adjustments. All intellectual contributions, ideas, analyses, interpretations, and original writing are entirely my own.

Contents

1	Introduction	1
1.1	Research Context and Situated Collaborative Practice	5
1.2	Research Questions and Objectives	6
1.3	Research Approach and Methods	7
1.3.1	Research through Design (RtD)	9
1.3.2	Material-Driven Design (MDD)	11
1.3.3	Technical HCI	13
1.4	Summary of Main Contributions	15
1.4.1	New biomaterial formulations and low-tech fabrication techniques	16
1.4.2	Interactive objects as proof of concept in interactive textile applications, highlighting dissolution as a design strategy	17
1.4.3	Open-source Desktop Biofiber Spinning Machine to fabricate fibers from biomaterials	18
1.5	Overview of Dissertation	19
2	Related Work	23
2.1	Introduction	24
2.2	Material-Led Design and Material Agency in HCI	25
2.2.1	Experiential Dimensions of Materials	25
2.2.2	Material Agency and Design Processes	26
2.2.3	Interactivity Beyond Electronics	27

2.3	Biodesign and Temporal Materiality	29
2.3.1	Biodesign Approaches and Applications	29
2.3.2	Temporal Dimensions and Material Values	32
2.3.3	Dissolution as an Interactive Property	33
2.4	Sustainability Frameworks and Life Cycle Thinking	34
2.4.1	Evolution of Sustainable HCI	34
2.4.2	Life Cycle Thinking in HCI	36
2.4.3	Sustainability Challenges in Interactive Textiles	38
2.5	Democratizing Access to Biomaterial Innovation	40
2.5.1	Challenges in Biomaterial Fabrication	41
2.5.2	Approaches to Accessible Fabrication	42
2.5.3	Knowledge Translation and Community Engagement	43
3	Biofoam as Interactive Material	45
3.1	Introduction	46
3.2	Process: Material Experimentation	48
3.2.1	Base recipe preparation	48
3.2.2	Adding color	51
3.2.3	Adding conductivity	53
3.2.4	Increasing water permeability	55
3.2.5	Recooking	56
3.3	Characterizing Biofoam	56
3.3.1	Density, squishiness and spring back time	57
3.3.2	Thickness	58
3.3.3	Durability	58
3.3.4	Compression and recovery time	59
3.3.5	Assessing the Biofoam Life Cycle	60

3.4	Exploring Fabrication Techniques	63
3.5	Exploring HCI Applications	65
3.5.1	Chameleon Accessories	66
3.5.2	Sensing	69
3.6	Discussion	72
3.6.1	Design considerations of biofoam in HCI	72
3.6.2	Dissolving as a design opportunity	74
3.6.3	Supporting sensory experiences in users	75
3.7	Conclusion	76
4	Designing Dissolving Wearables	77
4.1	Introduction	78
4.2	Dissolving Wearables	79
4.2.1	Fabricating Biofoam Strings and Yarns	79
4.2.2	Use Cases	83
4.3	Discussion and Limitations	87
4.4	Conclusion	89
5	Open-Source Biofibers Machine	90
5.1	Introduction	91
5.2	A Desktop Biofibers Spinning Machine	92
5.2.1	Machine Design	94
5.2.2	Biofiber Spinning Walkthrough	96
5.3	Fiber Wet Spinning Considerations	100
5.4	Material Exploration Using the Biofibers Spinning Machine	107
5.4.1	Adjusting Spinning Solutions for Tuning Color and Strength	108
5.4.2	Fine-Tuning Biofiber Diameter through Collector Speed	111
5.4.3	Adjusting Coagulation Bath for Enhanced Flexibility and Elasticity	112

5.4.4	Implementing Treatment Processes for Color and Coatings	113
5.5	Example Applications	114
5.5.1	Dissolving for Recycling and Reharvesting	115
5.5.2	Dissolving and Swelling to Trigger Interaction	116
5.5.3	"Etching" Flexible Circuits	118
5.5.4	Summary	119
5.6	Discussion	120
5.6.1	Lessons Learned From Working Across Disciplines	120
5.6.2	The Aesthetics of Biofibers	122
5.6.3	Towards Sustainable Smart Textile Design	123
5.7	Limitations and Future Work	124
5.8	Conclusion	126
6	Discussion, Implications, and	
	Future Work	128
6.1	The Role of Biomaterials in Expanding Interactive Textiles	129
6.1.1	Biodesign Practices Grounded in Material-led Exploration	131
6.1.2	Attuning to Biomaterial Affordances in Interactive Textile Design .	133
6.1.3	Dissolution as a Design Strategy for Interaction and Sustainability	137
6.2	Providing Additional Narratives in Material Agency and Material Design	141
6.2.1	Engaging and Reflecting on Material Agency and Material-led De- sign	142
6.2.2	Negotiating the Tension Between Ephemerality and Utility in Material- led Design	145
6.2.3	Rethinking Sustainability in HCI Through Material Engagement .	147
6.3	Beyond Access: Knowledge, Tools, and Systems in Biomaterials Devel- opment	150

6.3.1	Enabling Fiber-Level Customization for Biomaterial–Textile Integration	150
6.3.2	Addressing Knowledge Barriers in Open-Source Biomaterials	152
6.3.3	Conditions Shaping Access in Open-source Biomaterials	154
6.3.4	Biomaterial–Textile Integration as a Catalyst for Systemic Thinking	155
6.4	Limitations	157
6.5	Future Work	158
6.5.1	Expanding Biomaterial Affordances Exploration	158
6.5.2	Building Infrastructures for Shared and Situated Knowledge	159
6.5.3	Toward Material Ecologies of Biodesign	161
7	Conclusion	163
	Bibliography	169

List of Figures

3.1	Mapping of biofoam attributes (X axis) when specific ingredients (Y axis) are added to the base recipe	49
3.2	Natural additives used to give the biofoam color: a. turmeric powder, b. walnut hull powder, c. pine tree sap, and d. gelatin natural color	51
3.3	Attempts to incorporate stainless steel fibers into biofoam: a. whisking, b. felting, c. folding	53
3.4	a. Pouring the biofoam mixture into a mold, b. Biofoam drying at room temperature, c. Demolded biofoam after 24 hours	54
3.5	Non-conductive biofoam spring back time.	58
3.6	Conductive biofoam spring back time.	58
3.7	Compression testing performance of conductive biofoams.	59
3.8	Biofoam life cycle	61
3.9	Biofoam dissolving process to enable conductive fibers reharvesting with a magnet.	62

3.10	Various biofoam samples created with different fabrication techniques and modifications of the base recipe: a. The base recipe in various thicknesses; b. Colored with turmeric; c. In segments on top of a rubbery biofoam base; d. Hardened and improved water permeability with pine tree sap; e. Colored with walnut powder and cast in custom molds; f. Embroidered with conductive thread; g. Conductive biofoam with stainless steel fibers; h. Extruded into a mesh.	63
3.11	a. Demolding the biofoam sample. b. Biofoam acts like memory foam, c. Biofoam applied in layers.	64
3.12	Biofoam: a. extruded, b. couched, c. pleated.	65
3.13	Thermo- and UV-sensitive biofoam necklace.	66
3.14	Thermo- and UV-sensitive biofoam bracelet.	67
3.15	Thermo- and UV-sensitive facemask and other accessories	67
3.16	Dissolvable biofoam as a stabilizer for embroidery or patchwork: a.interface for embroidery, b. during embroidery, c. patchwork	69
3.17	Four force-sensitive resistors tested using a force meter to obtain force vs. resistance plots.	70
3.18	A digital force gauge is used to apply and measure a normal force to the sensors. A microcontroller is used to read the resistance between the two electrodes.	70
3.19	Force (N) vs. resistance (R) plots for each FSR sensor.	71
4.1	Different consistencies of biofoam meringue: a. foamy, b. soft peak, c. stiff peak, d. broken, e. cross-section of biofoam yarns at different consistencies.	81
4.2	Biofoam yarns of 2 mm diameter in various pastel colors.	82

4.3	"Seasonal Footwear" (crochet) loses the straps after dissolving, becoming more open to suit warmer seasons.	83
4.4	a. Crocheted bralette chest before dissolving. b. After dissolving the light blue biofoam, patches become hollow and expose the underlying layer in the bralette, which is orange.	85
4.5	"Unfolding Lace Top" swatch to test the unfolding stitch structure. a. before, and b. after dissolving the swatch in cold water.	86
4.6	"Unfolding Lace Top" (knit) unfolds into a new design upon dissolving.	86
5.1	An overview of Desktop Biofibers Spinning: (a) gelatin biofibers spinning process using our machine; (b) a spool with green gelatin biofibers, (c) gelatin biofibers woven into cloth.	92
5.2	Dry-jet wet spinning schematic of our machine. The multipurpose baths can be used for any post-production process such as coagulation, finishing, drying, or treatment.	93
5.3	Comparison between DIENES LabLine, a lab-scale wet spinning machine, and the Desktop Biofibers Spinning Machine. In both setups, an off-the-shelf (*)water bath can be used.	93
5.4	Biofiber spinning machine walkthrough to make yellow and flexible gelatin biofibers.	97
5.5	Fiber wet spinning overview; we marked the steps supported by our machine and what we further explored in this paper.	101
5.6	Spinning solution formula and preparation process to obtain spinning solution	102

5.7	Gelatin fibers spinning challenges: a. DIENES LabLine machine for fiber spinning, b. Spinneret modification consists of a heating wire around the area of the spinneret that goes inside the coagulation bath, wrapped with insulating foam to maintain the desired temperate at spinning time, and c. Coagulation bath setup adapted to handle two different liquid concentrations in the same bath. One comes from the dropping funnel and the other one is already filled in the bath. The pump sucks the liquid coming from the dropping funnel to maintain the desired concentration levels in the bath. This enabled the spinning of gelatin fibers using a nozzle of 120 holes with 100-micron resolution.	104
5.8	Step-by-step of the draw-down process: blob formation, grab the blob, draw down the blob, and attach the drawn fiber tangentially to the collector.	105
5.9	Material exploration space for fiber wet spinning, the various material formulations that we tested (a-e), which includes the material formula used in the fiber spinning walkthrough (c).	108
5.10	(a-d) Gelatin biofibers change color from light to dark green as the genipin content in its material formula increases in the following increments: (a) no genipin; (b) 0.12 wt% genipin; (c) 0.18 wt% genipin; (d) 0.24 wt% genipin.	109
5.11	Tensile strength of gelatin biofibers—pure and crosslinked—in both dry and wet conditions. Gelatin biofibers crosslinked with genipin were stronger in comparison to pure gelatin biofibers when dry and wet.	110
5.12	Material Explorations: (a) adjusting fiber diameter (thickness) via collector speed, (b) natural color of biofibers, (c) and yellow biofibers resulting from post-production food-coloring dye.	111
5.13	Biofibers coated with a photochromic paste.	114
5.14	Woven textile sensors with biofibers integrated into the cloth: a. moisture sensor and b. pressure sensor.	115

5.15	Dissolving biofibers in our woven moisture sensor enables reharvesting of conductive and non-conductive threads at the end of the sensor's life. This process also applies to our pressure sensor. The biofibers' change in color is due to the result of genipin (a crosslinker) in its composition. . . .	116
5.16	Dissolving as interaction: (a) woven butterfly that (b) unravels its wings when wet with water.	117
5.17	Swelling as an interaction: a woven structure that experiences color- and shape-change due to swelling when exposed to isopropanol.	117
5.18	Example application for etching flexible woven circuits. The etching process consists of (a) a 2-layer cloth woven with the biofibers on the weft of the top layer and stainless steel on the back; (b) drops of hot water are selectively added to the top layer of the cloth; (c) areas in contact with the water are dissolved; (d) the bottom conductive layer becomes exposed conductive after dissolving; (e) testing the dissolved and exposed area shows that it is conductive; (f) testing undissolved areas are not conductive.	118
5.19	Qualities and forms of biofibers to further explore: (a) luster, (b) variable texture, and (c) non-woven structures.	123
6.1	Synthesis of observed biomaterial affordances across my dissertation research projects. Illustration by Kunstin Xu.	134

List of Tables

3.1	Adapted DIY open source biofoam recipe from [55] with description of the purpose and characteristics of the core ingredients	48
3.2	Set-up experiment that compares water permeability between biofoam recipes in terms of evaporation time	55
6.1	Summary of Contributions of Core Chapters	130

List of Abbreviations

HCI	H uman C omputer I nteraction
SHCI	S ustainable H uman C omputer I nteraction
SID	S ustainable I nteraction D esign
MDD	M aterial D riven D esign
LCT	L ife C ycle T hinking
LCA	L ife C ycle A nalysis
LCIA	L ife C ycle I mpact A ssessment

Glossary

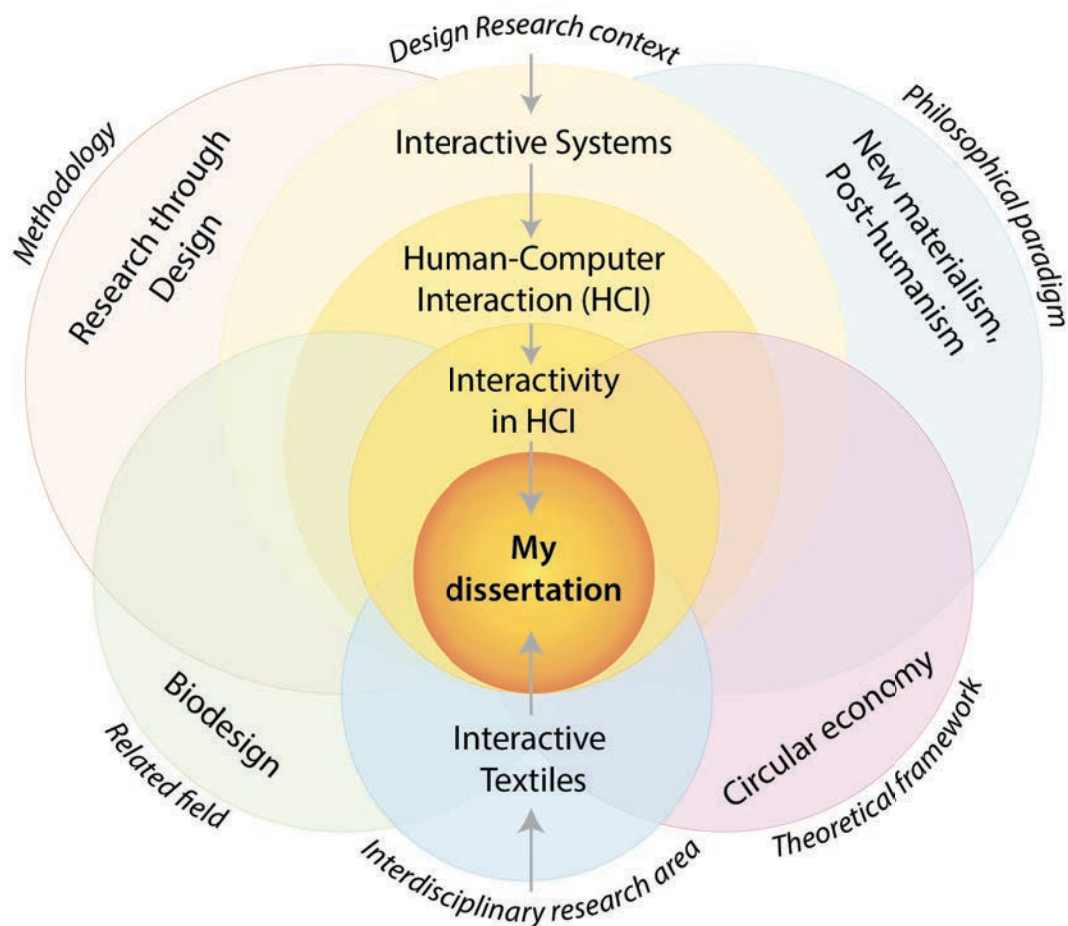
Biodesign	An interdisciplinary approach that brings together biology, design, and technology to rethink how materials, processes, and lifecycles shape design practice. In this dissertation, biodesign is framed as a practice-oriented and value-driven approach that engages biological materials or biomaterials to explore material transformation, temporality, and lifecycle thinking as part of sustainability.
Biological materials	Materials that originate from biological organisms or processes, including those produced by living systems such as mycelium or bacterial cellulose, and extracted biopolymers derived from animals (e.g., gelatin), plants (e.g., cellulose), or algae (e.g., agar-agar). These are considered in their raw or minimally processed form.
Biomaterials	Materials that have been actively processed or transformed from biological materials through a biofabrication process. The process to make a biomaterial often involves combining biological materials with other ingredients (e.g., plasticizers) to modify properties such as strength, elasticity, or flexibility. Biomaterials I made and presented in this dissertation include gelatin-based foams and fibers.
Biofabrication	A fabrication process specifically tailored to transform biological materials into biomaterials . In this dissertation, such processes include engineered systems, such as the Biofibers Spinning Machine (Chapter 5), and craft-based approaches including molding, extruding, or layering (Chapters 3-4). Hybrid combinations of these methods are also used, all aimed at shaping the biomaterial into a desired form or to tune its material properties.

Biomaterial agency	In this dissertation, it refers to the ways a biomaterial asserts itself within the design and biofabrication process by resisting, pushing back, or redirecting my actions in ways that shape the outcome. I discovered and negotiated this agency during biomaterial formulation, mixing, drying, or integration into artifacts or interactive textiles .
Biomaterial affordance	Refers to the design possibilities enabled by a biomaterial's inherent qualities. In this dissertation, affordances such as compressibility, translucency, solubility, or tactile response became apparent to me through sustained engagement with the biomaterial. Recognizing these affordances allowed me to leverage them to shape or enhance aspects of my design outcomes.
Interactive Textiles	Are designed textile structures that exhibit dynamic responses often through embedded electronic or mechanical components, and sometimes through material behaviors. In this dissertation, I explored responses enabled by the inherent properties and affordances of the biomaterials themselves.

Chapter 1

Introduction

Exploring Biodesign for Interactive Textiles: Research Questions, Methods, and Contributions



Sustainability is a necessary condition for responsible design. My research explores how sustainability can be approached not only as an environmental concern but as a design opportunity, particularly through the lens of material-led design. Working across biodesign, interactive textiles, and Sustainable Human-Computer Interaction (SHCI)¹, I have been drawn to design practices where materials are not merely chosen for their functional or aesthetic qualities but for how they shape interactions and values throughout their lifecycle.

I position my dissertation within a larger context, where my design practice is influenced by theory, methodologies, and philosophical paradigms; all of which shaped the research I present in this dissertation.

In my own design practice, sustainability becomes tangible through hands-on decision making, where material sourcing, making, use, and end-of-life are not separate phases but interrelated parts of a continuous design process. This orientation has led me to ask how materials themselves, especially biomaterials, can help reframe sustainability within the design of interactive systems.

Interactive systems, ranging from smartwatches that enable us to monitor our health to smart textiles that enhance clothing with sensing functionalities, have become integral to daily life. They shape how we work, communicate, and interact with our environments. However, the increasing prevalence of these technologies raises critical sustainability challenges, particularly in terms of resource consumption, waste generation, and the environmental costs associated with their production and disposal. As these systems rely on complex materials, energy-intensive manufacturing processes, and often have short life

¹Sustainable HCI refers to approaches in HCI that engage with multiple dimensions of sustainability by rethinking how technologies are designed, used, and embedded in everyday life.

cycles, their ecological footprint is significant. In response to these concerns, HCI research has increasingly focused on the broader implications of these systems, including their social, economic, and environmental consequences. Among these, environmental sustainability has gained particular attention from designers in HCI, who are uniquely positioned to intervene by making informed choices about materials, production methods, user interactions, and end-of-life strategies [168, 212, 217].

Early work in Sustainable HCI aimed to reduce the ecological footprint of technology by promoting user-centered strategies such as recycling, energy conservation, and repair [49, 132]. While these approaches helped bring environmental concerns into HCI discourse, they have since been critiqued as reductionist for focusing on individual behavior and limiting sustainability to user-level interventions [26, 113]. In response to these limitations, a growing but still limited body of work has begun to advocate for more systemic understandings of sustainability [87, 137]. Recent contributions in SHCI emphasize the need to engage with sustainability at infrastructural and sociotechnical levels, addressing the broader contexts in which technologies are designed, deployed, and maintained [25, 176].

While broadening the understanding of sustainability beyond individual behavior and product-level interventions is crucial, **my dissertation argues that sustainability can also be engaged as a design value, embedded in the ways designers work with and through materials.** In this context, material-led design, specifically, emphasizes the role of materials in shaping design ideas, processes and outcomes [75, 134, 156]. They broaden design possibilities by highlighting material agency [45, 112, 186] and embodied experience [5, 51], challenging conventional views of materials as passive substrates and instead

positions them as active forces that influence how ideas form, evolve, and are realized [76, 175, 190]. **To further frame my engagement with biomaterials and sustainability, I bring material-led design into conversation with biodesign.**

Biodesign [140], as defined in the glossary, is an interdisciplinary approach that integrates biology, design, and technology to innovate sustainable practices, often by leveraging biological materials, systems and processes, to reduce the environmental impact of design outcomes. While material-led design foregrounds the agency of materials in shaping design processes through their inherent properties, biodesign situates these materials within broader ecological and lifecycle considerations. In this dissertation, biodesign serves as a practice-oriented and value-driven context through which I engage sustainability, shaping how I work with biomaterials in relation to sourcing, making, transformation, and end-of-life. This framing supports my work with biomaterials, specifically gelatin, a by-product of the meat industry, as a central biomaterial across all projects in the dissertation. Gelatin's tunability, its responsiveness in texture, shape, strength, and form, enabled me to explore its potential in soft sensors, wearables, and interactive textiles. These qualities, along with its transformation over time, allowed me to engage temporality through dissolution and decay as interactive dimensions within my design practice. My dissertation contributions include biomaterial formulations, low-tech fabrication techniques, proof-of-concept prototypes, and an open-source machine for biofiber production. These design outcomes reflect a commitment to sustainability as a design value, equally integral to my work as aesthetics and functionality within interactive textile design.

In this way, **my work brings together material-led design as a methodological foundation, biomaterials as a medium, and biodesign as a**

practice-oriented and value-driven context that supports sustainability through lifecycle thinking. Situated within the broader context of Sustainable HCI, this dissertation offers an alternative way of engaging with sustainability, one that treats it as a design value embedded through hands-on practice, material entanglement, and attention to temporality [6, 173]. My dissertation aims to expand the design space of interactive textiles by showing how biomaterials, through their transformation and responsiveness, can shape how we think about interaction itself. Through three research projects, I explore how working with and through biomaterials opens up new possibilities for how sustainability can actively shape the design, materiality, and interaction of textiles, transforming both process and outcome. I offer detailed accounts and reflections for each research project in the chapters that follow.

1.1 Research Context and Situated Collaborative Practice

Throughout my Ph.D., I conducted research across two main labs: the Unstable Design Lab ², where I engaged with interactive textiles and design research, and the Living Matter Lab ³, where I focused on working with biological materials through a biodesign practice. One of the projects, the Biofibers Spinning Machine, also involved collaboration with Michael Rivera, then a postdoctoral researcher in the Unstable Design Lab, and now director of the Utility Research Lab ⁴, which focuses on sustainable design in digital fabrication.

These lab environments provided a rich context for working at the intersection of biodesign, sustainable fabrication, and interactive textiles. While

²Unstable Design Lab at CU Boulder: <https://unstable.design/>

³Living Matter Lab at CU Boulder: <https://www.colorado.edu/atlas/living-matter-lab>

⁴Utility Research Lab at CU Boulder: <https://utilityresearchlab.org/>

I led each of the three research projects presented in this dissertation, they were all developed in collaboration with other researchers and designers. These collaborators brought perspectives grounded in textile craft, interactive design, HCI, engineering, and living systems, contributing to both the technical execution and conceptual direction of the work. The hands-on nature of the projects created a space where disciplinary knowledge could intersect and inform the research in situated ways.

In each collaboration, I introduced a biodesign approach that emphasized sustainability through lifecycle thinking and material-led design. These values were carried differently across projects depending on the materials involved, the chosen fabrication techniques, and the envisioned applications. While collaborators brought their own disciplinary priorities and motivations, the collaborative structure supported a design process shaped by diverse ways of knowing through making [68].

1.2 Research Questions and Objectives

My interest in exploring how sustainability can be engaged through material-driven design processes led me to focus on gelatin as a base ingredient for biomaterials. The inherent properties and temporal qualities of the resulting gelatin-based biomaterials offered a way to investigate new interactions in the design of interactive textiles. This interest led to three research questions (RQs) with their respective research objectives (ROs) that guided the work presented in this dissertation.

RQ1: What unique opportunities for sustainable design emerge when engaging with gelatin in designing interactive systems?

- **RO1:** To investigate how biodesign practices grounded in material exploration influence the design of interactive systems.
- **RO2:** To examine how working with gelatin-based biomaterials shapes form, interaction, and functionality in these systems.

RQ2: How might the specific properties of gelatin-based biomaterials inform the aesthetics and functionality of interactive textiles?

- **RO3:** To explore how the agency of gelatin-based biomaterials, expressed through their properties and behaviors, influences the aesthetic and functional design of interactive textiles.
- **RO4:** To explore how material responsiveness, such as shape change and dissolution, mediates interaction and user experience.

RQ3: How might we enable biomaterial–textile integration?

- **RO5:** To explore biomaterial–textile integration through the design and development of a fabrication tool.
- **RO6:** To examine how an open-source tool can support access, experimentation, and knowledge-sharing around integrating biomaterials into interactive textiles.

1.3 Research Approach and Methods

The overarching methodology that guides this dissertation blends *Research through Design* (RtD) [68, 229] and *Material-Driven Design* (MDD) [103], informed

by a biodesign orientation. RtD frames the design process as a mode of inquiry, where knowledge is generated through iterative making, reflection, and the development of artifacts. MDD, in turn, offers a structured method for engaging with materials, particularly in the early stages of design. While RtD provided the broader methodological framing for the dissertation, MDD guided how I engaged with biomaterials like gelatin, attuning to their properties and affordances [73] through hands-on experimentation.

Biodesign provided an important orientation to this methodological blend. Rather than functioning as a standalone method, biodesign shaped the values, context, and questions that emerged through practice. It grounded my engagement with sustainability as situated, process-based, and materially entangled, shaping how I approached lifecycle considerations, ecological implications, and biomaterials affordances in design.

RtD enabled the generation of design knowledge through the production of prototypes as *proofs of concept*, which serve as the central contributions of this dissertation. MDD provided the methodological grounding for material exploration, supporting a process of discovery through which interaction possibilities, form factors, and fabrication methods were developed. Together, RtD and MDD provided me with flexibility in navigating different phases of the research, from material exploration to artifact development and envisioned applications. These methods foreground materials and making as central to design, which aligns with my approach that incorporates hands-on tinkering and autobiographical reflection.

In Chapter 5, I employed additional methods from Technical HCI [88] to evaluate the Open-source Biofibers Spinning Machine. While distinct in its epistemological stance, these validation methods were necessary to assess

the technical performance and reproducibility of the tool. The knowledge generated through the machine's validation complements the material-led design contributions discussed in this dissertation.

1.3.1 Research through Design (RtD)

RtD is a methodology where knowledge is generated through the act of making, with insights emerging from both the design process and the resulting artifacts. Gaver, a leading figure in design research, describes these artifacts as “provocative,” in that they embody ideas and invite reflection rather than solve predefined problems. This framing aligns with my own approach: the artifacts I developed using gelatin in various form factors were not driven by user needs but by material exploration. They highlighted the unique properties of gelatin biomaterials and, in turn, served as provocations, opening up discussions about the broader implications of biomaterials in the design of interactive textiles. In my own practice, I use iterative hands-on experimentation with biomaterials like gelatin and prototypes such as dissolvable garments as occasions to reflect on how biodesign might be incorporated into HCI, particularly within interactive textiles. Like Gaver, I believe that “the practice of making is a route to discovery, and that the synthetic nature of the design allows for richer and more situated understandings than those produced through more analytic means” [68]. This sustained engagement with various biomaterial formulations and fabrication techniques allowed me to become attuned to the agency of biomaterials. In the case of gelatin, I observed how it responded to manipulation by trapping air, changing color, and shifting in density with heat exposure. These behaviors shaped my design decisions during material exploration. Rather than relying solely on mechanical property analysis of

biomaterials, my approach draws on embodied practice [5, 51], using hands-on engagement to inform how I worked with each biomaterial in subsequent design iterations.

Aligned with Gaver's framing, several HCI researchers have used RtD to *proliferate* new design directions [67]. This kind of proliferation often takes the form of multiple prototypes that speculate, provoke, or reframe design or interaction possibilities. For example, Jiang et al.'s work on interactive smart textiles for emotion regulation [98], explored physiological feedback through textile-based prototypes, opening new design possibilities in embodied interaction through proof-of-concept prototypes. The Bio-Digital Calendar [16] proliferates new ways of seeing what interaction can be between humans and nonhumans by attuning to the growth of bacterial cellulose, particularly through the lenses of care, slowness, and more-than-human design.

My thesis aligns with this approach of proliferation, using prototypes (material samples and artifacts) as proofs of concept to provoke reflection on new design possibilities for interactive textiles informed by a biodesign approach. Through an iterative engagement with gelatin, I explored unique opportunities this biomaterial can offer to interactive textiles. The Biofibers Spinning Machine, for instance, was developed in response to a material-driven challenge: how to produce gelatin biofibers in sufficient quantity for biomaterial-textile exploration. While the machine technical validation is discussed in a later section, it belongs within this space of design proliferation. This tool enabled new forms of making with biomaterials at the fiber level and expanded the design space of interactive textiles by supporting the development of prototypes where gelatin fibers were integrated into textile-based interactive outcomes. In doing so, the machine sparked questions about how such

biomaterials could be worked with, who might use such tools, what they might learn, and how they would engage with the process. This hands-on engagement with gelatin also opened up reflection on alternative forms of interaction and the potential of biomaterials in interactive textile design.

1.3.2 Material-Driven Design (MDD)

Material-Driven Design (MDD) [103] is a method that best suits hands-on exploration of materials following a structured process. This method helps to foreground how material properties shape both the design process and its outcomes. HCI researchers and material-led designers have used this method to explore how materials, whether traditional (e.g., wood, metal) or emerging (e.g., biomaterials), mediate interaction between humans, technology, non-humans (e.g., living organisms), or a combination of them [12, 30, 102]. Oftentimes, this method also highlights the experiential and expressive qualities of such materials [71, 105].

For me, MDD offered vocabulary and structure to support my iterative engagement with gelatin. It guided how I explored and attuned to the affordances of gelatin, allowing me to foreground material responsiveness and transformation as active considerations in the design of interactive textiles. Through this process, I observed how properties such as water solubility, heat sensitivity, and decay could shape both how a material could be worked with and what kinds of interaction it might afford. These material qualities became especially relevant in the context of interactive textiles, where I engaged with temporality and transformation as part of my design process, and I attuned to material agency to inform my design decisions through continued, hands-on engagement.

Although MDD typically moves through four stages: Understanding the Material, Material Experimentation, Material Demonstrator, and Product Application [103]—my practice engaged with the first three. In some cases, such as the gelatin-biofoam prototypes in Chapter 3, I initially explored gelatin's potential as a drop-in material solution. However, working through the MDD stages enabled me to attune more deeply to the material's behavior and affordances, which shaped not only the applications in that project but also carried forward into subsequent explorations. In Chapter 4, for example, the approach to the *Dissolving Wearables* project was directly informed by material insights and design questions that emerged from the earlier project.

While my early concerns with sustainability focused on biodegradability and material breakdown, it was through the broader context of biodesign and material engagement supported by MDD that I began to explore the design possibilities of biomaterials for interactive systems beyond drop-in solutions. This shift led me to consider how biomaterials could shape new interactions, ones that foreground disassembly, reveal, and transient existence, where the impermanence and eventual disintegration of materials become intentional design features, as explored in Chapter 4. These directions expanded my design focus from end-of-life considerations to questions about how interactive textiles might be designed to accommodate material transformation and temporal change. Some of these explorations, however, required new tools and methods to enable these new forms of fabrication, and to explore how biomaterials might shape their design. This line of inquiry led to the development of the Biofibers Spinning Machine in Chapter 5, which required technical validation to assess their functionality and reproducibility.

1.3.3 Technical HCI

Technical HCI [88] is an area of HCI that focuses on incorporating functional technologies into interactive systems, bridging design with technical validation. It employs structured evaluation methods such as *Threshold*, *Ceiling*, and *Breadth of Coverage*, which assess the simplicity of and artifact's initial use (low threshold), the complexity or sophistication a tool can support (high ceiling), and the diversity of potential applications or outputs (breadth of coverage). These methods offer a framework to evaluate how a system performs across different levels of expertise and use cases, from basic operation to expert customization and broader applicability.

In the development of the Biofibers Spinning Machine in Chapter 5, these methods provided a valuable lens to guide and reflect on the design decisions. While the machine originated from a material-led design approach, the integration of validation methods stemmed from the interdisciplinary nature of the project. One of my collaborators, Michael Rivera, brought expertise in developing interactive systems and technical tools within HCI, and helped shape the machine's design toward goals of reproducibility, modularity, and broader technical contribution.

Threshold relates to how accessible the machine is for first-time users. In that regard, the machine required users to interface with it via G-code⁵, which demands a moderate to high level of technical expertise—particularly familiarity with serial command interfaces. Although we provided thorough documentation in the published paper [120], including a detailed six-step spinning walkthrough, operating the machine still required experience with

⁵**G-code** is a programming language used to control automated machine tools and 3D printers, directing their movements and actions.

digital fabrication. Informal testing by a colleague familiar with 3D printing, showed the system to be operable with guidance, but no formal usability studies were conducted at this stage. Since then, this collaborative project has evolved to further reduce the threshold. All the updates are documented in the project's GitHub repository [163] and Discord channel [183], which aims to support global replication of the machine.

Ceiling addresses the extent to which the machine supports advanced or expert-level use. The Biofibers Spinning Machine was developed as a fully open-source system, enabling experienced users to modify both hardware and firmware components. During fiber spinning exploration, I customized process variables—such as extrusion speed, collector rotation speed and direction, nozzle temperature, and number of baths—to control fiber characteristics. These adjustments allowed for fine-tuning of diameter, color integration, and material formulation changes. While the machine was primarily evaluated using gelatin-based spinning solutions, its architecture supports experimentation with other biomaterials currently being explored by collaborators. For HCI designers, this capacity to modify system-level parameters within a prototyping setting represents a high ceiling, offering access to material sophistication typically constrained to specialized lab-scale equipment [117].

Breadth of Coverage considers the diversity of outputs and applications the system can support. In our experiments, the machine successfully enabled the production of gelatin-based fibers with a range of visual and structural qualities, including differences in thickness, color, and mechanical properties through crosslinking. While the technical adjustments that made this possible reflect the system's ceiling, the resulting outputs demonstrate its capacity to support varied design goals. The machine was primarily used to prototype interactive

textiles within HCI research, but its flexibility also points toward potential applications in areas such as 3D printing, speculative material futures, and biomaterial experimentation. Its open-source release and modular architecture further expand the range of users and domains it may support.

While epistemologically distinct from my material-led inquiry, the methods from Technical HCI offered a structured way to validate the machine as a proof of concept. These methods helped collaborators and I articulate the tool's technical performance and its reproducibility, key qualities for enabling other designers and HCI researchers to build upon our work. In this way, Technical HCI methods complemented the practice-led contributions of this dissertation by situating the Biofibers Spinning Machine as both a functional prototype and a scaffold for broader material experimentation.

1.4 Summary of Main Contributions

This dissertation contributes to ongoing Sustainable HCI discourse by showing how biomaterials, when engaged through biodesign and material-led design, can foreground sustainability as a design value of interactive textiles. By focusing specifically on gelatin and examining its affordances and agency of the resulting biomaterials, my dissertation makes three contributions: (1) develops new biomaterial formulations and low-tech fabrication techniques, (2) uses these biomaterials to create interactive objects as proof of concept in interactive textile applications, and (3) develops an open-source machine to fabricate fibers from these biomaterials. These contributions demonstrate how incorporating sustainability as a design value informs and orients the design

process itself—shaping decisions, practices, and ways of working through the properties and behaviors of biomaterials.

1.4.1 New biomaterial formulations and low-tech fabrication techniques

The first contribution centers on the development of new biomaterial formulations using readily available ingredients and low-tech fabrication techniques. My collaborators and I used a material-driven design approach, which is rooted in sensory and embodied practice, to explore the tunable properties of gelatin and to create customizable biofoams and biofibers. Each material lent itself to different fabrication methods, design outcomes, and potential uses within interactive textile applications. By attending to each step during this iterative material exploration process, we were able to notice how specific ingredients and fabrication techniques could leverage particular characteristics of gelatin to create biofoams and biofibers with variable properties such as density, color, strength, water-resistance, or elasticity. For instance, we developed biofoams that change color when exposed to low heat or UV light, can be reshaped after significant heat exposure, and may dissolve when put in contact with hot water. Details about specific material formulations are included in every publication in Chapters 3, 4, and 5. Our approach not only offers a new way to work with biomaterials in the context of interactive textiles, but also emphasizes accessibility. By publishing recipes, we aim to democratize the process, making it available to designers and HCI researchers without access to specialized equipment. The combination of innovative formulations and low-tech fabrication methods opens up new avenues for designing interactive textiles through a biodesign lens. In line with Gaver’s notion of proliferation in design research, these biomaterial formulations and fabrication techniques

are not presented as final solutions. Instead, they function as provocations that invite others to experiment, adapt, and imagine new directions for interactive textiles informed by biodesign practice.

1.4.2 Interactive objects as proof of concept in interactive textile applications, highlighting dissolution as a design strategy

The second contribution relates to the interactive objects my collaborators and I created using gelatin-based biofoams and biofibers; these objects serve as proof of concept for integrating biomaterials into interactive textile applications. Among the prototypes we created are pressure sensors, interactive fashion accessories, garments, and woven textiles. With biofoam, we developed dissolvable pressure sensors by embedding conductive fibers into the material to measure changes in resistance when the biofoam experienced pressure. By attending to the life cycle of biofoam, we observed that the conductive fibers used in the sensor could be recovered by dissolving the surrounding biofoam at the sensor's end of life. These conductive fibers can then be recycled, reused, or spun back into new conductive threads. The interactive fashion accessories we developed included color-changing earrings, rings, a collar, and a mask; they combined biofoam with thermochromic and photochromic pigments. These accessories could be remelted and reformed, showcasing circular design principles. Similarly, using gelatin-based fibers, we created woven pressure and moisture sensors that incorporated these biofibers and conductive threads in layered structures. Using weaving as a fabrication technique allowed us to intentionally dissolve specific areas containing biofibers in order to customize or disassemble the woven sensors. This process enabled the recovery of the conductive materials and addressed a common challenge

in interactive textiles: separating electronic components from textile substrates. Through these explorations, dissolution emerged not only as a material behavior but as a deliberate design strategy—one that activates interaction through transformation while simultaneously supporting sustainability by enabling disassembly, repair, and material recovery. In this way, dissolution becomes both an interaction modality and a circular design approach, positioning material impermanence as a resource rather than a limitation in the design of interactive textiles.

The development of these interactive objects followed a hands-on prototyping and an iterative process, common when engaging in Research through Design (RtD), where prototypes are recognized as research contributions. Rather than offering finalized solutions, the proof-of-concept objects developed in this dissertation demonstrate how biomaterials can provoke new directions in the design of interactive textiles, foregrounding material transformation, impermanence, and end-of-life considerations. These explorations also offer an account of how biodesign can inform material-led approaches in return in the design space of interactive textiles, highlighting dissolution as one instance of such reciprocal material–design negotiation.

1.4.3 Open-source Desktop Biofiber Spinning Machine to fabricate fibers from biomaterials

The third contribution of this dissertation is the development of an Open-source Desktop Biofiber Spinning Machine that addresses a gap in prototyping fibers from biomaterials. Developed in response to practical challenges encountered while working with gelatin, the machine enables the fabrication and customization of biofibers through a desktop-scale dry-jet wet spinning

process. While it was primarily used with gelatin, the machine is designed to support a range of biomaterial formulations. It offers precise control over key parameters such as extrusion speed, nozzle temperature, and collector rotation, allowing for systematic material experimentation at the fiber level. This contribution extends material-led design by providing a tool that supports hands-on exploration at the fiber level. It was developed through iterative prototyping and tested using Technical HCI evaluation methods to assess the machine's functionality and adaptability.

1.5 Overview of Dissertation

Chapter 2, *Related Work*, lays the conceptual foundation for this dissertation by examining the intersections of material-led design, biodesign, and Sustainable HCI. The chapter begins by exploring material-led design approaches within HCI, highlighting how material agency can actively shape design processes and interactions. It then turns to biodesign, which in this dissertation serves as a value-driven and practice-oriented lens for engaging with biomaterials. Finally, the chapter connects these material practices to sustainability approaches in HCI, particularly those related to interactive textiles. Taken together, these perspectives reveal opportunities to engage sustainability as a design value, foregrounding material agency, embracing transformation and lifecycle, and expanding design possibilities through practice. This review identifies key gaps at the intersection of these domains and positions the dissertation's contributions within them.

Chapter 3, *Biofoam as Interactive Material*, introduces biofoam, a biodegradable gelatin-based biomaterial, as a soft and tunable material for

use in interactive textiles and HCI. Grounded in Material-Driven Design (MDD) and Research through Design (RtD), and informed by a biodesign orientation, the chapter explores how biofoam's inherent properties, such as dissolvability and density variation, can be customized through natural additives and fabrication techniques. These biofoam qualities supported the development of a series of proof-of-concept artifacts, including wearable accessories and dissolvable pressure sensors that integrate interactive attributes. The chapter contributes to the dissertation's broader argument of design proliferation by positioning biofoam as a tunable and transient medium that provokes new directions for interaction design. It also demonstrates how engaging with biomaterials through hands-on methods can foreground sustainability as a design value. This chapter lays the foundation for the following chapters on dissolvable wearables and fiber-based biofabrication.

Chapter 4, *Designing Dissolving Wearables*, marks a shift toward interactive textiles by formulating, fabricating, and integrating biofoam yarns in the design of wearable garments. This chapter explores how interactivity can emerge not through embedded electronics but through the biomaterial's inherent capability to dissolve. Using textile techniques such as crocheting, knitting, and weaving, it presents three proof-of-concept garments that demonstrate "design to dissolve" as an intentional, time-based interaction strategy. Rather than treating material dissolution as failure, the garments embrace material temporality and decomposition as meaningful parts of their design. In doing so, the chapter advances a biodesign-oriented approach to sustainability, one that combines biomaterials in craft practices to explore ephemeral interaction design. These garments extend the biomaterial investigations from Chapter 3 into the domain of wearable technologies, highlighting how ephemeral,

transformation-based interactions can expand the design space of interactive textiles.

Chapter 5, *Open-Source Biofibers Machine*, presents the development of a low-cost, open-source desktop machine designed to spin customizable fibers from biomaterials like gelatin. Developed in response to a material-led practical challenge encountered in earlier projects, the chapter situates fiber-level biofabrication as a critical yet underexplored stage for innovation in sustainable interactive textiles. The chapter details the machine's design, material formulations, and example applications, emphasizing its potential to support sustainable, customizable fiber production and advance biofabrication practices in HCI. Beyond being a technical contribution to HCI, the machine also operates as a proof-of-concept that opens new design possibilities by enabling hands-on experimentation with biomaterials at the fiber level—expanding the prototyping capabilities of researchers and designers working in interactive textiles. This contribution extends the dissertation's focus on biodesign and material-led inquiry by offering a tool that fosters broader engagement with biomaterials and supports hands-on practice, expanding how sustainability can be foregrounded as a design value through making.

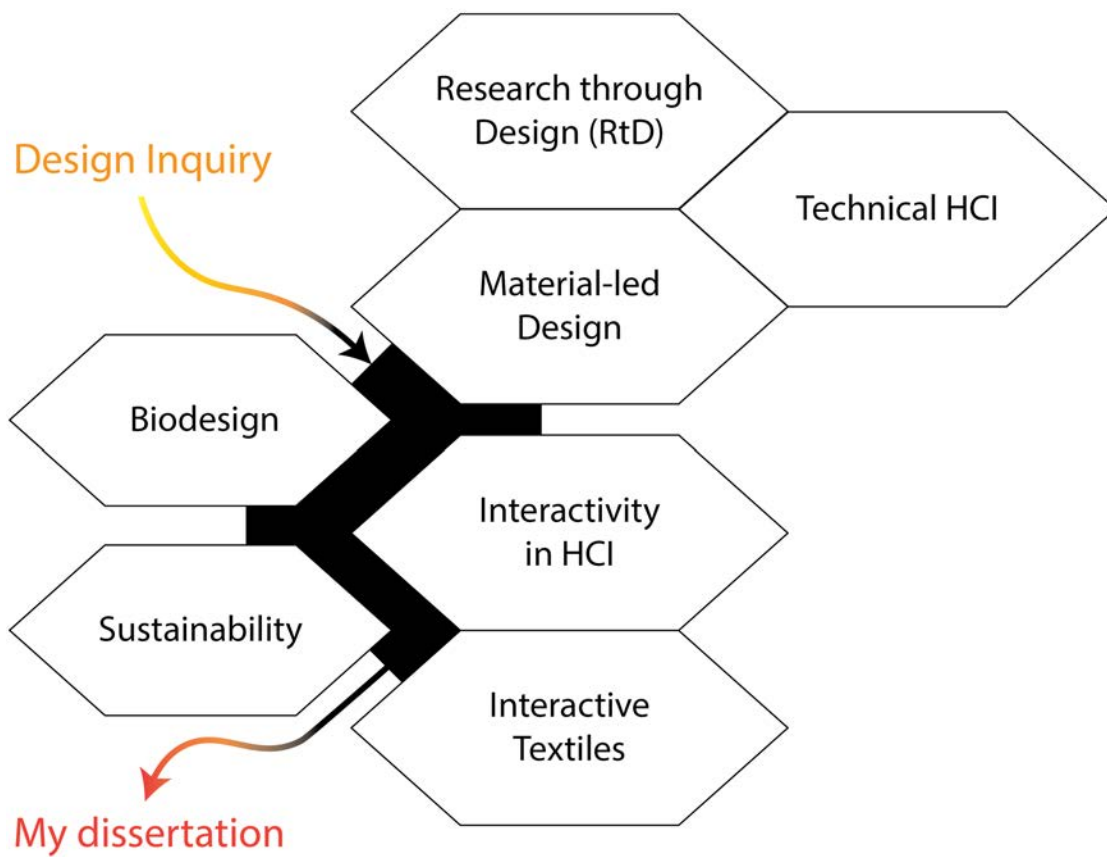
Chapter 6, *Discussion, Implications, and Future Work*, discusses the implications of the research findings within HCI and biodesign. It reflects on how material-led design reframes sustainability as ongoing engagement with materials and practices, and situates dissolution as a design strategy for exploring transformation, temporality, and sustainability in interaction design. The chapter also considers systemic and infrastructural factors such as access, open-source tools, and tacit knowledge that influence biomaterial-textile integration, and concludes with key limitations and future directions.

Chapter 7, *Conclusion*, consolidates the dissertation's main contributions and restates its central argument: that sustainability can be approached through material-led design practices in interactive textiles. It highlights the role of dissolution as a design strategy that connects interaction and sustainability, and outlines how the findings can inform future work in HCI, biodesign, and material-led design research.

Chapter 2

Related Work

Approaches to Material-Led Design, Biodesign, and Sustainability in HCI and Interactive Textiles



2.1 Introduction

This chapter surveys research across material-led design, biodesign, sustainable HCI, and interactive textiles to provide the conceptual foundation for this dissertation. Rather than treating these areas as separate domains, the chapter highlights how they intersect and complement one another in supporting new orientations toward sustainability in interaction design. These perspectives collectively inform how sustainability can be foregrounded as a design value through hands-on engagement with materials, and how temporal, sensory, and lifecycle qualities of materials can shape aesthetics, interactivity, and technical approaches.

The literature reviewed in this chapter supports and informs the three research questions guiding this dissertation: **RQ1**, how engaging with biomaterials through material-led design can foreground sustainability as a design value in interactive systems; **RQ2**, how material properties shape both aesthetic and functional dimensions of interactive textiles; and **RQ3**, how tools and fabrication approaches might support biomaterial–textile integration.

The chapter is organized to reflect these concerns, moving from discussions of material agency and experiential engagement with materials, to temporality and transformation in biodesign, to sustainability perspectives in HCI, and finally to challenges of accessibility, fabrication, and knowledge sharing. Together, these literatures frame how this dissertation positions sustainability not as a fixed outcome, but as something embedded and expressed through materials, processes, and practices.

2.2 Material-Led Design and Material Agency in HCI

Material-led design has gained increasing attention within HCI for the ways it foregrounds materials as central to the design process—not only in terms of physical properties, but also in how they shape ideas, methods, and possibilities for interaction. Instead of viewing materials solely as functional components, this body of work foregrounds their sensory, temporal, and experiential roles within the design process. In parallel, discussions of material agency invite a shift in how design processes are framed, attending to how materials can guide, resist, or transform design trajectories. These perspectives support a relational approach to interactivity that extends beyond electronics, recognizing that interaction can also emerge from the transformations, temporalities, and affordances of the materials themselves.

2.2.1 Experiential Dimensions of Materials

In recent years, the HCI community has witnessed growing recognition of materials as active participants in design processes rather than passive elements being manipulated. This perspective is captured in design frameworks like Giaccardi and Karana's "materials experience" [71], which extends understandings of materiality beyond physical properties to include sensory engagement and meaning-making. The materials experience framework is particularly relevant here, as it defines "materiality" as a *material experience*, emphasizing the perceptual and affective qualities of materials. This approach invites designers to attend to the affordances of materials, opening space for new modes of engagement and exploration through multisensory interaction. The framework highlights how materials influence both design processes and

user experiences. Each new material brings distinct qualities that can prompt designers to envision alternative configurations of function and aesthetics. For instance, in this dissertation, biofoam (see Chapter 3) could be seen as a biodegradable replacement for conventional foams in packaging or footwear. However, framing it merely as a substitute risks narrowing the designer's perspective and missing the broader experiential and interactional affordances the material can offer. The materials experience framework thus supports this dissertation's exploration of biomaterials, not as ecological substitutes for conventional materials, but as generative agents that expand interaction possibilities—sensory, functional, and aesthetic—while also introducing new ways to think about sustainability through material engagement.

2.2.2 Material Agency and Design Processes

The notion of material agency—that materials can resist, shape, or redirect a designer's intent—has gained traction in HCI as an important lens for understanding how design unfolds [75, 112, 186]. This aligns with design researcher Devendorf and interaction design researchers Fernaeus and Sundström in the framing of materials “speaking back” to designers [45, 47, 58]. A related idea appears in anthropologist Ingold's distinction between the *hylomorphic model*, where form is imposed, and the *morphogenetic approach*, where form emerges through direct engagement with material processes [91–93]

This dissertation builds on two key strands of related work. First, the growing integration of biomaterials in HCI as part of sustainable and biodesign-oriented practices [15, 73, 122, 199]. Second, research that positions materials not as passive substrates but as active participants in shaping the design process and imaginary [154, 213]. Parisi's concept of material tinkering

[156] exemplifies this shift, offering a method of iterative experimentation through which materials' unexpected behaviors can redirect design directions. This approach is particularly relevant to biomaterials, which often resist standard fabrication techniques and require designers to attune to their shifting properties [21, 27, 114, 170].

In Chapter 3 and Chapter 4, this perspective allows us to move beyond “instrumenting” the material with electronic components, and instead explore how its inherent qualities—such as squeezability, water solubility, or fragility—can be *tuned* to invite interaction. The making of the material (e.g., boiling, mixing) and its end-of-life dissolution also become integral parts of interaction and meaning-making. Framing material engagement in this way directly intersects with sustainability concerns. Rather than treating environmental constraints as external limitations, a material-led approach enables designers to reframe material limitations as opportunities—inviting sustainable, creative, and situated forms of interaction.

2.2.3 Interactivity Beyond Electronics

Interactive textiles in HCI have traditionally relied on electronic components such as sensors, actuators, and conductive threads [192]. However, a growing body of research is expanding this view by exploring how the inherent properties of materials themselves (such as durability, fragility, deformability, and responsiveness) can become central to interaction design [76, 175, 213]. This shift opens up new design possibilities for interactivity that move beyond embedded electronics, an area I further explored in this dissertation.

Aligned with this broader perspective, designers in the HCI community have grown in interest in working with living organisms and biomaterials

for designing interactive systems [73]. For example, the DIYBio [50] and wearable technology communities have incorporated biological materials into the creation of wearables [218], displays [3], growable devices [85, 199], and embodied interactions [146, 147]. While these developments mark a growing interest toward designing with biological and biomaterials, a five-year CHI review (2015–2020) [195] shows that petroleum-based materials continued to dominate prototyping practices during that period. Since then, however, interest in biomaterials and their potential for enabling alternative interaction modes has gained further traction. In response to the challenges of material sustainability, and often under the banner of Sustainable Interaction Design (SID) [24, 49], HCI researchers have explored alternative material approaches using biomaterials to design and prototype interactive materials or systems. These explorations include agar- or cellulose-based bioplastics [15, 114, 178], gelatin- or agar-based foams [122, 177], SCOBY leather [19, 143], bio-based clays and pastes [17, 18, 21, 168], mycelium skin [199], and mycelium composites [70, 74, 107, 198, 211]. These prior explorations demonstrate interest of the HCI community in biomaterials, not only for their sustainability credentials but also their interactive and temporal qualities, showing how biomaterials' unique properties can expand interactive possibilities.

In parallel, some HCI researchers have turned to living organisms as interactive components [62]. Microbes [109, 218], bioluminescent algae [147], and other organisms have been used as sensors, actuators, and aesthetic agents [3, 77, 108], repositioning the site of interaction within the material's own lifelike behavior. Together, these approaches expand dominant notions of interactivity in HCI by foregrounding material responsiveness as a meaningful and legitimate site of design—beyond electronics and toward more integrated,

process-oriented forms of interaction.

2.3 Biodesign and Temporal Materiality

While the previous section explored how material-led design in HCI foregrounds material agency and interactivity beyond electronics, this section turns to biodesign as a practice-oriented space where designers engage with biological systems, biomaterials, and ecological processes. Biodesign spans diverse domains, from synthetic biology to bio-art, and encompasses a range of perspectives on how living and bio-based matter can be integrated or inform design processes. Within this broader landscape, my work engages biodesign as a value-driven orientation that invites consideration of temporality, transformation, and lifecycle thinking. By bringing biodesign into dialogue with material-led design, I explore how this intersection can open new directions for interaction design, particularly within the context of interactive textiles.

2.3.1 Biodesign Approaches and Applications

Biodesign has emerged as a fast-growing interdisciplinary field over the past ten years [203]. This interdisciplinary practice brings together living materials, biological processes, and design methods to explore alternative technological and ecological futures [78]. It encompasses a wide range of domains [73], from speculative art and architecture [9, 86] to functional applications that incorporate biotechnology and synthetic biology [38]. Across these areas, biodesign invites collaboration not only between disciplines, but also between designers and organisms—where biological materials are engaged not merely as raw materials, but as co-creators in the design process [7,

8, 16]. In my own practice, I see biodesign as creating opportunities to reimagine sustainability—particularly through its engagements with life cycles, transformation, and multispecies relationships—even if these are not always positioned as central concerns within the broader field.

Working at the intersection of HCI, biodesign, and interactive textiles, I recognize a growing body of work that intersects with biodesign practices and orientations. This includes frameworks such as Biological HCI [157], biodigital hybrids [62, 109], material-driven explorations [30, 103], and living interfaces [138], which enable HCI researchers to explore how biological systems participate in interaction design—whether as sensors, materials, or co-creators. For instance, some work has focused on integrating engineered organisms into interactive systems, drawing from synthetic biology and living computation [108]. Others have emphasized growing materials—such as mycelium, microbial cellulose, or SCOBY—as a way to challenge conventional design processes and values [30, 110]. Within this landscape, some researchers have begun to explore how such practices might inform the design of wearable systems. For example, recent discussions around *Wearable Bio-HCI* [228] highlight efforts to integrate bodily fluids [31, 153, 200, 219, 225], living matter [19, 198, 227], or biomaterials into wearable interfaces [15, 82, 114]. These projects often address functional concerns such as sensing or responsiveness, but also open up new terrain for thinking about care [20, 128, 146, 222], cohabitation, material temporality [7, 123], and nonhuman relations in design [86, 222, 223]. Even when not explicitly labeled as biodesign, I find these works collectively reflecting a shift toward rethinking the relationships between biological processes, material affordances, and Human-Computer/Technology Interaction.

In parallel, within interactive textile research, there has also been a growing interest in incorporating biomaterials and biological processes as a way to move beyond electronics-driven interaction. A recent literature review on biomaterials in e-textiles [81] notes that while interest is growing, many projects still use biomaterials mainly as surface treatments or passive substrates [19, 143, 225]. Yet textiles are multi-layered systems, where interaction can be embedded at various levels—from structural fibers to material transformation. Although there is limited exploration of biomaterials at the fiber or yarn level integrated into the very construction of textiles, a few projects have begun to investigate this possibility by producing alginate monofilaments with conductive and pH sensing capabilities [106, 224], carboxymethyl cellulose (CMC) bioplastic with optical sensing capabilities [81, 83], or my own work with gelatin-biofoam yarns [123] in Chapter 4, and gelatin biofibers [120] in Chapter 5, both with thermal and photo-sensitive capabilities.

While these examples demonstrate promising directions, my research team and I found that prototyping at the fiber level, without specialized equipment, remained challenging due to a lack of accessible and customizable fabrication tools. Aligned with our interest in addressing this gap (see Chapter 5), a couple of open-source wet-spinning machines have recently emerged. These machines target alginate-based extrusion through setups designed for workshop facilitation, rapid assembly, or reproducible experimentation [131, 226]. I see these initiatives not as isolated efforts, but further supported by contributions from designers and biomaterial innovators in distributed networks such as Fabricademy [57], or the Biodesign Challenge [14], to mention a few. The ethos of these communities for shared knowledge on biomaterial recipes has supported experimentation across contexts. All together, these initiatives reflect

the growing interest in tools that support hands-on, adaptable, and sustainable prototyping workflows.

My research builds on this line of inquiry by asking how biomaterials, particularly in a fiber form, can shape new possibilities for interactive textiles. The Biofibers Spinning Machine introduced in Chapter 5 not only allows for fine fiber customization but also enables the exploration of biomaterials' affordances and their unique temporal qualities.

2.3.2 Temporal Dimensions and Material Values

Working with biomaterials introduces distinctive temporal qualities that shape both the design process and the resulting interactions. These temporal dimensions include both the time required to develop biomaterials and the transformative behaviors of the materials themselves. In previous work, designers acknowledge that working with biomaterials introduces specific values into the design process. For instance, working with grown materials requires attention to slowness [146, 222] and intentionality [19] due to the slower growth of living organisms compared to manufactured outputs. Similarly, working with materials derived from food waste requires innovative fabrication techniques to shape bio-based raw materials into various forms, incorporating design considerations of imperfection and uncertainty [18, 104, 156]. These temporal dimensions of biomaterials challenge conventional design expectations and create opportunities for reconsidering both design processes and outcomes. Design theorist Jonathan Chapman's concept of "emotional durability" [34] addresses cultural attachments to permanence, while Professor of Sustainability and fashion, Kate Fletcher's "craft of use" [59] offers an alternative perspective that finds value in how materials are worn, cared for, and

transformed over time. When viewed as an "active" property of biomaterials, their temporal qualities create unique design challenges and opportunities that can transform constraints into generative parameters for interactive experiences.

2.3.3 Dissolution as an Interactive Property

Temporal transformations, particularly dissolution and degradation, represent a promising yet underexplored dimension of material-based interactivity. Regarding dissolving textiles (more in Chapter 4), textile artists and craftspeople have been designing with dissolving materials for years. For instance, they have used commercially-available dissolving thread to temporarily secure quilt layers, albeit not exclusively using biomaterials. Chalayan's Spring/Summer 2016 collection featured dresses that dissolved to reveal Swarovski-crystal-embellished gowns [125]. Textile artist Sasha de Koninck used dissolving embroidery materials in her "Knotting.Knotted.Knot" work [115], washing pieces away to explore states of emotion and anxiety, and designer Sofia Guridi integrated biomaterials that dissolve to reveal hidden images in their textile piece "Cambio de Piel - Change of skin" [80].

These examples illustrate how dissolution can be leveraged as an interactive property beyond mere degradation, creating expressive possibilities through transformation. This connects to HCI researchers Tsaknaki and Fernaeus' exploration of impermanence as an active element in interaction design, positioning temporal material properties as central to user experience rather than peripheral considerations. Despite these artistic explorations varying from interactive products to interactive textiles, there remains a gap in systematically investigating dissolution as an interactive property in the context of HCI. In particular, I am interested in considering how dissolution can serve not just

aesthetic purposes but functional ones related to sustainability, disassembly, and material recovery within interactive textiles.

2.4 Sustainability Frameworks and Life Cycle Thinking

Sustainability in HCI has been addressed through a range of frameworks that shape how environmental concerns are understood and acted upon in design. This section begins by tracing the evolution of Sustainable HCI, from early frameworks such as Sustainable Interaction Design to more recent approaches that address multiple stages of a product's lifecycle. It then turns to Life Cycle Thinking, outlining its origins, applications, and emerging presence in HCI practice. Finally, it considers how these perspectives intersect with the specific sustainability challenges of interactive textiles, where materiality, electronic integration, and end-of-life considerations present complex design constraints and opportunities. Together, these subsections provide the context for how I approach sustainability in this dissertation, as a design value—embedded in material-led practice and informed by lifecycle thinking, and also as a practical concern addressed through the development of the Biofiber Spinning Machine that supports sustainable approaches in interactive textile design.

2.4.1 Evolution of Sustainable HCI

Sustainability concerns have become increasingly prominent in HCI research over the past decades, with evolving frameworks for addressing environmental impacts of interactive systems. Sustainability in Human-Computer Interaction (SHCI) has sparked extensive discussions within the HCI community [49, 87, 119, 176] around social, ethical, and environmental sustainability [26, 119,

216]. Regarding the latter, Sustainable Interaction Design (SID) [24, 132, 169], as proposed by a leading figure in HCI, Eli Blevis, is a framework that sets a foundation for considering environmental sustainability in HCI. It outlines five principles aimed at providing direction for interaction designers to adopt sustainable practices beyond invention & disposal, renewal & reuse. Current approaches often focus on specific stages of product lifecycles: "Current research claiming sustainability within HCI often refers to SID when the focus of their work is mainly related to strategies aiming to address sustainability in the use and end-of-life stages of a product alone. Later work and research within Sustainable HCI [23, 137] expanded this framework and incorporated other design strategies in other stages of the product's life. For instance, we can find design strategies examples in the fabrication stage (a.k.a. manufacturing) to achieve energy efficiency through the development of batteryless, or self-powered devices [10, 11, 136, 182]. Numerous researchers have applied strategies such as design for longevity, renewal, and reuse, all of which can be considered to be part of the use and end-of-life stages in a product's life cycle. In the raw material stage, we can see approaches that aim to materialize sustainability [206, 207] through the use of design-to-decay strategies that involved the use of biobased, biodegradable and compostable materials [74, 179, 181, 198, 211]. These frameworks have significantly shaped how sustainability is understood and practiced within HCI, offering foundational strategies for reducing impact and rethinking design and user practices. Complementing these efforts, emerging lines of inquiry are beginning to explore how sustainability might also inspire new ways of thinking, making, and engaging with materials [151, 154, 155, 170, 177]. Within this broader conversation, I engage sustainability as a generative lens that opens

possibilities for considering how materials, their transformations, and their lifecycles shape not only interaction but also the values embedded in design processes. This perspective resonates with ongoing work in HCI that embraces lifecycle thinking—where sustainability is addressed as a continuous, materially grounded practice across sourcing, making, use, and end-of-life.

2.4.2 Life Cycle Thinking in HCI

Life Cycle Thinking (LCT) offers a comprehensive framework for addressing sustainability across a product's entire lifecycle—from raw material extraction and production to use and end-of-life. It originated in environmental science and industrial ecology through the development of Life Cycle Assessment (LCA), a method used to quantify environmental impacts across each stage of a product's life. While LCA is rigorous and data-intensive, LCT has emerged as a more accessible, design-oriented mindset—enabling designers to reflect on environmental impacts throughout the design process without relying on formal assessment tools. As sustainability strategist Leyla Acaroglu describes, LCT acts as a “thinking tool” that helps designers navigate complex systems by making the often-invisible impacts of design decisions more visible and actionable [1].

This approach is not confined to a single discipline. LCT has informed practices in architecture, product design, fashion, and increasingly, in HCI. Within HCI, for example, LCT informed the development of the Sustainable Prototyping Life Cycle (SPLC)[121], a framework I co-authored back in 2020 to help designers assess and reflect on the environmental impacts of digital fabrication. This approach has since been acknowledged by HCI researchers exploring sustainable unmaking practices[181], prototyping paradigms [216], material selection [21, 168], and framework or tool development [139].

Prior to this, I worked in a research team with an LCA expert to develop Yupana[196], a tool that uses Life Cycle Impact Assessment (a simplified version of LCA) to estimate the environmental impact of 3D printing and laser cutting. This was motivated by a broader interest in translating life cycle principles into actionable tools for the maker community in HCI. More recently, projects like DeltaLCA[221], a tool that offers ways to compare electronics design decisions through LCA, exemplify a growing interest in this area—alongside initiatives like the Ecological HCI Special Interest Group [130] and frameworks such as the Sustainable Physicalization Practices (SuPPra) Matrix [139].

While full LCA can offer deep insights, it often requires specialized knowledge and data access. LCT, in contrast, provides a more approachable entry point for designers to begin engaging with lifecycle considerations in practice. My own shift from LCA to LCT emerged through a growing interest in how sustainability could be embedded in material-led design processes. Rather than focusing exclusively on quantitative measures, I began to explore how sustainability could be integrated into early decision-making through material sourcing, fabrication techniques, and attention to transformation and decay. This orientation aligns with biodesign, where lifecycle thinking is present not only in materials but in ecological processes and temporalities. Over time, LCT became a way for me to frame sustainability not just as a metric, but as a generative force—something that informs how materials are selected, how interactions are imagined, and how values are embedded in design work.

Although HCI researchers rarely name LCT explicitly, its principles are often embedded in practice—particularly in work that attends to sourcing [48], material impact [70, 198], and end-of-life strategies [35, 180]. These considerations become especially relevant in interactive and wearable textiles,

where materiality, disposability, and energy use intersect. In my dissertation, I integrate LCT with material-led design and biodesign approaches, treating sustainability not as a constraint but as a generative design parameter that shapes how I source, work with, and embed materials within systems. This lens helps guide decisions—such as selecting biobased, locally sourced, or waste-derived fibers—while also expanding how I consider the broader ecosystems in which designed artifacts are situated. These considerations foreground the complex and evolving sustainability challenges designers navigate when working with hybrid materials and embedded electronics.

2.4.3 Sustainability Challenges in Interactive Textiles

Interactive textiles have primarily been discussed in HCI through the lens of smart textiles—fabric-based systems augmented with electronics that enable sensing, actuation, or computation [42, 160, 204]. While smart textiles typically rely on electronic components, interactive textiles can also encompass systems whose responsiveness emerges from the material properties themselves—such as tactility, transformation, or environmental sensitivity. This broader framing opens up additional ways of addressing sustainability, not only through technological integration but also through how materials behave, break down, and persist over time.

Research in this area has enabled a range of applications, from gesture recognition [149, 214] and health monitoring to interactive fashion [61, 218] and assistive technologies [36, 126]. These systems often rely on specialized conductive materials [54], such as carbon-black-infused foams [220], integrated with traditional textile techniques. Alongside these developments, a growing body of work has begun to surface the sustainability concerns associated with

combining textile and electronic components, particularly around disposability, repairability, and the complexity of recycling [53, 63, 162].

While blending electronics into textiles has expanded the design space of interaction, it also raises pressing sustainability challenges [53]. Smart textiles frequently combine components from multiple waste streams—textile and electronic—that are difficult to separate for proper recycling or disposal. Many are made from synthetic materials that do not readily biodegrade, contributing to long-term waste and plastic pollution [63, 162]. These issues are compounded by limited access to recycling infrastructure capable of handling such hybrid materials. As a result, addressing sustainability in smart textiles requires holistic approaches that consider the entire lifecycle of a system—from material sourcing and fabrication to use and end-of-life [64, 84].

As a response to this pressing challenge, HCI researchers have explored interventions at different stages of the smart textile lifecycle through repair [99], reuse [100], and disassembly [215]. Parallel efforts in material research communities have focused on biodegradable and DIY biomaterials [101, 116, 133], often shared through open-source archives and initiatives [14, 57, 135, 158]. These include biomaterials derived from waste streams or living organisms, often intended to decompose naturally and reduce long-term environmental impact [124, 141]. These practices emphasize localized sourcing, compostability, and ecological regeneration.

Biomaterials offer new possibilities for sustainable and embodied interaction within interactive textiles, particularly through their temporal, aesthetics and transformative behaviors [82, 110, 123]. Although more widely explored in product and industrial design, biomaterials have only recently begun to enter interactive textiles discourse. Existing work has looked at ways to

embed biomaterials into interactive textile [81], including the development of fully biodegradable capacitive sensorss [83] and using textile structures to support disassembly [120, 224]. In practice, fabrication processes at this intersection of biomaterials and textiles often take the form of DIY methods, which can present challenges for reproducibility, or laboratory-based techniques requiring specialized equipment. This creates an opportunity for approaches that can make working with biomaterials more accessible while engaging with sustainability as a design value grounded in lifecycle thinking. In my dissertation, I take this approach, exploring how biomaterial prototyping tools can extend sustainable design practices in interactive textiles. The Biofiber Spinning Machine developed in this work supports such engagement by enabling designers to produce biomaterial fibers in forms suited for textile integration, opening possibilities for lifecycle-oriented and materially attuned interaction design. The next section examines how such tools and open approaches contribute to ongoing efforts to democratize biomaterials innovation.

2.5 Democratizing Access to Biomaterial Innovation

Material-led, biodesign, and sustainability-oriented approaches open new possibilities for interactive textiles, yet their exploration is often constrained by the accessibility of biomaterials fabrication itself. Engaging with biomaterials, particularly in forms suited for textile integration, requires not only technical capability but also opportunities for designers to participate in shaping these materials and their applications. This section examines how limitations in fabrication processes, access to equipment, and knowledge-sharing structures

restrict participation in this space, and how emerging approaches seek to broaden it. It begins by outlining the challenges in biomaterial fabrication, particularly for fiber-based forms. It then surveys accessible fabrication strategies developed in HCI and related fields, noting their potential and constraints. Finally, it considers the role of knowledge translation and community engagement in enabling broader participation, situating these perspectives within my own practice and the development of tools such as the Biofiber Spinning Machine.

2.5.1 Challenges in Biomaterial Fabrication

The integration of material-led design, biodesign, and sustainable approaches in interactive textiles faces significant fabrication challenges that have limited exploration in this space. While biomaterials have achieved visual similarity to their conventional counterparts, research is still in progress to improve their physical properties, durability, and fabrication processes so that bio-based materials will be viable alternatives [194]. Fiber-based biomaterials present particular challenges. Without accessible tools and workflows for fiber design, exploration of new and more sustainable material choices is unlikely, if not impossible. Moreover, it's worth noting that the materials with perhaps the greatest potential for sustainability benefits—namely, biobased materials—often lack adequate support or remain under-explored within the textile design pipeline, particularly in the context of yarn production. Industrial equipment proves poorly suited to biomaterial experimentation. On an industrial scale, synthetic fibers are typically made from stable liquid solutions using specialized machines for wet or dry spinning. However, these machines are less suitable for biobased liquid solutions, which tend to be less stable during the fiber spinning

process. The complexities of fiber spinning prototyping pose considerable challenges, particularly when contemplating the engagement of designers and researchers in HCI seeking to explore this fiber design space. First-hand experience highlights specific barriers. Our first-hand experience at the Institute of Advanced Textiles (ITA) at RWTH Aachen in Germany during the summer of 2022 revealed challenges tied to the production of biofibers from a gelatin liquid solution using standard wet spinning equipment. The room-sized equipment (4m long) required substantial spinning solution quantities—a minimum of 500 mL—to perform a single test. These challenges represent not just technical hurdles but barriers to broader participation in biomaterial innovation. Without accessible tools and techniques, the exploration of biomaterials' interactive and temporal qualities remains limited to specialized contexts, hindering the integration of material-led, biodesign, and sustainable approaches.

2.5.2 Approaches to Accessible Fabrication

Researchers in HCI and related fields have explored alternative fabrication approaches for biomaterials, demonstrating both possibilities and limitations for democratizing access to biomaterial innovation. In HCI, Alganyl [15] has optimized an open-source bioplastics recipe, characterized it, and explored possible design applications. Research into fiber and filament-based production techniques highlights innovative approaches to textile design, revealing challenges and constraints that influence the trajectory of sustainable smart textile innovation. In many cases, innovators in the textile design domain must construct custom systems to facilitate their work. For instance, [56] developed a desktop filament production system capable of depositing "smart" materials in cylindrical layers. Similarly, [39] demonstrated the production of thin,

strong, and highly conductive carbon nanotube filaments using a specialized wet spinning machine. While showcasing the potential of fiber design, these custom systems pose challenges as they are often designed for specific materials, lack tunability, and are challenging for others to replicate.

The HCI community has explored various fiber fabrication approaches, though primarily with petroleum-based materials. Researchers have explored various techniques to create fibers in the context of 3D printing. For example, Rivera et al [167] developed an open-source 3D printer that produces PLA fibers from PLA via melt electrospinning. Others have investigated using 3D printing to create hair-like structures [118, 152, 210]. While many of these creative fiber design approaches have relied on unsustainable materials such as thermoplastic filaments and photopolymer resins, recent work has begun to explore fabrication methods using biomaterials. For example, two open-source machines have been developed to extrude alginate-based like yarn filament [131, 226], offering a promising direction for expanding the range of materials available for textile integration. Building on such efforts, there is an opportunity to further explore accessible tools specifically suited for working with biomaterials in fiber form. Expanding this space could open new possibilities for designers and researchers to explore the interactive and temporal qualities of biomaterials and to integrate material-led, biodesign, and sustainable approaches in their practice.

2.5.3 Knowledge Translation and Community Engagement

Democratizing access to biomaterial innovation requires not just technical tools but also approaches to knowledge translation and community engagement that enable broader participation in this emerging field. Material design

communities have begun developing resources for sharing biomaterial knowledge. These communities [116, 133] have explored creating sustainable materials and DIY biomaterials [57, 158] through open-source material archives [101, 135]. These material archives focus primarily on recipes for materials that can be made into sheets or molded. In contrast, we believe that focusing on fibers—the backbone of all textiles—can open a new design space to address sustainability challenges in interactive textiles. By lowering barriers to participation, these approaches can help cultivate a more diverse community of practitioners able to connect material experimentation with ecological thinking, fostering new directions for sustainable and material-led interactive textile design.

Chapter 3

Biofoam as Interactive Material

A Biodesign Approach to Material Exploration and Fabrication

Techniques for Interactive Soft Materials



Reproduction Note: *This chapter reproduces material from the publication: Eldy S. Lazaro Vasquez, Netta Ofer, Shanel Wu, Mary Etta West, Mirela Alistar, and Laura Devendorf. 2022. Exploring Biofoam as a Material for Tangible Interaction. In Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22). Association for Computing Machinery, New York, NY, USA, 1525–1539. <https://doi.org/10.1145/3532106.3533494>. It appears here with permission from the publisher, with minor changes to formatting and terminology to fit the dissertation.*

3.1 Introduction

This chapter explores gelatin biofoam, or biofoam for short, a biodegradable biomaterial, within the context of soft interactive materials. The focus is on its potential applications in interactive textiles such as soft sensors and wearables. Using biodesign principles with an emphasis on life cycle thinking and material-driven design (MDD), this exploration investigates how the material's intrinsic properties guide the design process, contributing to more sustainable design practices.

Biofoam, adapted from an open-source DIY recipe, was chosen for its low-density, biodegradable, and tunable characteristics, making it ideal for interactive textile applications. In this project, my collaborators and I explored how biofoam can be modified with natural additives to achieve properties like color, water permeability, and conductivity, and how it can be fabricated for use in wearable technologies and Human-Computer Interaction (HCI). Key to this material exploration is biofoam's dissolvability and reusability, which are leveraged in applications such as color-changing accessories and pressure sensors.

The methodology guiding this work is Research through Design (RtD), where material experimentation and fabrication provide insights into biofoam's interactive potential. This chapter introduces biofoam as a novel material for soft interactive textiles, showcasing how it can be integrated into sustainable design practices and innovative applications. The findings presented here lay the foundation for future studies on wearable interfaces driven by biodesign. Biofoam's capacity for dissolution is a key affordance, leading into the next chapter, which delves deeper into dissolvable wearables. Additionally, the challenges encountered in fabricating biofoam for repeatable and scalable interactions inform the open-source fabrication methods discussed in the final chapter on biofibers.

Overall, this chapter supports the dissertation's argument that biodesign is a holistic design practice encompassing sustainability, life cycle thinking, innovation, and material-driven design. It advances the dissertation's first two major contributions: the development of new biomaterial formulations and low-tech fabrication techniques, and the creation of interactive objects as proof of concept. Through material exploration, this work demonstrates how biodesign principles can foster sustainable innovations in soft interactive materials, paving the way for future advancements in HCI and wearable technologies. In adapting and thinking *with* materials [65], we highlight the particular affordances biofoam offers for tangible interaction, recyclability, and fabrication processes.

3.2 Process: Material Experimentation

We explored biofoam and its potential to be used as an interactive material, involving the material’s entire life cycle: raw material use, fabrication, interactive use, and end-of-life. In this section, we detail our material experimentation, which informed the design explorations in later sections. First, we describe the preparation of the base recipe in Appendix A in [122], replicating an existing DIY, open-source biofoam recipe [55]. Then in Sections 3.2.2-3.2.3, we detail our modifications to the base recipe and our observations of how these modifications tuned certain properties of the biofoam, familiarizing ourselves with potential design considerations and applications of the material. In that process, we incorporated ingredients in the recipe and used various fabrication methods to achieve different materialistic qualities in the biofoam. Figure 3.1 maps the specific attributes that each tested ingredient contributed to the biofoam. Full recipes for all the biofoam variations we achieved in this study are described in detail in Appendices A and B in [122].

3.2.1 Base recipe preparation

The base ingredients of biofoam are gelatin, glycerin, water, and dish soap, as shown in Table 3.1. These ingredients are easy to find, affordable, and largely

TABLE 3.1: Adapted DIY open source biofoam recipe from [55] with description of the purpose and characteristics of the core ingredients

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

derived from industrial by-products [166]. Additional ingredients, described in subsections 3.2.2–3.2.4, can be added to the base recipe to modify properties such as density, color, aroma, water permeability, or conductivity (Fig. 3.1).

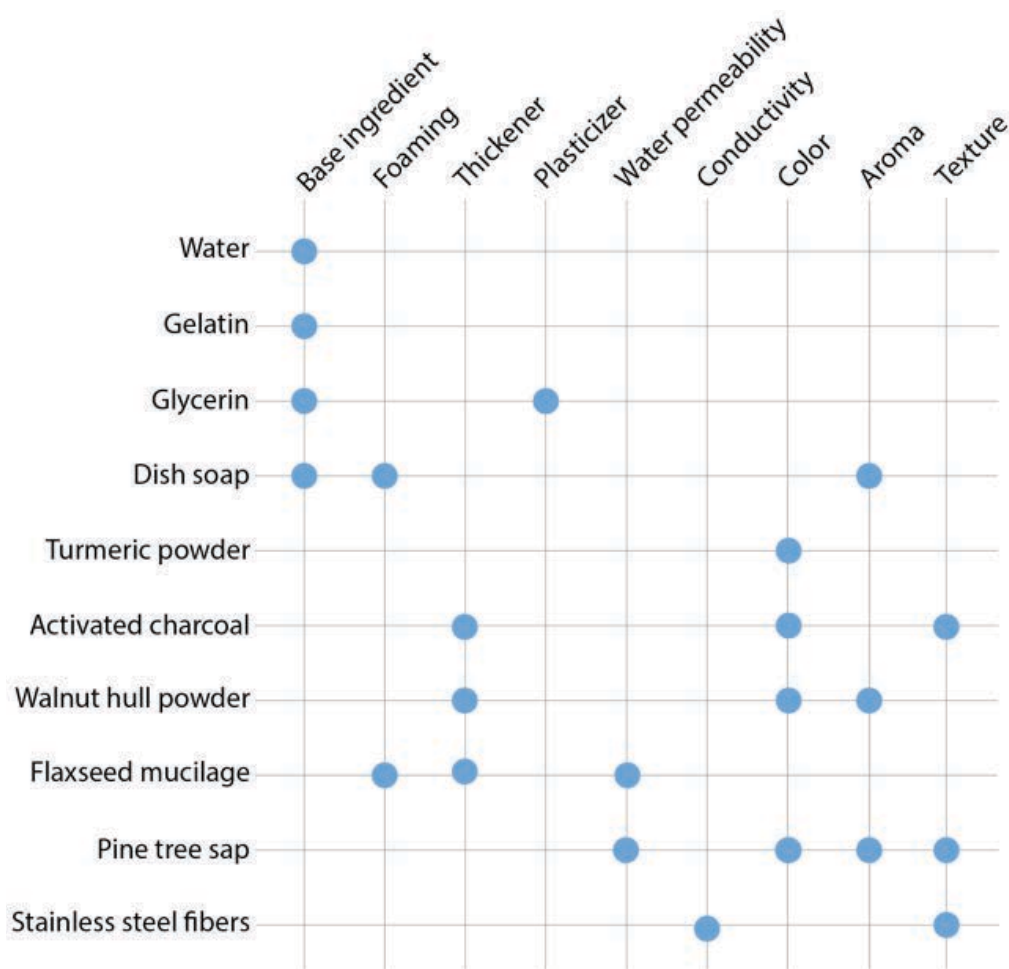


FIGURE 3.1: Mapping of biofoam attributes (X axis) when specific ingredients (Y axis) are added to the base recipe

Step 1: Mixing. To prepare the biofoam, we mixed 300 ml of tap water with 24 g of powdered gelatin⁶ in a beaker (or stainless steel pot) and stirred until the powder was fully incorporated. We then placed the beaker on a hot plate and

⁶Knox Unflavored Gelatin, 16 Oz. <https://www.amazon.com/Knox-Original-Gelatin-Unflavored-16-Ounces/dp/B06XDPCXYJ>

kept stirring as the mixture heated to 80°C (175°F), and continued stirring until the gelatin fully dissolved.

Step 2: Cooking. Next, we added 24 ml of glycerin and stirred the mixture until it reached a syrupy, honey-like viscosity. The mixture reduced to about one-third of its original volume. The cooking time varies with ingredient amounts and stove type. In our process, using a Duxtop⁷ 1800 W portable induction cooktop, our base mixture of one liter reached the desired viscosity in about two hours.

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

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

⁷Duxtop 1800 W Portable Induction Cooktop. <https://www.amazon.com/Duxtop-8100MC-Portable-Induction-Countertop/dp/B0045QEPYM>

3.2.2 Adding color

Following previous work of coloring bioplastics [15], we first colored the biofoam with a synthetic food-grade pigment to test its effectiveness in our material. Even though food-grade pigments worked well in the biofoam, we wanted to test other pigments that were not *synthetic*. We conducted several experiments using *natural* powders (i.e. *sourced directly from nature*) such as turmeric powder (Fig. 3.2a), walnut hull powder (Fig. 3.2b), and activated charcoal. We found that liquid or water-soluble pigments would be preferable for coloring the biofoam because they mix well with water which is the carrier and mixing fluid in our recipes. These natural powders are water soluble and were added in the biofoam mixing process to ensure a uniform color over the entire material.

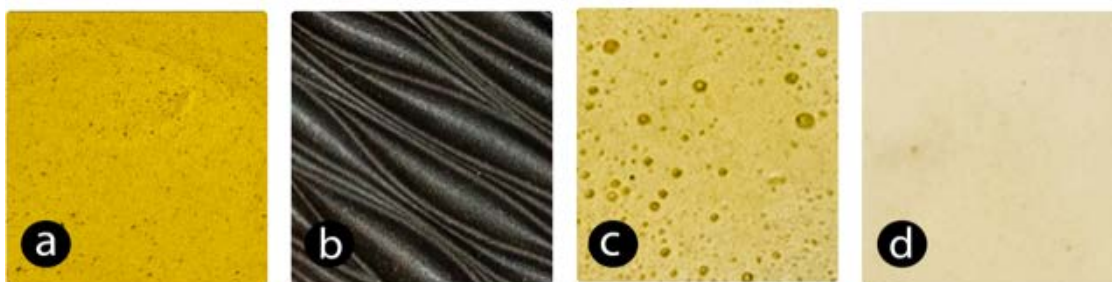


FIGURE 3.2: Natural additives used to give the biofoam color: a. turmeric powder, b. walnut hull powder, c. pine tree sap, and d. gelatin natural color

We noticed in our exploration that other ingredients used to tune the biofoam in other ways resulted on adding color to it as well. For instance, we used pine tree sap to increase the water permeability of the biofoam (see details in Section 3.2.3) and found that the sap added a yellow tint to the resultant sample (Fig. 3.2c), as well as a slight floral fragrance. Furthermore, we noticed that adding such powders could alter the recipe's proportions and/or the

material's final properties. For instance, adding walnut hull powder to the base mixture made our samples brittle after drying.

We researched the properties of the different natural powders we used in our exploration and found that powders' density, grain size and solubility are important characteristics to pay attention to when incorporating powders in our recipes. To illustrate, based on our observation and making experience, the biofoam with walnut hull powder added to the recipe (see Appendix A.4 in [122]) requires an additional thickener or plasticizer (like glycerin) in the mixture to prevent brittleness and cracking. Thus, we added flax mucilage as a natural thickener or emulsifier [4, 161, 188] (3% of the base mixture), finding that it not only prevented brittleness and cracking but also reduced the samples' shrinkage during drying. We also found that additional dish soap (6% of the base mixture) was needed in this case to compensate for the added ingredients, in order to sufficiently generate air bubbles in the foam-making process. On the other hand, the biofoam with turmeric powder recipe (see Appendix A.2 in [122]) was less prone to cracking than the samples with walnut hull powder. Understanding the intricacies of this phenomenon is reserved for future work.

We also explored adding bio-compatible thermo- and photochromic pigments to the biofoam base recipe (see Section 3.5.1). We used a thermochromic blue pigment that changes color to white above 36°C (98°F), a thermochromic orange pigment that changes color to white above 36°C (98°F), and a photochromic white pigment that changes color to blue with UV exposure. We prepared the pigments with a ratio of 1:8 (1g of pigment per 8g of solvent), using Dye-Na-Flow⁸, a thin water-based paint, as the solvent. We found that

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

a 1:10 ratio of pigment-solvent mixture to biofoam mixture (i.e. 1g of prepared pigment per 10g of biofoam base mixture) worked well. After dissolving the biocompatible pigment in the solvent, we added it to the base mixture when it reached the syrup-like consistency on the hot plate. We stirred the prepared pigment into the biofoam mixture for two minutes with the hot plate turned off. Then, we proceeded with pouring the heat-sensitive or UV sensitive biofoam in the desired mold.

3.2.3 Adding conductivity

From the start of our explorations, we were interested in producing a conductive biofoam for electronic applications. We attempted to incorporate conductive stainless steel fibers into the recipe with different techniques. Stainless steel fibers are readily available in thread-like forms for e-textiles or as roving for spinning and fiber art. We tested integrating conductivity using whisking, felting, and folding processes (Fig. 3.3).



FIGURE 3.3: Attempts to incorporate stainless steel fibers into biofoam: a. whisking, b. felting, c. folding

As shown in Figure 3.3, whisking and felting were both unsuccessful techniques, resulting respectively in the fibers clumping around the whisk

(Fig. 3.3a), and in the fibers clumping unevenly in the foam (Fig. 3.3b). Finally, we turned to *folding*⁹, a technique commonly used in baking to incorporate ingredients with contrasting densities and successfully achieved a conductive biofoam by folding the stainless steel fibers into the foamed mixture (Fig. 3.3c).

Using a spatula, we folded the conductive fibers into the biofoam for two minutes and stopped when the fibers were mostly dispersed through the foam, while the mixture had a loose enough consistency to be poured into a mold (Fig. 3.4a). In trials with various lengths of stainless steel fibers, we found that fibers longer than 5 cm were more likely to clump together instead of distributing throughout the material. After testing lengths ranging from 1 cm to 5 cm, our experiments found that fibers which were 2.5cm in length in average were most successfully folded into conductive biofoam. We poured the mixture into a silicone mold (Fig. 3.4a) to create a 8.5 cm × 8.5 cm × 2.3 cm sample, and let it dry in a ventilated area at room temperature (Fig. 3.4b). We demolded the sample after 48 hours (Fig. 3.4c) and allowed it to fully dry outside of the mold for three more days. Note that drying time depends on the size of the sample.

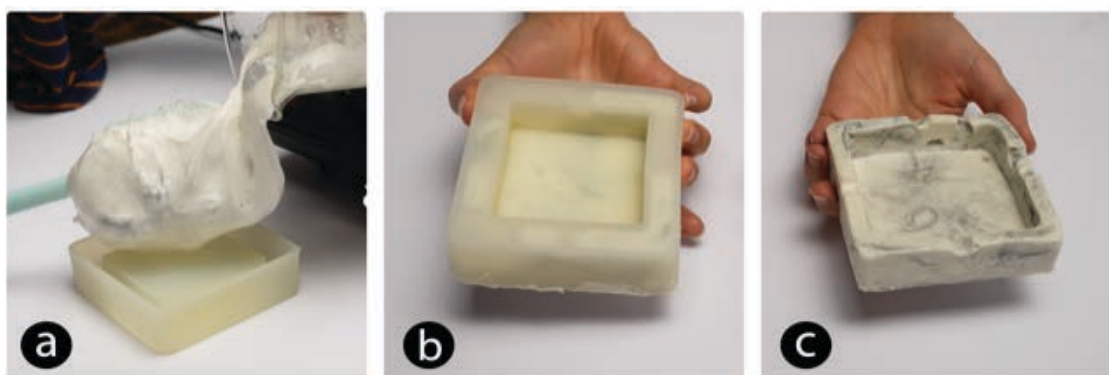


FIGURE 3.4: a. Pouring the biofoam mixture into a mold, b. Biofoam drying at room temperature, c. Demolded biofoam after 24 hours

⁹Folding technique. <https://www.washingtonpost.com/food/interactive/2021/how-to-fold-ingredients/>

3.2.4 Increasing water permeability

Through observation, we noticed that the biofoam dissolves in water, which led us to research ingredients that could help increase the water permeability of the biofoam. We discovered that adding pine tree sap [148] in a liquid form (10% of the base mixture) increases the water permeability properties of the biofoam. Some research also suggests that flaxseed mucilage may also increase water permeability [161]. To study how the different biofoam recipes we created react to water, we designed an experiment that compares the property of water permeability in terms of evaporation time. For that, we pipetted a 30 μ l water droplet on a polyurethane foam piece, as a control sample and compared its evaporation time with droplets of the same size pipetted on the biofoam base recipe, biofoam with conductive fibers, biofoam with charcoal, biofoam with walnut hull powder and flax mucilage, and biofoam with pine tree sap. The results in Table 3.2 report the time when we stop noticing any droplet on the biofoam surface.

TABLE 3.2: Set-up experiment that compares water permeability between biofoam recipes in terms of evaporation time

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

As shown in the table, droplets on both the base recipe and charcoal samples disappeared significantly faster than on the control surface, suggesting that some of the water permeated into the biofoam rather than simply evaporating. The sap sample retained the droplet for the longest time, indicating greater water resistance, as the droplet had more difficulty permeating the material's membrane. We acknowledge that this experiment is preliminary and offers only

an initial insight into the material's behavior. Further investigation is needed to account for additional factors, such as the role of the contact angle at the liquid–solid interface in droplet evaporation.

3.2.5 Recooking

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

3.3 Characterizing Biofoam

After producing several different kinds of biofoam we became increasingly interested in the capacity of the material to squish and slowly recover to its original shape. First, we studied this qualitatively, gaining a general assessment to describe the material to broader audiences that could help communicate the unique sensory qualities of the material. Next, we considered how this quality

of the material could be used for pressure sensing, and therefore began to conduct more systematic characterizations on the conductive biofoam samples (Section 3.3.4) as well as analyzing our findings with a lens on the life cycle of the material (see Section 3.3.5).

3.3.1 Density, squishiness and spring back time

The density of the biofoam can be tuned by adjusting the ingredients and whisking time. Any additives to the base recipe (e.g., natural powders, stainless steel fibers) also affect density. For example, the density of biofoam with pine tree sap ranged from 0.54 to 0.65 g/cm³. When adding conductive fibers, we obtained densities between 0.35 and 0.48 g/cm³, depending on whisking time, which influences the size and number of air bubbles incorporated into the mixture. Whisking for 30 seconds produced a density of 0.30 g/cm³, whereas 90 seconds yielded 0.48 g/cm³. We also found that molding in thin layers helps prevent air bubbles from bursting, compensating for the higher density introduced by additives. Pouring the biofoam with thermochromic pigment into 0.5–3 mm sheets resulted in a threefold lower density (0.13 g/cm³).

Through observation, we tested squishiness and spring-back time by manually applying the same pressure on conductive and non-conductive biofoam samples, then measuring the time needed for each to recover using a stopwatch. The non-conductive biofoam returned to its shape in about three seconds when pressed with one finger on the sample edge (Fig. 3.5), whereas the conductive biofoam took about five seconds (Fig. 3.6). We infer that the longer recovery time results from fillers in the biofoam mixture, such as the added conductive fibers.

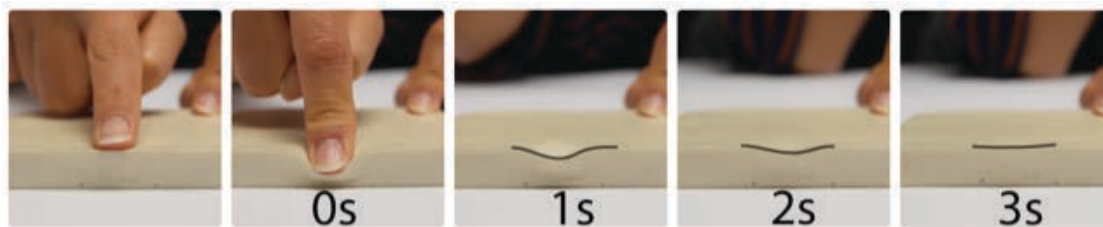


FIGURE 3.5: Non-conductive biofoam spring back time.



FIGURE 3.6: Conductive biofoam spring back time.

3.3.2 Thickness

We produced a variety of biofoam samples with varying thicknesses from 1 mm to 4 cm using the molding technique. Having a variety in thicknesses made us think about material application and limitations. For instance, the pleating technique worked best in a biofoam sheet below 1 mm thickness. In contrast, hand embroidery worked best in 2 mm thick biofoam. We also found that 1 mm biofoam sheets were translucent, useful when embroidering the biofoam (as applied in Section 3.5.1).

3.3.3 Durability

After storing the samples at room temperature on a shelf for 5 months, we noticed that our biofoam samples had changed slightly—for example, the 3D-molded samples appeared more coarse on the surface, and were rougher to the touch. We did not notice significant change in the biofoam's

color or spring-back time in the biofoam sheets. However, we noticed the conductive biofoam pressure sensors had become less compressible. In terms of recyclability, even our oldest, five-month-old biofoam scraps still dissolved in warm water, allowing us to make new biofoam samples from the discard.

3.3.4 Compression and recovery time

We characterized three conductive biofoam samples using ASTM D3574, a foam compression test. All samples had a density of 0.29 g/cm^3 and a thickness of 9.4 mm (0.37"). They were conditioned undeflected and undistorted at $23 \pm 2^\circ\text{C}$ (73°F) and $50 \pm 5\%$ relative humidity for at least 12 hours before testing. Each sample was produced at least seven days prior. We reliably predicted the compression of the conductive biofoam from 0% to 72%. In particular, stiffness from 0% to 50% compression was fairly linear, as shown in Figure 3.7 (pink line).

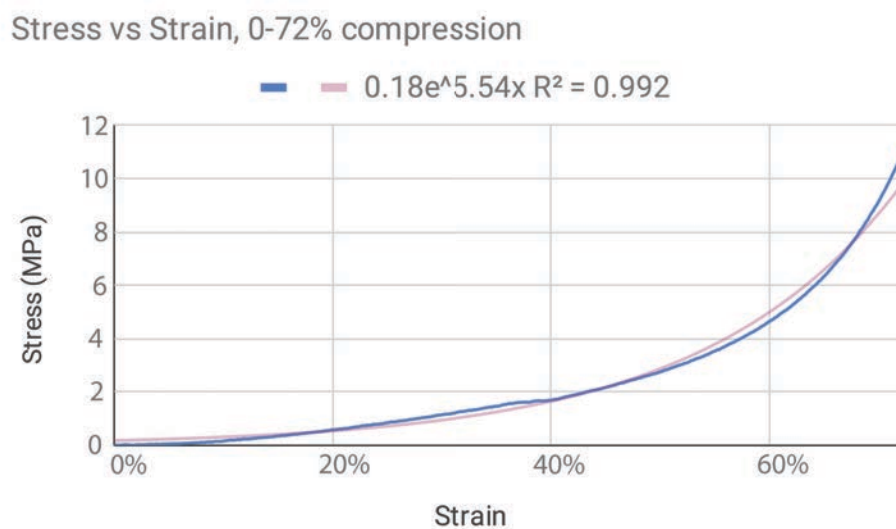


FIGURE 3.7: Compression testing performance of conductive biofoams.

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

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

3.3.5 Assessing the Biofoam Life Cycle

We followed the Sustainable Prototyping Life Cycle [121] to perform a qualitative life cycle assessment of the biofoam. The biofoam has a closed-loop life cycle (see Fig. 3.8), characterized by five phases:

Raw materials: Most of the core ingredients used to make the biofoam samples can be sourced as industrial byproducts, including glycerin, gelatin, and conductive fibers. Some naturally occurring additives, such as flax seeds and powders (turmeric, walnut hull, activated charcoal), are not grown or produced locally but can still be obtained from neighboring states. These ingredients remain affordable and require minimal processing.

Transportation: All of the materials we used were sourced domestically, within 800 miles. Pine tree sap was harvested locally, from our own neighborhoods and backyards. We further reduced transport distances by not buying new tools or materials and instead reusing silicone molds from the lab and incorporating recycled stainless steel fibers from past projects.

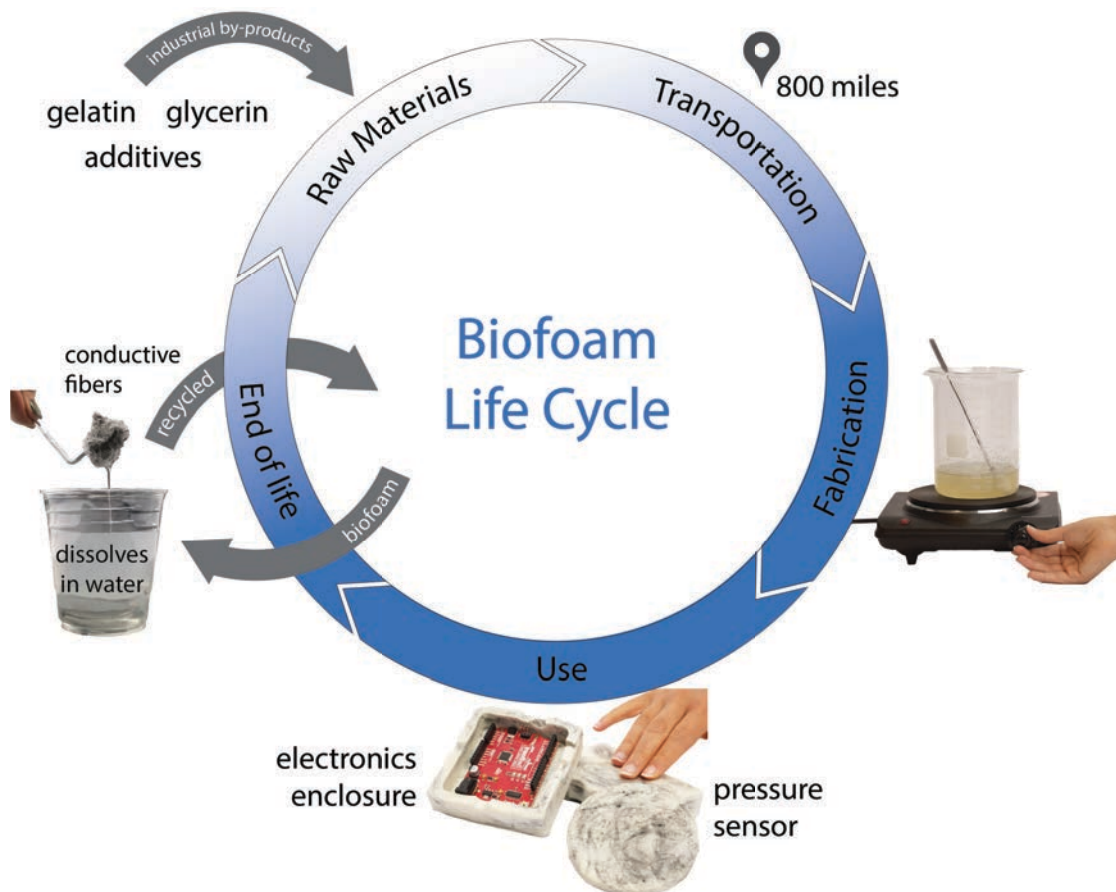


FIGURE 3.8: Biofoam life cycle

Fabrication: We used both craft and digital fabrication techniques in our design exploration and biofoam sample development. The main impact of this phase comes from the energy required for laser cutting and for cooking multiple biofoam batches. The induction cooktop consumed about 2 kW/h; using it for 16 hours resulted in 32 kW of power use, equivalent to the CO₂ emissions from burning 25 pounds of coal. Offsetting this footprint would require 1219 square feet of U.S. forest for one year. Since all co-authors have backyards, we could collectively sequester the CO₂ generated in this phase over the course of the project.

End of life: When the biofoam is no longer in use, it can be “ended” by dissolving it in water (Fig. 3.9) or by composting it to biodegrade. For conductive biofoam, dissolving is the more environmentally friendly option, since the stainless steel fibers can be recovered with a magnet, as shown in Fig. 3.9. After collecting the fibers, the remaining base ingredients and any natural additives (e.g., turmeric powder) can biodegrade. The biofoam dissolves quickly in warm water because gelatin, its main structural component, melts at 32°C–34°C (90–93°F), though it also dissolves in cold water more slowly. Additional ingredients in modified recipes raised the optimal dissolving temperature to 50°C (122°F).

We also tested biodegradability in a controlled environment at 45°C (115°F), assuming disposal in a landfill. The sample degraded in 120 days. As shown in our failed experiments, biofoam waste from prototyping can also be reused as raw material for new batches, including foams containing natural, thermochromic, or photochromic pigments.

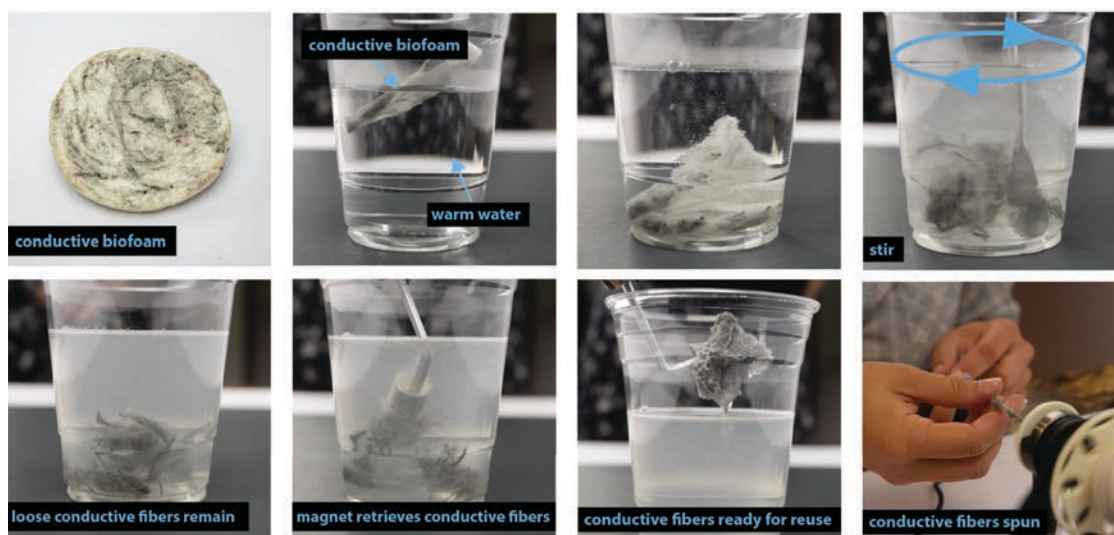


FIGURE 3.9: Biofoam dissolving process to enable conductive fibers reharvesting with a magnet.

3.4 Exploring Fabrication Techniques

In this section, we summarize the fabrication techniques used in our material experiments. Through making a variety of biofoam recipes (Fig. 3.10), we noticed that the properties of biofoam and the fabrication techniques used to shape it mutually influence one another, forming a core dialogue when designing with biofoam as a material. Across our experiments, we used a combination of craft and digital fabrication techniques to shape the material. The biofoam can be molded, layered, extruded, sewn, embroidered, pleated, cut, and laser engraved. We provide detailed instructions for our most commonly used techniques (molding, extruding, and layering) in Appendix B in [122].

Molding: The biofoam can be cast with various details by pouring the mixture into a mold (see Fig. 3.11a, b). Overall, we were most successful when we poured the biofoam mixture into the mold immediately after whisking/folding, while the mixture was still hot. We also used a spatula to scrape the biofoam out of the cooking container, and push the mixture into the

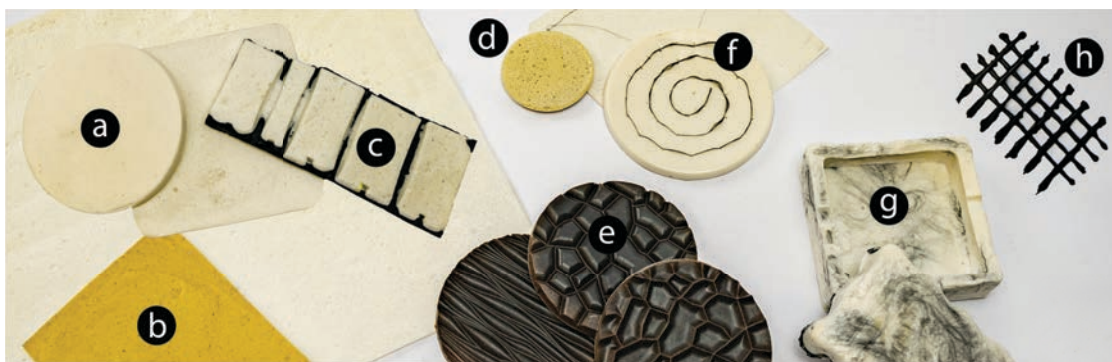


FIGURE 3.10: Various biofoam samples created with different fabrication techniques and modifications of the base recipe: a. The base recipe in various thicknesses; b. Colored with turmeric; c. In segments on top of a rubbery biofoam base; d. Hardened and improved water permeability with pine tree sap; e. Colored with walnut powder and cast in custom molds; f. Embroidered with conductive thread; g. Conductive biofoam with stainless steel fibers; h. Extruded into a mesh.



FIGURE 3.11: a. Demolding the biofoam sample. b. Biofoam acts like memory foam, c. Biofoam applied in layers.

mold, to work as quickly as possible. The biofoam is most malleable when hot, and will also begin drying and curing once exposed to air. When we delayed pouring for too long, the samples conformed poorly to the mold. For these failed experiments, we recooked the sample at 80°C (175°F) and repeated the fabrication process from there.

Layering: This technique involves pouring layers of different biofoam recipes in the same mold. For instance, Fig. 3.11c shows a sample where the bottom layer (layer 1, color black) was made with a recipe that resulted in a more dense biofoam (longer whisking time to achieve small air bubbles in the mixture), and it was colored with activated charcoal powder. After letting the bottom layer sit for 10 minutes, we poured the upper layer (layer 2, color white), which was less dense (shorter whisking time to achieve bigger air bubbles in the mixture). This layering technique produced foldable biofoam structures, with differences in layer density creating distinct pleat-like formations.

Extruding: We extruded the biofoam using a syringe (Fig. 3.12a) and cutting various nozzle opening sizes too. This fabrication technique requires the biofoam mixture to be less dense than the mixture used for molding or layering.

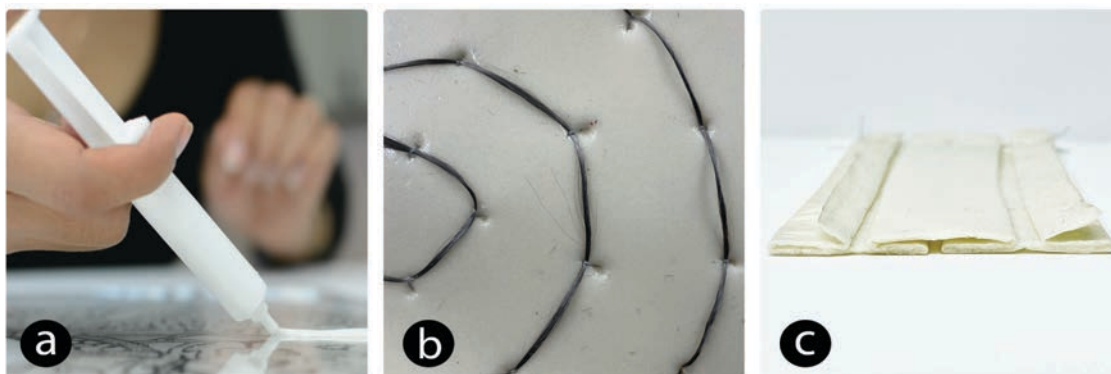


FIGURE 3.12: Biofoam: a. extruded, b. couched, c. pleated.

This can be achieved by whisking it for a longer time until it gets a meringue consistency. In Section 3.5.1, we show how extruding the biofoam in different thicknesses can be used to make wearables.

Sewn, pleated, laser engraved. The biofoam can be easily cut with scissors, sewn by hand (Fig. 3.12b), or using a sewing machine. We also pleated a 2 mm thickness biofoam sheet. When working with fabric, pleating is achieved through heat-sealing the pleats into place, however, as the biofoam is by default not heat resistant, we cold-set the pleated biofoam in between books for 24 hours (results can be seen in Fig. 3.12c). Finally, we tested the option of laser engraving a 4 mm biofoam sample. After testing multiple parameters, we received a clean 2 mm etching without any burning marks in the biofoam surface at 7% power and 50% speed, a gentle etching at 5% power and 50% speed, and a deep 4 mm etching at 7% power and 50% speed.

3.5 Exploring HCI Applications

Combining the various fabrication methods with the material's tunable properties allowed us to imagine several applications for biofoam in HCI.

Initially, we created biofoam wearable accessories that have biocompatible thermo- and photochromic pigments, and lastly pressure sensors that we characterized and envision future use as tangible interactive objects.

3.5.1 Chameleon Accessories

We developed a collection of accessories we called "Chameleon accessories" because of their ability to change color when they are worn. The collection includes one necklace (Fig. 3.13, two bracelets (Fig. 3.14, one face mask (Fig. 3.13a), and two rings and one pair of earrings (Fig. 3.15b).

Each accessory in the collection incorporates biocompatible thermochromic and photochromic pigments to enable material interactions, allowing the pieces to function as visible and tangible sensors through color change. These biofoam

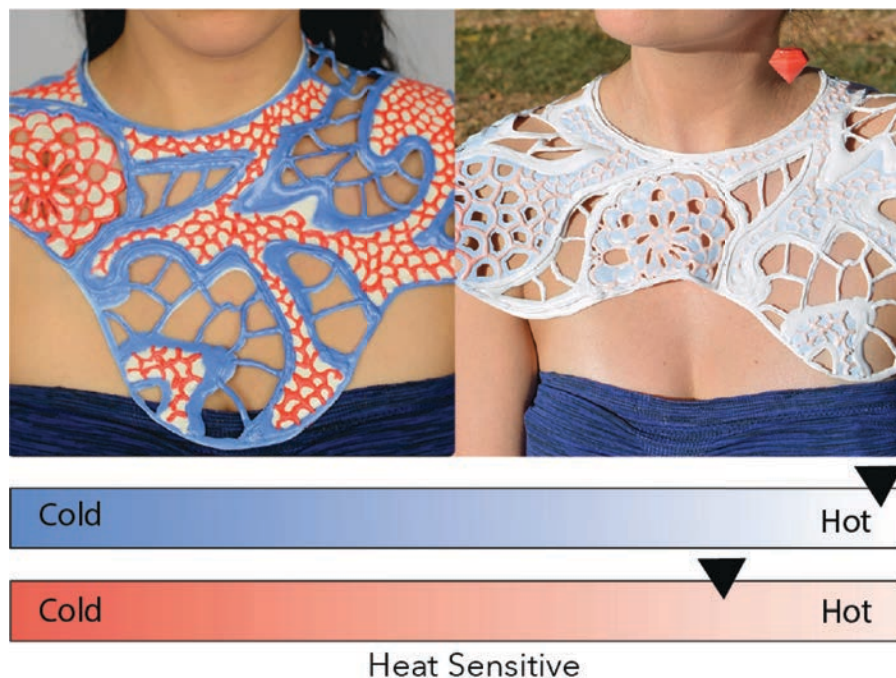


FIGURE 3.13: Thermo- and UV-sensitive biofoam necklace.

recipes can be found in Appendix A in [122]. We used a thermochromic blue pigment that turns white at 36 °C (98°F), a thermochromic orange pigment that also turns white above 36 °C (98°F), and a photochromic white pigment that shifts to blue under UV light.

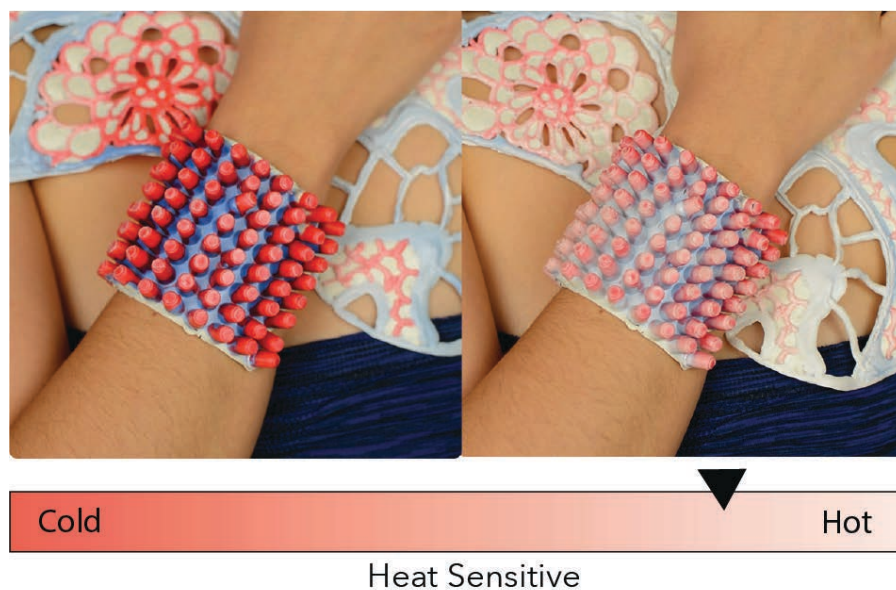


FIGURE 3.14: Thermo- and UV-sensitive biofoam bracelet.

The waste generated during the accessories' prototyping process was reused as raw material ingredients to make new biofoam and accessories.

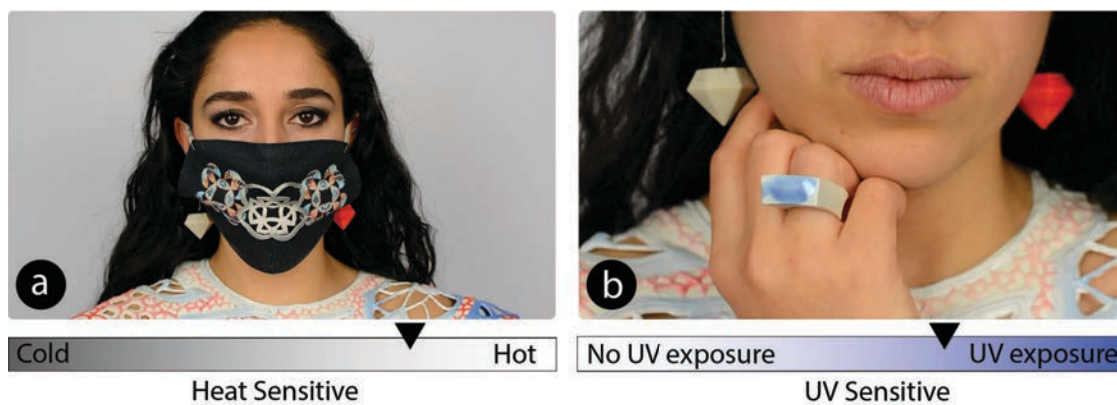


FIGURE 3.15: Thermo- and UV-sensitive facemask and other accessories

Necklace: We used a handheld 3D extrusion technique to make the necklace (Fig. 3.13a). We first drew a lace-inspired pattern onto a piece of white paper, then placed a piece of translucent acrylic on top. The acrylic served as a non-stick base on which to extrude the biofoam. We used the biofoam layering technique in this process to add volume to the necklace and create areas where the UV-sensitive biofoam was more exposed.

Bracelets, rings, and earrings: We used a combination of molding and layering techniques to make these accessories, reusing existing silicone molds in the lab. We layered a photochromic biofoam mixture on the bottom and a thermochromic biofoam mixture on the top for the bracelets (see Fig. 3.13b). This allows us to see the material changing color when worn outside under the sun. The rings and earring were made using only biofoam with photochromic pigment (see Fig. 3.15b).

Face mask: We laser cut a 1 mm biofoam sheet and sewed it on top of a cloth face mask (see Fig. 3.15a). This biofoam sheet was made using only thermochromic pigment in the recipe. The laser cutting parameters we used were 7% power and 50% speed. The wearer was able to control the color of the biofoam on the mask by inhaling cold air using her mouth and exhaling warm air through her mouth.

Furthermore, we tested the biofoam as a stabilizer for embroidery and patchwork (Fig. 3.16a, b). We used a 2 mm biofoam sheet to embroider a patch that was later attached to a jeans jacket. This worked because the sheet was translucent enough to draw guidelines on and then follow them during embroidery. Moreover, by dissolving the biofoam rather than composting it, we could use it as a water-soluble substrate that functions as an interface in embroidery (Fig. 3.16c).

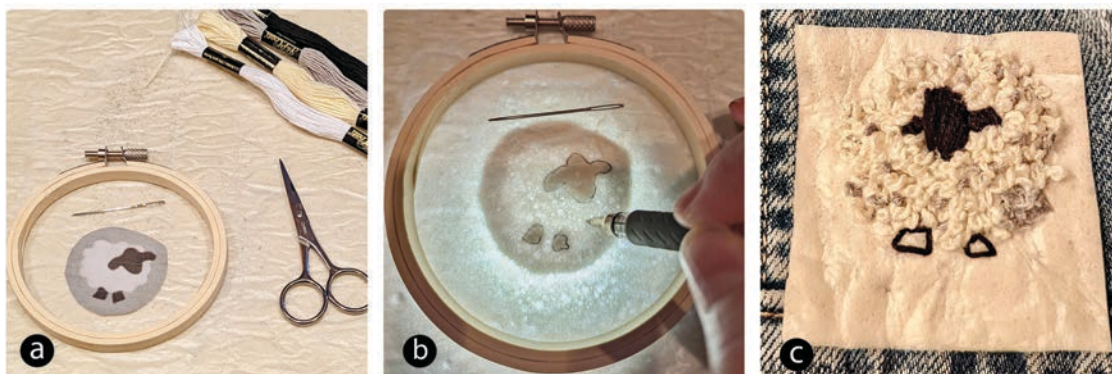


FIGURE 3.16: Dissolvable biofoam as a stabilizer for embroidery or patchwork: a.interface for embroidery, b. during embroidery, c. patchwork

3.5.2 Sensing

Conductive biofoam can serve as capacitive touch sensors, force-sensitive resistors (FSRs), and soft shielding for Faraday cages or ESD protection. We found the FSRs particularly compelling as the compression interaction is built into the foam and conductivity, compression, and recovery time can be tuned simply by altering the recipe. The form of the sensor can also be customized by molding the mixture into specific shapes and textures lending to further play with the interaction and design. For example, Bae and West felted stainless steel fibers into various shapes to inform interactions like press, pinch, and touch [13]. There is a wide range of practical and creative uses for customizable biofoam FSRs, from smart shipping packaging to soft controllers [144] and robotic skin [111]. We molded twelve cylindrical FSRs, 5 cm in diameter and 2 cm in height, from a single recipe (see Appendix A.6 in [122]) and used the *folding* technique with 5 g of 8 microns stainless steel roving fiber of average length of 2.5 cm. We randomly selected and tested four out of these twelve sensors to obtain force vs. resistance performance characteristics, shown in Fig. 3.17.

Electrical Characterization: We constructed circular electrodes from a

copper taffeta fabric (5 cm in diameter) and placed them on the top and bottom of the biofoam FSR. By creating a voltage divider with the biofoam FSR (Fig. 3.18), the variable voltage as a result of an applied pressure can be read by a microcontroller's ADC input.



FIGURE 3.17: Four force-sensitive resistors tested using a force meter to obtain force vs. resistance plots.

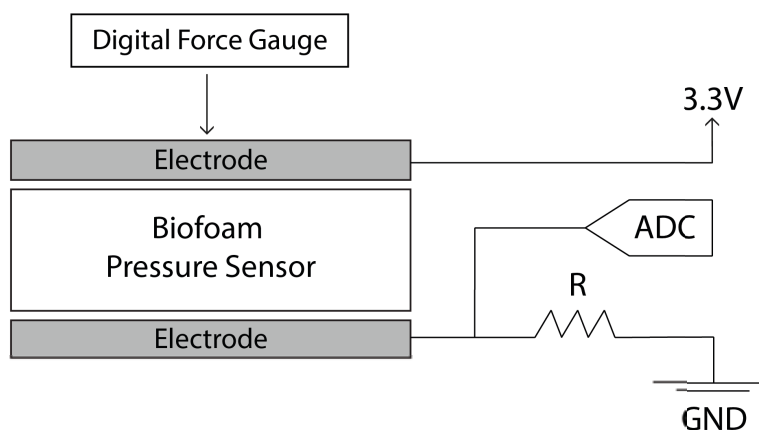


FIGURE 3.18: A digital force gauge is used to apply and measure a normal force to the sensors. A microcontroller is used to read the resistance between the two electrodes.

A normal force was applied in 5 N increments from 15 N (1529.57 g) to 60 N (6118.30 g) using a digital force gauge. At each increment, 100 samples were recorded at 10 Hz and converted to resistance using the following formula:

$$Resistance = R_{div} * ((3.3 / (ADC * 3.3 / 1023)) - 1),$$

where R_{div} is the 330 ohm fixed resistor of the voltage divider and ADC is the reading from the ADC pin of the microcontroller. The resistance values were then averaged to obtain the plots, as shown in Figure 3.19 where sensor 1 and sensor 4 exhibited characteristics similar to typical FSRs [60], however their resistance values varied by orders of magnitude.

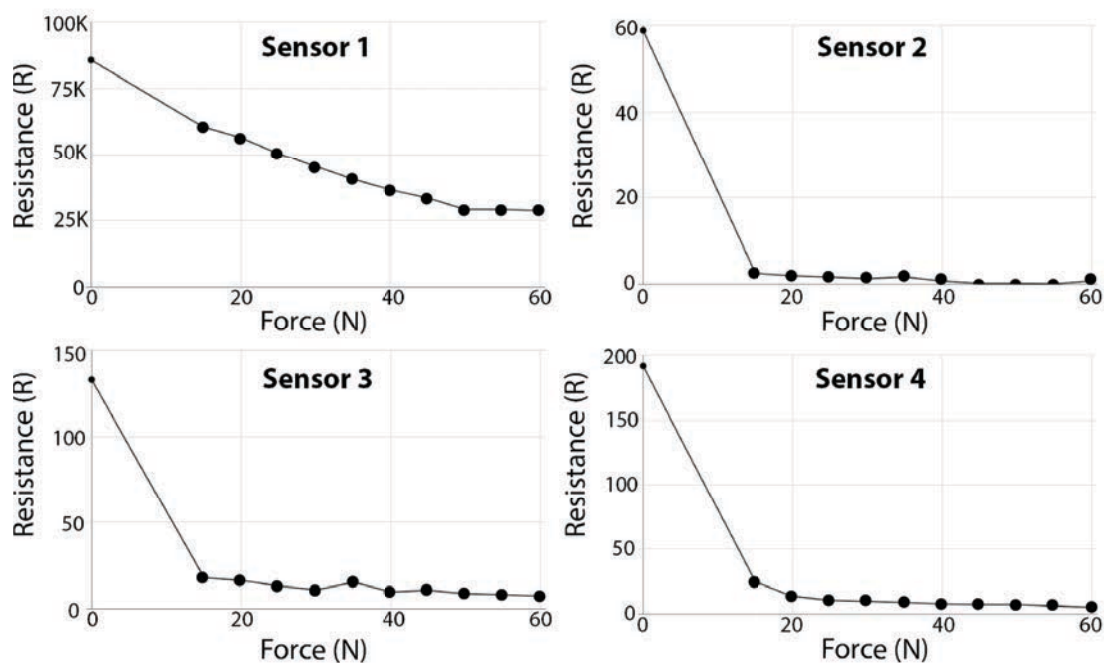


FIGURE 3.19: Force (N) vs. resistance (R) plots for each FSR sensor.

At this time, the disbursement of the individual stainless steel conductive fibers and how they settle during molding and casting processes is uncontrolled. Additionally, the fibers may become intertwined or felted and consequently untangled during compression and recovery which potentially changes the

characteristics of each sensor with each use. Interestingly, sensor 2 and sensor 3 exhibited a similar unexpected behavior of increasing instead of decreasing its resistance when 35N (3569.01 g) was applied.

3.6 Discussion

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

3.6.1 Design considerations of biofoam in HCI

Our approach was motivated by an attention to materiality and attuned to development and use as highly sensory and creatively productive activity. This attention was cultivated through each step of the biofoam life cycle, from cooking the materials from raw ingredients and modifying the recipe to achieve particular qualities, to using the materials in standard HCI prototyping workflows, to dissolving and experimenting with possibilities at the moment of material destruction. We believe this linear relationship through time opens up an interesting perspective on the role of temporality of material interaction. Where we typically describe a material as a given set of affordances or properties, here, we followed a set of base ingredients

through multiple forms and states, studying possibilities for interaction and customization along the way. For instance, during the fabrication process of the biofoam, various ingredients' materiality and properties at play made us question design considerations of durability, malleability, fragility, density, viscosity, biodegradability, and so on. This influenced reflection beyond the realm of "tangible" experience towards questioning other sociocultural and environmental considerations such as how our ingredients are sourced, the distances they travel to reach our lab, or the potential impact on people and our planet the biofoam could have at its end of life.

We compare the temporality of fabricating the biofoam to the temporality of cooking. Design considerations of tunability (ability to be modified), accessibility (easy to find), and replicability (easy to make) accompanied us throughout the fabrication process just as they do when considering making a new recipe for dinner. Since we were familiar with various cooking techniques, fabricating the biofoam from scratch was less intimidating in comparison to other hand-craft techniques that require higher levels of expertise such as pottery or quilting. The similarity of our experiences cooking food to cooking biofoam helped us set our expectation for the outcomes. Specifically, when we didn't get what we wanted to expected, the stakes did not feel as critical, and we simply started again with a new technique (often drawn directly from our experiences cooking and baking). For instance, while looking for the right technique to embed the conductive fibers in the biofoam, we tried multiple techniques that were inspired by cooking: First, we tried whisking the conductive fibers into the mixture however the conductive fibers clumped and stuck onto the whisker. In a second attempt, we had already spent time interacting with the material and had a better idea of its possibilities;

through continuous observation we found similarities in making biofoam and a meringue recipe. This led us to think of using a folding technique to was the conductive fibers in the biofoam just as one folds a dry mixture into whipped egg-whites without removing the airy texture.

3.6.2 Dissolving as a design opportunity

Biofoam, like most materials, has a finite lifespan – a piece of biofoam will reach a point where it has been squished, pressed, or squeezed one too many times, and will no longer recover or function. Previous research projects such as Unmaking [179] and Unfabricate [215] highlight how a design's obsolescence and breakdown does not need to mean the end of its material life. Rather, designers can embrace this inevitable decay as an agent that changes artifacts over time, provoking users and designers alike to engage with sustainability and recycling efforts [215]. In looking towards deconstruction as a design resource, we ask, "How can we design with biofoam's ability to dissolve in water, and use it as interaction?". To this effect, this material integrates well into a growing discourse within HCI on themes of decay [127], obsolescence [89, 97], living materials [48], and material drift [75, 190].

We believe that by focusing on the biofoam's entire life-cycle in design, current interactive designers' attention could shift from 'how to shape the material from a human-centric approach' to a more material-centric approach such as Being the machine [45], or Wabi-Sabi [189]. This creates space for observation and material experience focused on the material's temporal aspects, making it simpler to trace the relationships between different materials and the dimensions of acknowledged fabrication processes and practices [6].

3.6.3 Supporting sensory experiences in users

We found that fabricating the biofoam and using it as an interactive material offered unique sensory experiences. For instance, cooking provided a natural sensory-rich experience that helped us learn and develop a greater understanding of the material through an embodied experience. Other senses such as smell, touch, and sound were more present in the use phase. For example, we found that additives not only played a technical role in the recipe but also effected the scent and visual profile of the material. Specifically, walnut hull powder added a pleasant smell to the samples in addition to functioning as a binder and we found ourselves using walnut hull more often because of its nice smell. Similarly, the use of non-scented organic soap was a decision made after trying scented soaps that made the biofoam samples smell like clean dishes. Here, smell associations became a powerful part of the interaction, demanding attention whether we designed them intentionally or not.

In regards of the visual and sonic qualities of the biofoam, using the molding technique allowed for serendipitous material discoveries. For instance, when we molded the biofoam bracelets using a microcentrifuge tube rack, the outcome (see Fig. 3.15b) was visually inviting and the texture made us want to pull and poke the bracelet while wearing it. We wanted to enhance this inherent desire by adding heat sensing pigment which would further react to touching. When we began to interact with the cured foam samples, we realized they each possessed their own individual sound qualities that inspired us to want to record biofoam ASMR in the future. Here we found biofoam shifting our attention from the overarching scenarios of use to attending to the micro-sensory details.

3.7 Conclusion

This chapter established gelatin-based biofoam as a tunable, low-tech, and sustainable material for interactive textile design. Through iterative formulation, the project showed how density, elasticity, water resistance, and color responsiveness could be adjusted to create interactive prototypes such as dissolvable pressure sensors and thermochromic accessories. These explorations positioned material formulation, making, and decay as active sites for shaping interaction, shifting attention from electronics-first approaches, to interactions grounded in the material's evolving properties.

In relation to **RQ1**, the project demonstrated how biodesign practices rooted in material exploration integrate sustainability from the outset, with lifecycle thinking, by-product sourcing, and reusability guiding material and fabrication decisions. In relation to **RQ2**, it highlighted material agency—how behaviors such as compression change, dissolution, and thermal color shifts inform both aesthetic and functional design.

By making biofoam recipes and fabrication methods openly available, the work reinforced the dissertation's commitment to accessibility and community-driven material innovation. As the first of the dissertation's three projects, Biofoam for Tangible Interaction laid the groundwork for later explorations into dissolution-based wearables and fiber-level biomaterial fabrication, illustrating how sustainability can be enacted as a design value through the hands-on development of new materials for interactive textiles.

Chapter 4

Designing Dissolving Wearables

A Material-Driven Design Approach to Interactive Textiles



Reproduction Note: *This chapter reproduces material from the publication: Eldy S. Lazaro Vasquez, Lily M. Gabriel, Mikhaila Friske, Shanel Wu, Sasha De Koninck, Laura Devendorf, and Mirela Alistar. 2023. Designing Dissolving Wearables. In Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing (UbiComp/ISWC '23 Adjunct). Association for Computing Machinery, New York, NY, USA, 286–290. <https://doi.org/10.1145/3594739.3610781>. It appears here with permission from the publisher, with minor changes to formatting and terminology to fit the dissertation.*

4.1 Introduction

This chapter focuses on designing dissolving wearables by fabricating and working with gelatin biofoam yarns, expanding the exploration of biomaterials and their unique affordances. This work builds upon the dissertation's emphasis on material agency and how it can shape the design and functionality of interactive systems. By crafting wearables such as "Seasonal Footwear," a "Reveal Bralette," and an "Unfolding Lace Top" (Fig. 4.2) using techniques like crocheting, and knitting, this chapter demonstrates how the dissolving property of biofoam can be leveraged to create ephemeral and interactive designs, advancing the dissertation's claim that design can engage with the temporality of materials as an interaction. This chapter addresses the dissertation's exploration of sustainability by introducing a "design to dissolve" approach, and proposes a way to embrace obsolescence as part of the design, and the process itself becomes a source of interaction and meaning. This work contributes to the field by demonstrating how traditional textile craft techniques can be

integrated with biomaterials, and how dissolving can be used as a unique design affordance in wearable technology, showcasing a new pathway for the development of sustainable, interactive textiles.

4.2 Dissolving Wearables

In this study, we explore *dissolving* as an intentional design affordance for fashion wearables. We demonstrate this concept through three use cases, showcasing the potential of biofoam yarns with dissolving attributes when combined with other materials using traditional textile craft techniques such as weaving, crocheting, and knitting. The selection of a bio-based material was guided by considerations of comfort and tactile experience. Moreover, this work serves as an initial effort to gain insights into the behavior of biofoam yarns when blended with other materials and subjected to various levels of stress during fabrication and wearing.

4.2.1 Fabricating Biofoam Strings and Yarns

Biofoam strings, resembling yarns, serve as the primary "building blocks" for crafting "Seasonal Footwear", "Reveal Bralette", and an "Unfolding Lace Top". While the detailed process to create biofoam is documented in our previously published paper with the open-source recipe [122], for this study, we used recycled biofoam scraps available in our lab. Moreover, we developed a tutorial¹⁰ presented at a DIS'23 workshop [197], outlining the fabrication of biofoam strings, which can be found as supplemental material. To obtain the strings, we devised a user-friendly technique adapted from traditional

¹⁰How to make biofoam strings. <https://www.softrobotics.io/post/how-to-make-soft-biofoam-strings-exploring-an-affordable-and-accessible-fabrication-method>

cake piping. Employing syringes of varying diameters and pipe bags, we meticulously extruded the biofoam into strings of diverse thicknesses and textures. Below, we outline the steps involved in our process.

Melting biofoam scraps: We chopped the biofoam scraps into small pieces using scissors. Then, we added half a cup of chopped biofoam to 20 ml of boiling water in a pot. Keeping the mixture at a constant temperature of 140°F, we stirred with a silicone spatula until the biofoam scraps fully melted. One of the challenges at this phase occurred when there were density inconsistencies (lumps) in the biofoam scraps. In this case, the gelatin, the main component of the biofoam, visually started sticking to the bottom of the pot. To address this, we added the same initial amount of water to the pot (20 ml), removed the pot from the heat, and continued stirring with the silicone spatula. After the mixture became more homogeneous, we placed it back on the stove at 140°F and stirred until reaching a "soft" or "stiff" peaks meringue stage (Fig. 4.1b, Fig. 4.1c).

Making biofoam meringue: In successful biofoam extrusion, the meringue stage (foamy, soft, stiff, or broken) plays a crucial role. Paying close attention to this step is essential. If the biofoam meringue is in its *foamy stage*, the strings will contain numerous air bubbles that evaporate during drying, resulting in a flattened shape (Fig. 4.1a, Fig. 4.1e). An increased amount of air also affects the follow-up interaction, as airy strings tend to compress upon touch. Piping the biofoam at the *soft peak stage* creates a half-moon cross-section in the strings (Fig. 4.1b, 4.1e). This stage is suitable for novice crafters as it allows time for testing extrusion steadiness and allows for trial and error. Piping at the *stiff peak stage* produces the most rounded strings (Fig. 4.1c, Fig. 4.1e). This stage is ideal for experienced crafters who can maintain a constant extrusion speed to avoid clogging. The mixture hardens quickly at this stage, requiring fast and steady

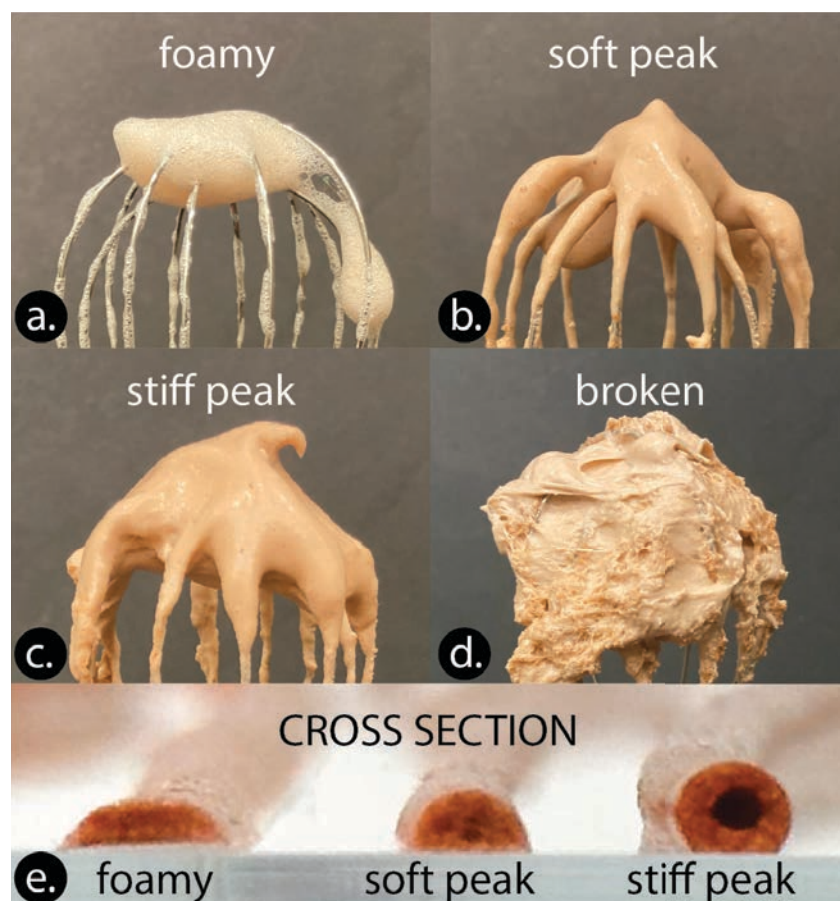


FIGURE 4.1: Different consistencies of biofoam meringue: a. foamy, b. soft peak, c. stiff peak, d. broken, e. cross-section of biofoam yarns at different consistencies.

extrusion. If the biofoam meringue is in a *broken stage* (Fig. 4.1d), typically due to excessive stirring, it is best to fix the consistency or start over. Extruding from a piping bag with a broken meringue is likely to be unsuccessful due to the high risk of clogging. To fix the consistency, we recommend adding a bit of hot water and stirring until soft peaks appear on the spatula.

Extruding biofoam strings and making yarns: We used a pipe decorating tip set¹¹ to extrude biofoam strings. The extruded strings were dried for at least 12 hours on a non-stick surface, like acrylic or non-stick silicone, to ensure proper

¹¹Wilton 55-Piece Cake Decorating Tip Set. <https://tinyurl.com/4bzvcdum>

curing and reduce stickiness. To prevent clogging during extrusion, we kept a cup of hot water nearby and dipped the metal tip in it for one minute when necessary (see supplemental material for illustration). Initially, our extrusion process was slow, leading to quick setting inside the bag. In such cases, we had to put the biofoam back in the pot and recook it to restart the process of making biofoam meringue. After extensive experimentation (Fig. 4.2), we found that using only piping tips with 1 and 2-mm diameters was the best option for producing larger amounts of biofoam strings while preserving the original color of the biofoam scraps. The volume of our piping bags allowed a maximum length of 1 m for the extruded strings. To elongate the strings, we developed two methods to adhere multiple strings together. The first method involved dipping one end of a string in warm water and immediately placing it on top of a second dry biofoam string end. Water caused the biofoam string to swell and function as glue. We then pressed the two string ends together for a couple of seconds and released the pressure afterward to verify successful joining. The second method, spinning, was used only when making 2-ply biofoam yarns.



FIGURE 4.2: Biofoam yarns of 2 mm diameter in various pastel colors.

4.2.2 Use Cases

We used biofoam yarns to craft dissolving wearable fashions, envisioning three use cases for this feature: 1) "Seasonal Footwear" (Fig. 4.3), 2) "Reveal Bralette" (Fig. 4.4), and 3) "Unfolding Lace Top" (Fig. 4.6). In the first two cases, users intentionally trigger the dissolution process, while the third case explores how weather conditions like rain or humidity might contribute to the wearable's dissolution or shape change. As the biofoam yarns dissolve, they leave behind non-dissolving yarns, forming new wearable patterns and structures.

Seasonal Footwear: We crafted this wearable, as shown in Fig. 4.3, by customizing a crocheted sandal that blends biofoam, cotton yarn, and a flip-flop base. After wearing them in the Spring, the sandals can be transformed into more open sandals for the Summer. The user triggers the transformation intentionally by washing the sandals, causing the biofoam to dissolve. Thus, the Summer sandal is the result of one washing machine cycle with warm water.



FIGURE 4.3: "Seasonal Footwear" (crochet) loses the straps after dissolving, becoming more open to suit warmer seasons.

As Spring sandals, they feature heel and ankle support entirely crocheted with biofoam yarn, which dissolves completely during washing. The top of the vamp is crocheted with a blend of cotton and biofoam yarn, partially dissolving as the biofoam yarn serves a decorative purpose without compromising the wearing comfort and stretchiness of the sandals. We made several iterations, deciding which sections to create with biofoam and which with standard cotton. To cover the rubber strap, we applied a single crochet stitch, creating a base for continuous crocheting. Using a blend of cotton and biofoam yarn, we employed a single crochet stitch to cover the top section of the sandal, reducing stitches to accommodate the triangle shape. We crafted a back strap out of biofoam to secure the Achilles heel and upper ankle, attaching it to the side straps. Finally, we created a lace by chaining and threaded it through the top ankle strap.

Reveal Bralette: We crocheted a bralette that through *dissolving* reveals a new design upon interacting with water (Fig. 4.4). The bralette features light blue biofoam yarn, matching the color of other yarns and concealing the dissolving elements. The bralette's overall design draws from various crocheted granny square designs, traditional motifs that are also popular in contemporary crochet fashion. We selected a granny square design with long, spoke-like stitches (dark blue) to ensure structural integrity after the biofoam yarn dissolved. Alternating rings of biofoam and cotton yarns were supported by these non-dissolving stitches, and we secured them with matching yarn to prevent unraveling when the biofoam dissolved. Our approach not only prevents the garment from "falling apart" but also allows us to intentionally create a design that changes upon dissolution. For example, we designed the bottom border to transform, hanging differently after interacting with water (Fig. 4.4b). By using chain stitches made with either biofoam or light-blue yarn, specific stitches dissolve



FIGURE 4.4: a. Crocheted bralette chest before dissolving. b. After dissolving the light blue biofoam, patches become hollow and expose the underlying layer in the bralette, which is orange.

upon contact with water, releasing the orange yarn strings and bringing a new dimension to the design. We envision wearing the *Reveal Bralette* at a festival where water exposure could trigger a transformation, presenting a color pop or transitioning to a more lacey pattern. This concept could be extended to full clothing pieces, where a second skin is revealed as the soluble material interacts with warm water, offering novel possibilities in fashion design.

Unfolding Lace Top: We designed this wearable to use *dissolving* to alter its shape (Fig. 4.6). Using hand-knitting techniques, we created an unfolding stitch structure and knitted a sample swatch to test different stitches and yarns (Fig. 4.5). The structure consists of densely knitted cords with lace bands in between; the lace uses thinner yarn and open stitches, forming a lighter fabric. Biofoam yarn is placed between the cords, scrunching the lace into a pleat.

To construct the garment, we knitted a bra base and sewed in the lace panel. Applying water with a spray bottle while wearing the top gradually dissolved the biofoam. Some segments unfolded earlier while others stayed folded, depending on water placement, and movement from the wearer accelerated

dissolution. We hypothesize that unfolding is shaped by how water reaches the garment—whether applied intentionally or through environmental factors like rain.

The “Unfolding Lace Top” structure could be incorporated into various garments, such as a jumpsuit, to produce more dramatic shape changes. Even multiple identical pieces would transform differently based on water exposure and wearer movement. For instance, a set of dance costumes could yield unique silhouettes in each performance.



FIGURE 4.5: “Unfolding Lace Top” swatch to test the unfolding stitch structure. a. before, and b. after dissolving the swatch in cold water.



FIGURE 4.6: “Unfolding Lace Top” (knit) unfolds into a new design upon dissolving.

4.3 Discussion and Limitations

While our wearables did not incorporate electronics in their design, we believe our fabrication process and hand-craft techniques could support future prototypes that integrate electronics alongside the dissolving materials to make interactive wearables. Dissolving biomaterials in wearable electronic textiles could support the current body of research within HCI of design for decay and decompose [19, 127, 199], disassembly [215], and unmaking [179]. All of which can be tied to sustainability goals. With this understanding, we could develop more sustainable e-textiles using "dissolving" as an interactive feature. For instance, when a moisture sensor is embedded in a knitted garment that incorporates biofoam yarn, the contact of the garment with sweat or moisture (e.g., from the wearer's skin) could initiate the biofoam yarn dissolution, thereby triggering the sensor to measure and transmit data. Conversely, the garment could contain embedded electronics that actively control the dissolving process, utilizing mechanisms such as small water capsules that activate when compressed, thereby enabling the development of programmable dissolvable garment designs. Our paper additionally facilitates the reduction of barriers to entry for hand-craft methods in prototyping dissolving wearables since current innovations and research in sustainable wearable electronic textiles require specialized equipment to make and use their materials [52]. Furthermore, we would like our fabrication method could be used to inform future tool designs in wearable technology research.

Reflecting on textile craft techniques: We chose techniques that allow customization of a garment's structure or stitch density. Knitting and crocheting supported this level of customization better than weaving. For instance, while

the dissolution or unraveling of woven structures leads to complete garment disassembly, knitting or crocheting enabled us to explore other design attributes such as revealing or unfolding. Furthermore, crocheting with blended biofoam and cotton yarn produced a tight mesh that, after dissolving, loosened and became airier, showing a clear change in stitch density (Fig. 4.6b, Fig. 4.5).

Designing to dissolve: When designing dissolving wearables, we adopted a body-conscious approach, carefully considering the placement of biofoam dissolving sections on the body and how the body interacts with the material. This required a different mindset, where designers must detach themselves from their labor, knowing that it will eventually dissolve away. Wearables made with dissolving biofoam materials become ephemeral, with a limited lifespan due to their ability to dissolve upon interaction with water, such as in rain or sweat. However, this ephemeral nature also presents an opportunity for these wearables to record and physicalize aspects like weather or emotions.

Limitations: The biofoam yarn's characteristics are highly dependent on the environment. For instance, while knitting the *Unfolding Lace Top*, co-author Shanel, traveled from a humid to a drier climate, causing the biofoam yarn to become less sticky and less elastic as it dried out. This difference in tactile experience did not make it easier or more difficult to work with the biofoam, but it was noticeable. Another limitation arises from the residues left behind after the biofoam dissolves, particularly in unintended scenarios like exposure to rain or during water fights at festivals. This also affects the non-water soluble yarn left behind, making it slightly crunchy. This observation led us to recognize the importance of intentionally placing the biofoam, transforming the act into a deliberate design decision rather than a mere experiment.

4.4 Conclusion

This chapter foregrounds **dissolving** as a design affordance, showing how material decomposition could be intentionally embedded into wearable artifacts as a form of interaction. Working with gelatin-based biofoam yarns, the project explored short-term applications such as one-time reveals, gradual transformations, and shape changes triggered by water exposure. These interactions positioned dissolution not as a failure mode to be avoided, but as a temporal and expressive quality that could carry meaning in use.

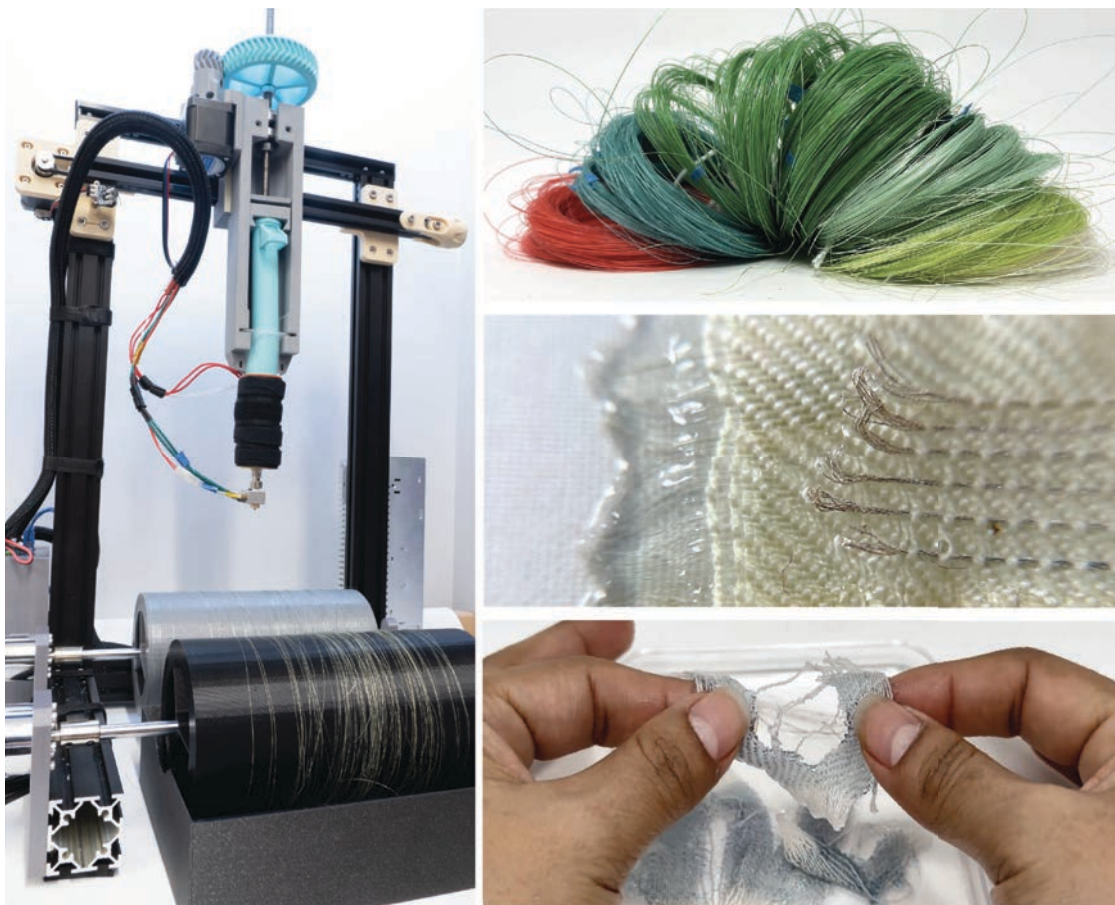
In relation to **RQ1**, the work demonstrated how biodesign practices grounded in material exploration embedded lifecycle and transformation into the earliest stages of wearable design. Dissolving shifted the design process toward thinking with end-of-life as an active site of interaction, expanding possibilities beyond electronics-first approaches. In relation to **RQ2**, the project showed how the rate, texture, and visual dynamics of dissolution could be treated as aesthetic and functional parameters, influencing both the look and behavior of the garments.

By integrating dissolving biomaterials into textile craft through knitting and crocheting techniques, the project bridged material-led experimentation with wearable textiles. This alignment reinforced the dissertation's broader argument that sustainability can be a creative driver, opening new forms of interaction through material properties like dissolution, temporality, and transformation. *Designing Dissolving Wearables* thus contributed a tangible example of how interactive textiles can be reimaged when ephemerality is embraced as a core design resource.

Chapter 5

Open-Source Biofibers Machine

A Research-through-Design Approach to Designing a Low-cost, Open-source Spinning Machine



Reproduction Note: *This chapter reproduces material from the publication: Eldy S. Lazaro Vasquez, Mirela Alistar, Laura Devendorf, and Michael L. Rivera. 2024. Desktop Biofibers Spinning: An Open-Source Machine for Exploring Biobased Fibers and Their Application Towards Sustainable Smart Textile Design. In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, Article 856, 1–18. <https://doi.org/10.1145/3613904.3642387>. It appears here with permission from the publisher, with minor changes to formatting and terminology to fit the dissertation.*

5.1 Introduction

This chapter presents the design and development of the Open-source Biofiber Spinning Machine, a desktop-scale fabrication tool created to enable fiber-level experimentation with biomaterials in the context of interactive textiles (see Fig. 5.1). Building on the material-led explorations of gelatin-based biomaterials in the previous chapters, this project addresses the practical challenge of producing consistent, customizable fibers from gelatin-based formulations. By introducing a dry-jet wet spinning process adapted for a low-cost, open-source platform, the work expands the possibilities for integrating biomaterials into textile structures and supports the dissertation's focus on accessibility, sustainability, and lifecycle thinking.

The machine was conceived in response to limitations encountered when making gelatin-based yarns, where small-batch, manual fabrication processes constrained scale, repeatability, and design flexibility. My collaborators and I designed, built, and iteratively refined this machine capable of controlling

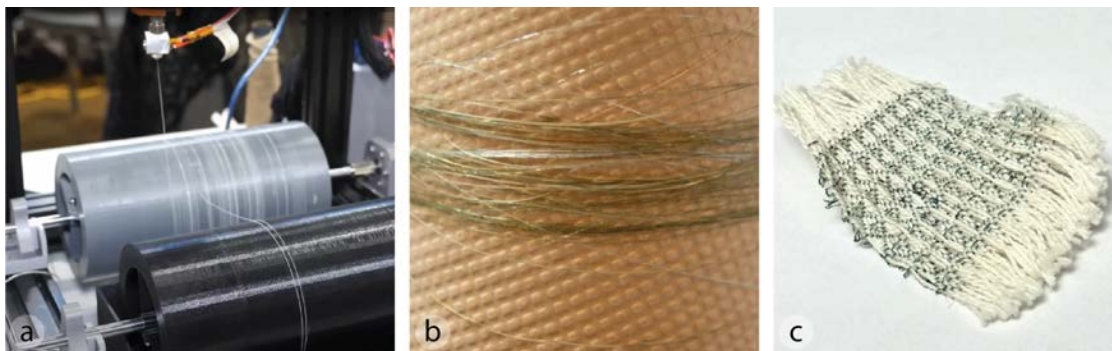


FIGURE 5.1: An overview of Desktop Biofibers Spinning: (a) gelatin biofibers spinning process using our machine; (b) a spool with green gelatin biofibers, (c) gelatin biofibers woven into cloth.

parameters such as extrusion speed, nozzle temperature, and collector rotation, enabling the fine tuning of fiber properties like diameter, elasticity, and color [120]. Methodologically, this work combines Research through Design (RtD) with elements of Technical HCI evaluation, using hands-on prototyping both to explore material-machine interactions and to assess the tool’s performance. The contribution of this chapter lies in advancing fiber-level biomaterial fabrication as a design space—one where interactive textile designers can work directly with the properties of the fibers they produce, rather than relying solely on inaccessible pre-existing industrial spinning machines. This work supports the dissertation’s third main contribution: the development of an open-source fabrication tool for biomaterials, positioned as part of a systemic approach to sustainable interactive textiles.

5.2 A Desktop Biofibers Spinning Machine

Our Desktop Biofibers Spinning Machine is designed to mimic a dry-jet wet spinning process, a variation of wet spinning (Fig. 5.2). A comparison between our machine and a lab-scale wet spinning system is shown in Fig. 5.3.

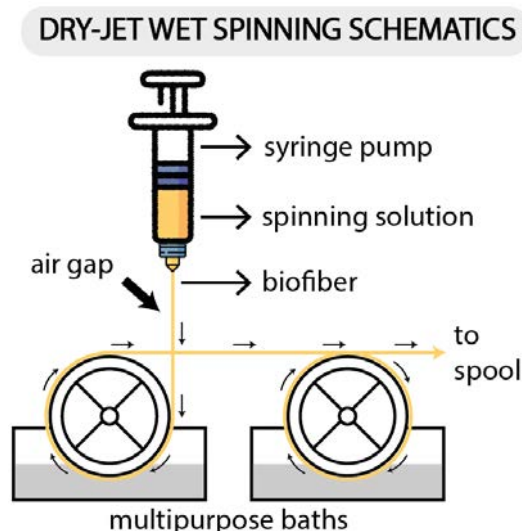


FIGURE 5.2: Dry-jet wet spinning schematic of our machine. The multipurpose baths can be used for any post-production process such as coagulation, finishing, drying, or treatment.

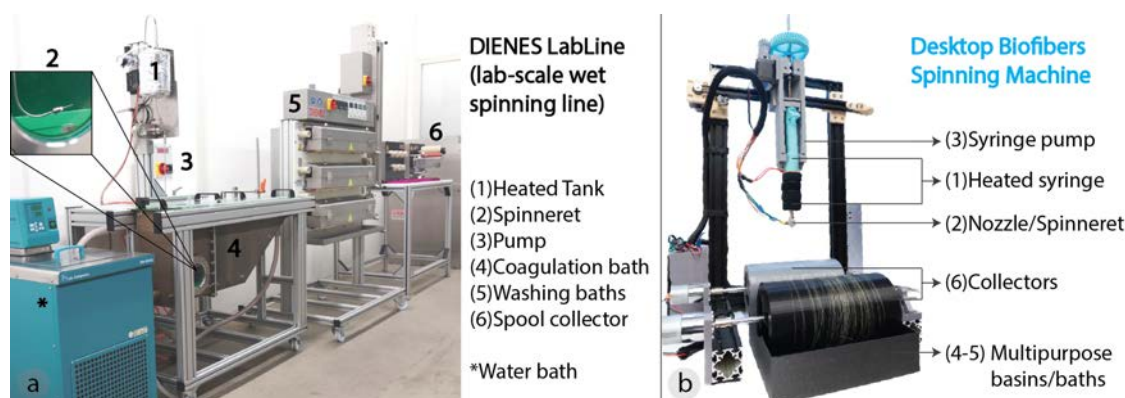


FIGURE 5.3: Comparison between DIENES LabLine, a lab-scale wet spinning machine, and the Desktop Biofibers Spinning Machine. In both setups, an off-the-shelf (*)water bath can be used.

Crucially, our machine enables biofibers with customizable properties to be produced from liquid biobased solutions. This accessibility allows researchers and designers to experiment with diverse biomaterial formulations at a desktop scale, supporting rapid iteration without the specialized infrastructure typically required for fiber manufacturing. Next, we describe the machine's design and outline the fiber-spinning process.

5.2.1 Machine Design

The Desktop Biofibers Spinning Machine is inspired by desktop 3D printers and is constructed from readily available components (e.g., aluminum extrusions). It is designed to be modular—different components of the machine can be swapped or extended to enable different material explorations and further customization in produced fibers. The full bill of materials, part files, and associated firmware are open-source and available at: <https://github.com/utilityresearchlab/desktop-biofibers-spinning/>.

Mechanical Components. The machine has several major components: the frame; the X-axis carriage; the syringe pump; the heated syringe; the nozzle/spinneret; the expandable Y-axis; and the collectors and basins. The basis of the machine is a frame made of various aluminum extrusions, similar to many open-source 3D printer designs. These frames enable various parts to be mounted and easily adjusted. The X-axis carriage is similar to one on a typical 3D printer. The X-axis carriage moves across from left to right based on user-specified commands. It is mounted on the vertical portion of the frame and its height determines the air-gap distance for the spinning process. In our setup, a motor-driven syringe pump is mounted onto the carriage. However, the carriage has mounting holes that enable other types of extrusion mechanisms (e.g., pneumatic) to be used instead. We use the open-source Large Volume Extruder (LVE) syringe pump [164] with a 60 mL luer lock syringe¹² on our machine to facilitate extruding potentially viscous material solutions. The syringe is heated with a 12V/25W silicone heater wrap secured to the syringe using hook-and-loop straps. The nozzle/spinneret attached to the tip of the syringe can either consist of a luer lock syringe tip (any size) or a standard

¹²60 mL Syringe: <https://www.amazon.com/dp/B007RYA22I/>

3D printer hot-end nozzle attached using a luer lock-to-M6 adapter¹³. The latter setup enables material solutions to be heated to a specific temperature at extrusion time. In addition, any size standard V6/M6-threaded 3D printer nozzle can be used.

The Y-axis of the machine—along the base of the frame—enables collector assemblies to be placed and the distance between them to be easily adjusted. Each collector assembly consists of a DC motor fixed to an 8 mm linear rod using a M5-to-M8 motor coupler, a 3D-printed roller (the collector), a latch mechanism, and printed brackets. The roller is fixed to the linear rod such that it rotates based on a user-specified speed in revolutions-per-minute (RPM). The latch mechanism allows the roller and rod assembly to be supported while rotating, but easily removable when the fiber spinning process is completed. Each collector is accompanied by a 3D-printed basin (multipurpose bath) that is placed underneath the collector. The basin serves as a container for various fiber production (e.g. coagulation bath) and post-production processes (e.g., finishing, drying, treatment, etc.). As a fiber is wound around a collector, it is coated by the solution in the basin. While the current machine setup features two collectors, the Y-axis of the frame can be extended with an adapter to support additional collector assemblies for further fiber post-production processing.

Electronics. The machine is controlled using an Arduino Mega 2560 Rev3 microcontroller¹⁴ coupled with a RAMPS 1.4 control board¹⁵. This combination is commonly used in open-source 3D printers. It provides the necessary functionality to run multiple heaters, temperature sensors, and motor drivers.

¹³Luer Lock to M6 Adapter: <https://www.amazon.com/gp/product/B087SXXK6S/>

¹⁴Arduino Mega 2560 Rev 3: <https://store-usa.arduino.cc/products/arduino-mega-2560-rev3>

¹⁵RAMPS 1.4: http://reprap.org/wiki/RAMPS_1.4

We use NEMA 17 stepper motors to drive the X-axis and the syringe pump. We use auxiliary pins on the RAMPS board to run additional Adafruit TB6612 1.2A DC Motor Drivers¹⁶, which control the 10 RPM DC motors of the collectors. A standard 3D printer hot-end assembly consisting of an NTC 3950-100K thermistor and a 12V/30W cartridge heater is used to heat the nozzle. Lastly, we use an additional NTC 3950-100K thermistor secured to the syringe heater wrapped with Kapton tape for temperature feedback.

Firmware. Our machine runs a variation of the Marlin 2.1.1 Firmware¹⁷, commonly used for desktop 3D printers. We modified the firmware to support the control (e.g., speed and direction) of multiple DC motors. These motors are used to independently drive the machine's collectors. We also made adjustments to various machine-related parameters including the steps/mm for the syringe pump motor; the min/max temperature ranges; and the temperature calibration for the syringe heater wrap and the nozzle heater. The temperature calibration was adjusted to accommodate the relatively low processing temperatures of many biobased material solutions (typically <100 °C). We communicate with the machine using G-code¹⁸ commands sent through Repetier-Host¹⁹, a commonly used 3D printer host controller software.

5.2.2 Biofiber Spinning Walkthrough

To illustrate the practical use of our machine, we provide a walkthrough of the fiber spinning process (Fig. 5.4). We describe each step of the process, producing

¹⁶Adafruit TB6612: <https://www.adafruit.com/product/2448>

¹⁷Marlin 2.1.1: <https://marlinfw.org/meta/download/>

¹⁸G-code Reference: <https://marlinfw.org/meta/gcode/>

¹⁹Repetier-Host: <https://www.repetier.com/>

gelatin biofibers that are flexible and yellow as an example (Fig. 5.9c). More details about fiber wet spinning considerations can be found in Section 5.3.

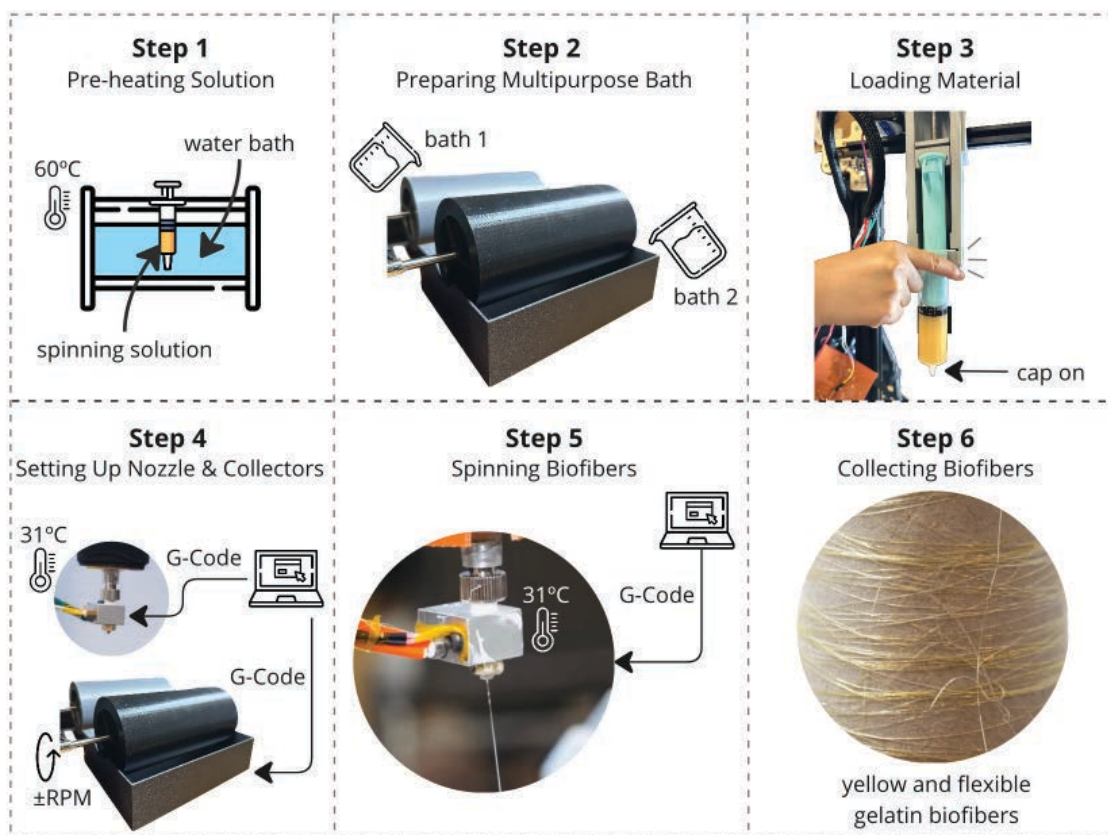


FIGURE 5.4: Biofiber spinning machine walkthrough to make yellow and flexible gelatin biofibers.

Step 1: Pre-Heating the Spinning Solution. We place a capped syringe containing the spinning solution in a 60 °C water bath for 15 minutes. As it warms, the solution should transition from gel-like to syrup-like. We then gently invert the syringe to check consistency; if the viscosity is still too high, the syringe is returned to the bath for another 5–10 minutes before re-evaluating. Once the desired consistency is reached, we proceed to the next step. For full instructions on preparing and storing the spinning solution, see Section 5.3.

Step 2: Preparing the Multipurpose Baths. This step involves the preparation and pouring of solutions into their respective basins. To create the gelatin biofibers, we designate the first basin (located directly below the syringe pump) as a coagulation bath which will precipitate the biofibers. The second basin (towards the front of the machine) is designated as the finishing bath which will add flexibility and color to the biofibers. In the first basin, we pour an off-the-shelf isopropanol solution (90% concentration) until the liquid reaches the bottom of the collector. For the second bath, we mix isopropanol (90% concentration), glycerine (5% concentration), and 3 drops of yellow food coloring in a separate container. We stir the mixture until the color is uniform and then pour it into to the second basin until it reaches the bottom of the collector.

Step 3: Loading the Material into the Machine. We retract the machine's syringe pump until the pre-heated syringe's plunger can be slotted in. This can either be done by manually turning the pump's drive gear or using the host controller software to send a retraction G-code command (e.g., `G1 E-40 F30` to retract 40 mm at 30 mm/min). We insert the syringe into the pump. We then secure the silicone heater wrap around the body of the syringe, ensuring that its associated thermistor is in direct contact with the lower section of the syringe's wall. Throughout this step, it is important to keep the syringe capped to prevent material loss. In host controller software, we set the heater wrap's temperature to be 40 °C using the G-code command: `M104 T1 S40`. We then wait until the temperature is reached.

Step 4: Setting Up the Nozzle and the Collectors. We remove the cap from the syringe and quickly attach the desired nozzle—either a luer lock syringe tip or the 3D printer hot-end using the luer lock-to-M6 adapter. In this case,

we use the 3D printer hot-end with a 0.4 mm diameter nozzle. In the host controller software, we set the temperature of the nozzle to be 31 °C using the G-code command: M104 T0 S31. We then wait until the nozzle temperature is reached. Afterward, we prime the nozzle by repeatedly extruding a small amount at a slow speed using the G-code command: G1 E0.1 F1. Once the spinning solution emerges from the tip of the nozzle, we set the speed of the collectors by sending the G-code command M3 S100, where the speed value is out of 255 and proportional to the max RPM of the collector's DC motor: $RPM_{\text{collector}} = (value/255) * RPM_{\text{max}}$. A value of 100 with a 10 RPM DC motor results in a collector speed of 3.9 RPM. While this setup maintains the same speed for all collectors, this will be customizable in future iterations of the machine.

Step 5: Spinning Biofibers. Once the collectors are in motion, we send the following G-code commands to home and zero the X-axis; set the machine and the extruder into relative movement mode; and reset the extrusion distances to zero:

```
G28      ; Home and zero the X-axis
G91      ; Enable relative mode for X-axis
M83      ; Set extruder to relative mode
G92 E0    ; Reset extrusion distances
```

Next, we compute a spinning command with our calculator spreadsheet²⁰ by inputting the following parameters: the amount of material to be extruded (0.1 mm); X-axis movement distance (2 mm); extrusion speed (0.2 mm/min);

²⁰Project GitHub: <https://github.com/utilityresearchlab/desktop-biofibers-spinning/>

and X-axis speed (4 mm/min). We send the generated spinning command, `G1 F4.005 E0.1 X2`, to the machine and follow a draw-down process (Fig. 5.8) to pull the material from the nozzle onto the first collector. This initiates the spinning of the first biofiber. As the fiber passes through the first bath, then attach it to the second collector. This causes the fiber to pass through the second bath, gaining a coating that provides the fiber flexibility and color. We then repeatedly send the spinning command to continue biofiber spinning through the length of the X-axis.

Step 6: Collecting the Biofibers. Once the biofibers are produced, we either remove the last collector by unscrewing the shaft coupler and sliding the latch mechanism open. Alternatively, the basins can be removed and the biofibers left to dry on the machine. After drying, the biofibers are wound onto a bobbin to be integrated into textiles using different techniques such as weaving and knitting. Refer to Section 5.5 for example applications. While this walkthrough gives an overview of making gelatin biofibers with our machine, it is important to note that it only offers a glimpse into what is possible with fiber spinning. In the next section (Section 5.3), we provide a detailed description of what is involved in fiber spinning and various aspects we considered before beginning the fiber production process and in our machine's design. We then offer various material explorations with our machine in section 5.4.

5.3 Fiber Wet Spinning Considerations

This section presents each stage of fiber dry-jet wet spinning (process captured in Fig. 5.5) and explains the rationale behind our own design and material approach. We also describe associated experiments that we performed at ITA

and how they were carried out with our Desktop Biofibers Spinning Machine. The goal of this section is to offer other HCI researchers and designers an understanding of what is involved in the fiber spinning process as well as support their potential exploration in fiber spinning.

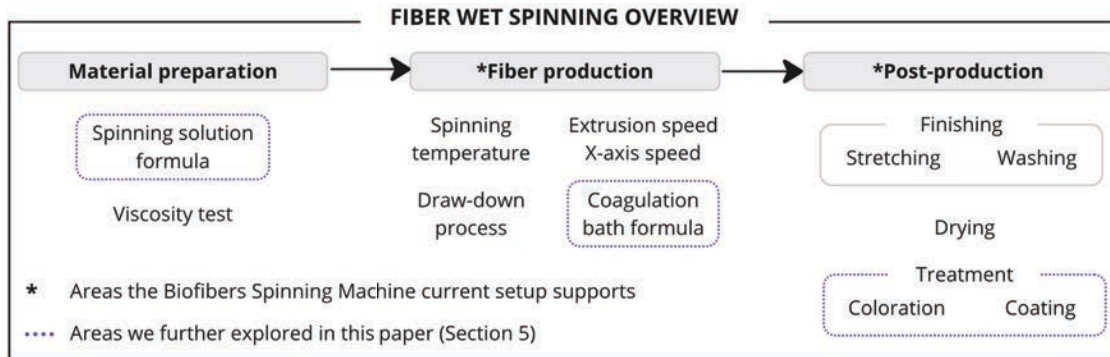


FIGURE 5.5: Fiber wet spinning overview; we marked the steps supported by our machine and what we further explored in this paper.

As shown in Fig. 5.5, making fibers through wet spinning requires an initial spinning solution, often referred to as *spinning dope*. To obtain strong and flexible fibers, the formulation of the spinning dope must consider the length of polymer chains and their alignment and distribution during the spinning process. In the realm of gelatin-based spinning solutions, materials science researchers have proposed formulations that often use expensive chemicals (e.g., crosslinkers that cost over USD 200 per 50 mg [90]); require a controlled environment (e.g., precise humidity and temperature levels); and are handled with specialized lab equipment (e.g., high-temperature ovens, fume hoods) [32]. Acknowledging that these requirements may not be accessible to HCI researchers and designers, we opted for a formula based on prior research [184, 185] that relies on only three relatively easy-to-find ingredients: gelatin, water, and isopropanol. Furthermore, our own fabrication experience at ITA using lab-scale equipment

(e.g., DIENES LabLine), led us to develop methods and tools to make gelatin spinning solutions without specialized equipment.

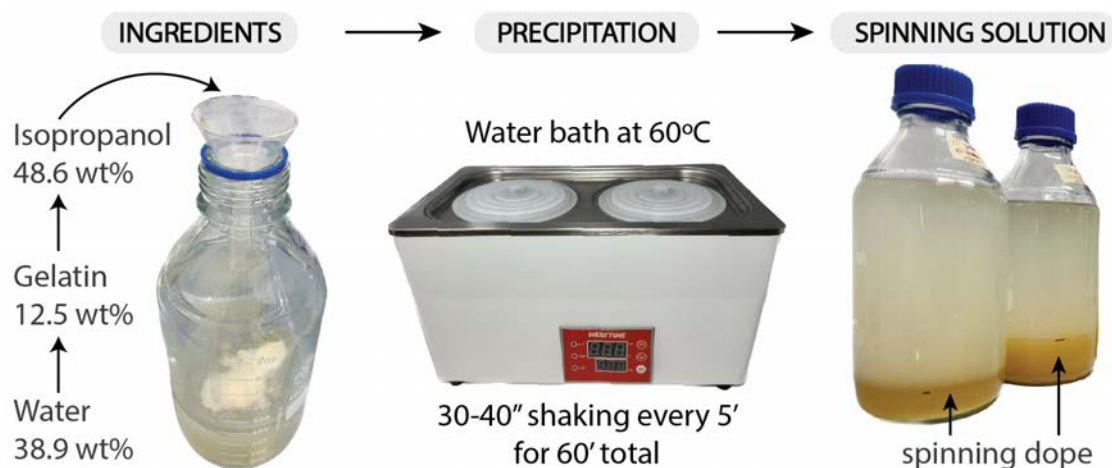


FIGURE 5.6: Spinning solution formula and preparation process to obtain spinning solution

Spinning Solution Formula: We mix gelatin (12.5 wt%), water (38.9 wt%), and isopropanol (48.6 wt%) (see Fig. 5.6), in a heat-resistant container, and place the mixture in an off-the-shelf water bath²¹ at 60°C. Across the next 60 minutes, we shake the container for 30 s to 40 s every 5 minutes. This process induces a two-phase separation, or precipitation, caused by gelatin chain aggregation and the formation of longer polymer chains. After overnight cooling, we decant the top layer (a mixture of isopropanol, gelatin, and water) for reuse and retain the precipitated *spinning solution* at the bottom. We then refrigerate the spinning solution, which can last for over a year and support continued experimentation.

Viscosity Test: Upon learning that the optimal viscosity for the DIENES LabLine at ITA is between 10 Pa to 12 Pa, we conducted experiments with various polymeric concentrations (5 wt%, 7.5 wt%, 10 wt%, and 12.5 wt%) at temperatures ranging from 27 °C to 60 °C, covering temperatures below and

²¹ Electric Lab Water Bath (2 openings): <https://a.co/d/aFHgRin>

above gelatin's melting point [72]. These experiments involved measuring viscosity with a rheometer and establishing a correlation with the gelling temperature, commonly referred to as the "sweet spot" [72]. We found that at 35 °C, the viscosity remains unaffected by shear rate. While at 27 °C, the solution is more viscous but gels quickly. Based on these results, our "sweet spot" is a spinning solution with 10 wt% or 12.5 wt% polymeric concentration spun at a temperature between 30 °C to 40 °C. Consequently, we adjusted the original formula [184, 185] to increase the polymeric concentration to 12.5 wt%. This adjustment allowed us to replace the more expensive pure gelatin used in previous research (\$54 per 110 g [2]) with a locally-sourced commercial 300-bloom gelatin²² (\$4.60 per 100g). Our experiments, including tests run on the ITA RWTH Aachen's DIENES LabLine machine, demonstrated that the 12.5 wt% solution was able to compensate for the potential lower purity of the gelatin which could have affected the length of the polymeric chains.

Spinning Temperature: Synthetic fibers like acrylics can be spun at room temperature, while biobased materials like gelatin and agar-agar typically require heat for melting. Due to the higher polymeric concentration in our spinning solution, we modified the ITA setup by adding a heating wire around the spinneret assembly and insulating it with a foamy material, while leaving the spinneret exposed (Fig. 5.7b). We achieved the best results spinning pure gelatin fibers by heating the nozzle to 31 °C when the room temperature was about 22 °C and setting up the syringe wrap to 52 °C. This experience highlighted the essential role of a heated nozzle in spinning biobased materials, which we carried over to the design of our machine.

Extrusion Speed: In our experiments at ITA, the DIENES LabLine machine

²²Meinmetzger: <https://www.meinmetzger.de/index.php/aspik-eins-a-qualitaet-300-bloom.html>

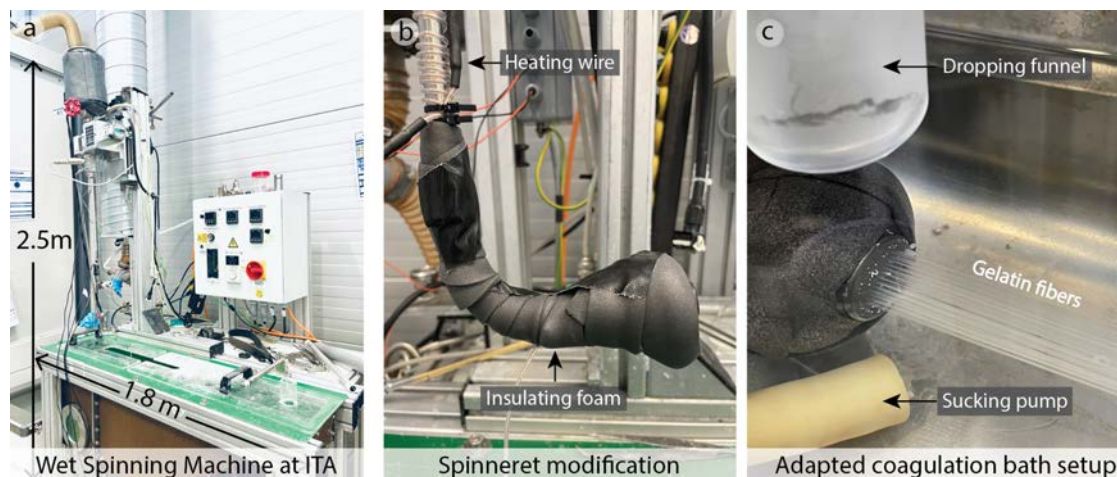


FIGURE 5.7: Gelatin fibers spinning challenges: a. DIENES LabLine machine for fiber spinning, b. Spinneret modification consists of a heating wire around the area of the spinneret that goes inside the coagulation bath, wrapped with insulating foam to maintain the desired temperature at spinning time, and c. Coagulation bath setup adapted to handle two different liquid concentrations in the same bath. One comes from the dropping funnel and the other one is already filled in the bath. The pump sucks the liquid coming from the dropping funnel to maintain the desired concentration levels in the bath. This enabled the spinning of gelatin fibers using a nozzle of 120 holes with 100-micron resolution.

(Fig. 5.7a) constrained the spinning speed to 2.5–3 RPM, with motion only along the Z-axis. The system used a gear pump with a flow rate of 0.6 ml/RPM and a spinneret with 150 holes of 120 μm diameter. Our machine, by contrast, uses an X-axis carriage feed rate of 0.01 mm min^{-1} and an X-axis travel of 4 mm, independent of the amount extruded. The collector operates at 3.9 RPM. In our experiments, we initially extruded 0.05 mm of material per step. After we found the "sweet spot" for extrusion, we sent a G-code command in the host controller software to extrude 0.1 mm of material continuously across the 180 mm length of the collector.

Draw-Down Process (Drawing): Drawing is a technique that mechanically pulls a blob of material (mass of spinning dope accumulated around the nozzle) while it is still in a semi-molten state to align and orient the polymer chains

along the length of a fiber. In a wet spinning process, drawing happens inside the coagulation bath, however, in a dry-jet wet spinning process as with our machine, the fiber is extruded in an air gap before reaching the coagulation bath (Fig. 5.2). As shown in Fig. 5.8, we wait until a blob (approximately 3 mm in diameter) forms on the tip of the heated nozzle. Then, with 90-degree tweezers, we grab the blob and draw it down towards the first collector which is already in movement, to tangentially attach the fiber to it. If unsuccessful, we restart using the same blob, which means tapping the blob on the tip of the nozzle until we see a fiber forming while drawing it down.

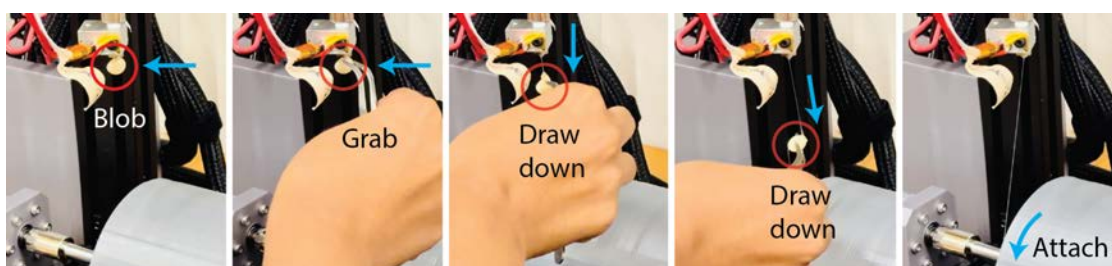


FIGURE 5.8: Step-by-step of the draw-down process: blob formation, grab the blob, draw down the blob, and attach the drawn fiber tangentially to the collector.

Coagulation Bath: The coagulation bath is the liquid environment that immerses the extruded spinning solution. It triggers a process where the solvent in the spinning solution diffuses into the bath, causing the polymer to precipitate and solidify into fibers. At ITA, we obtained the best results using 40% isopropanol only near the nozzle to allow extrusion without clogging, followed by immersion in isopropanol (80-90% concentration). The complexity of a dual bath setup with an immersed nozzle led us to use dry-jet wet spinning instead. In our machine, the newly spun fiber passes through an air gap before the coagulation bath, simplifying the previous process by avoiding liquid concentration differences (Fig. 5.2). We obtained the most flexible biofibers

using 5 wt% glycerin in isopropanol (80% concentration) coagulation bath. Refer to section 5.4 for more experiments in the coagulation bath.

Stretching and Washing (Finishing): For many polymers, washing in water removes impurities from the spinning process, neutralizing any chemical treatments applied during spinning. Since water is a solvent of gelatin, it will dissolve our biofibers. As a result, we skipped washing from our workflow until we found a more suitable washing formula. Fibers like polyester, or nylon, benefit from a stretching process because it improves the orientation of the polymer chains along the fiber axis. At ITA, this process was achieved by rotating the godet rolls at different speeds in the washing baths. However, we found that gelatin fibers become weaker the more we stretch them when they are in a semi-molten state. We thus skipped stretching from our workflow.

Drying: Various methods can be used to remove excess water from the cured biofibers, such as air drying, hot rollers, or ovens. The temperature and humidity levels during drying can affect the fiber's structure and properties. In our case, we have chosen to let the fibers dry at room temperature since our main objective in this project was to explore an accessible fiber design space that can be replicated without additional equipment specialized equipment.

Treatment: In a conventional fiber wet-spinning process, the fibers are first dried and subsequently subjected to further treatments, such as coloration or coatings. We designed our machine with flexibility in mind, thus the baths are multipurpose and can be used for treatment. We present our treatment experiments performed in the second bath in section 5.4.

This section offers an overview of fiber wet spinning (Fig. 5.5) of this process and all the various aspects involved such as spinning solution formula, viscosity, spinning temperature, extrusion speed and feed rates, draw-down,

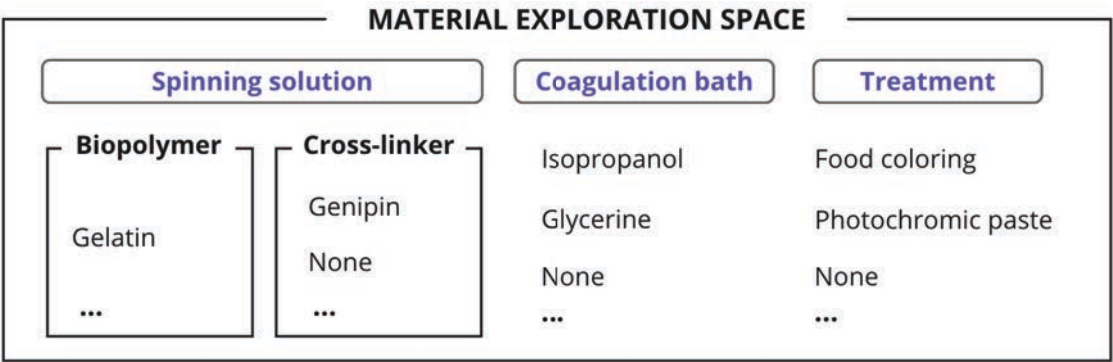
coagulation bath, finishing (stretching and washing), drying, and treatment, which collectively contribute to the production of fibers. We aimed to offer other HCI designers and researchers a deep insight into the fiber wet spinning process, hoping this can motivate and facilitate their material and design explorations within this new fiber design space.

5.4 Material Exploration Using the Biofibers Spinning Machine

The primary motivation for our material exploration is to customize biofibers at different stages of the fiber spinning process using the Desktop Biofibers Spinning Machine. In this research, our material exploration focused on customizing gelatin fibers by altering the spinning solution formula (material preparation), adjusting the fiber diameter by fine-tuning the collectors' speed using our machine (fiber production), and modifying the formula of the multipurpose baths during fiber production and post-production. The visual representation in Fig. 5.9 illustrates the wide range of possibilities and potential combinations that can be tested, all stemming from using a single biopolymer as the starting point—in our case, gelatin.

The text highlighted in purple within the material exploration space indicates the areas we examine in this section and the listed material combinations (Fig. 5.9a, Fig. 5.9e) are the ones we have tested and summarized their outcomes.

Through customization, we achieved a range of qualities in our gelatin fibers: (1) altering the spinning solution led to variations in strength, flexibility, and color-change properties; (2) adjusting the collector's speed allowed us to explore a wide range of fiber diameters; (3) adjusting the coagulation bath formula



Combinations we tested:

- a Gelatin + None + Isopropanol + None
- b Gelatin + None + Isopropanol and glycerine + None
- c Gelatin + None + Isopropanol and glycerine + Food coloring
- d Gelatin + None + Isopropanol and glycerine + Photochromic paste
- e Gelatin + Genipin + Isopropanol and glycerine + None

..... Fiber spinning walkthrough example

FIGURE 5.9: Material exploration space for fiber wet spinning, the various material formulations that we tested (a-e), which includes the material formulation used in the fiber spinning walkthrough (c).

had an impact on the fibers’ flexibility and elasticity; and (4) implementing treatment processes enabled us to introduce color into the fibers and facilitated color-change effects when coating the fibers with a photochromic paste.

5.4.1 Adjusting Spinning Solutions for Tuning Color and Strength

Our initial spinning solution (Fig. 5.9a) contained gelatin, water, and isopropanol. To enhance the strength and flexibility of the resulting fibers, we added a biobased crosslinker to the spinning solution formula and a plasticizer to the coagulation bath.

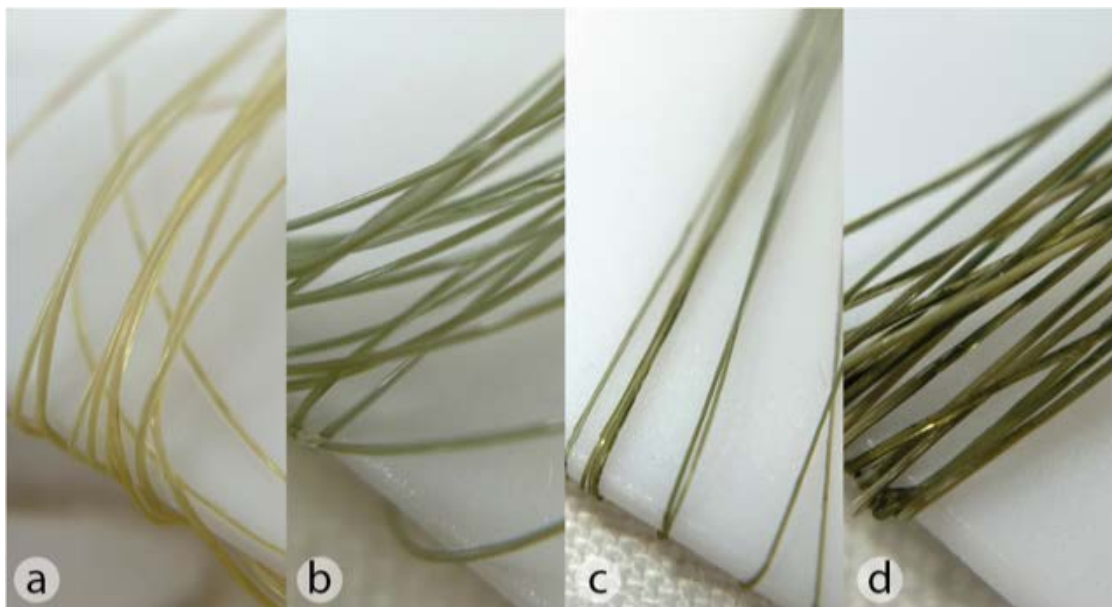


FIGURE 5.10: (a-d) Gelatin biofibers change color from light to dark green as the genipin content in its material formula increases in the following increments: (a) no genipin; (b) 0.12 wt% genipin; (c) 0.18 wt% genipin; (d) 0.24 wt% genipin.

Conventional crosslinkers used in previous research are costly, alter gelatin's biodegradability, and require specialized equipment and controlled environments due to potential toxicity concerns [33]. Seeking an alternative, we explored genipin—a natural crosslinker derived from the gardenia fruit (*Gardenia jasminoides*) [165].

Genipin is known for its biocompatibility and safety in biomedical and food-related applications [142]. In our use, genipin not only improved the mechanical properties of the gelatin fibers but also introduced color-changing effects transforming the natural color of gelatin fibers (Fig. 5.10a) into various green tonalities (Fig. 5.10b, Fig. 5.10d). Employing concentrations of 0.12 wt% (Fig. 5.10b), 0.18 wt% (Fig. 5.10c), and 0.24 wt% (Fig. 5.10d) in 10 mL of the spinning dope respectively, genipin significantly increased the overall strength of the fibers in both dry and wet states (Fig. 5.11).

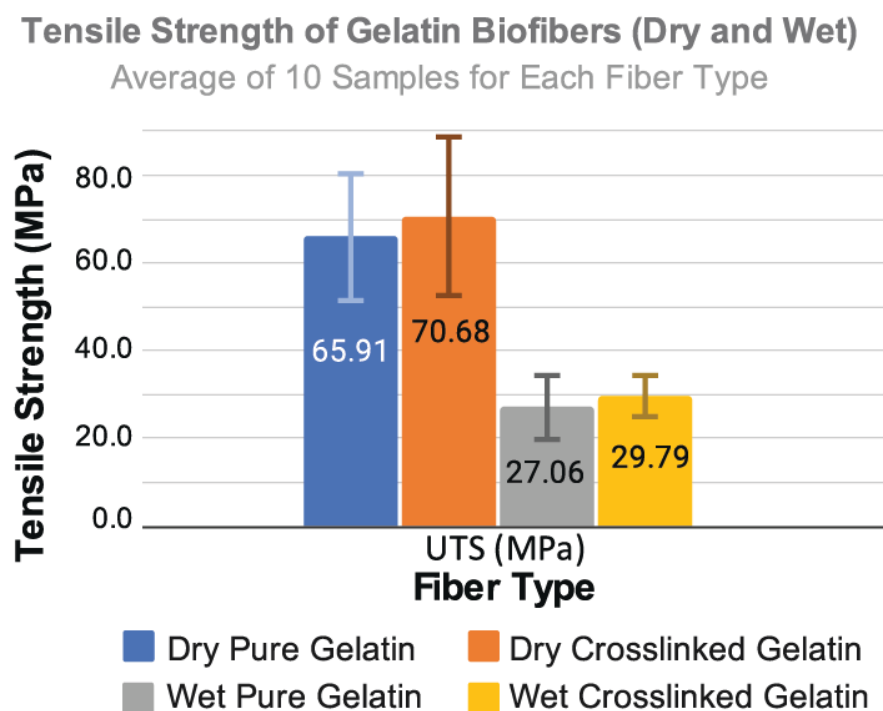


FIGURE 5.11: Tensile strength of gelatin biofibers—pure and crosslinked—in both dry and wet conditions. Gelatin biofibers crosslinked with genipin were stronger in comparison to pure gelatin biofibers when dry and wet.

Adjustments in extrusion speed on our machine accommodated the increased viscosity of the spinning solution with genipin.

Dry crosslinked gelatin fibers had a tensile strength of approximately 71 MPa—the highest among all samples and conditions. Furthermore, through tactile observation, we noticed that genipin increased the flexibility of the biofibers. Gelatin biofibers, regardless of the concentration of genipin, retained their flexibility even after being spun and stored at room temperature for over 2 months. Inspired by these positive outcomes, we delved into further enhancing flexibility through various coagulation bath formulas, as detailed in Section 5.4.3.

5.4.2 Fine-Tuning Biofiber Diameter through Collector Speed

After extensive experimentation with various spinning solution formulations, we found a method to adjust the diameter of biofibers—by controlling our machine's collector speed. We systematically modified the first collector's speed from 2.3 RPM to 3.9 RPM during our tests, while keeping the extruded amount and extrusion speed constant. The resulting diameters, shown in Fig. 5.12a, ranged from 0.03 mm to 0.20 mm, with a clear trend of decreasing diameter with higher collector speed.

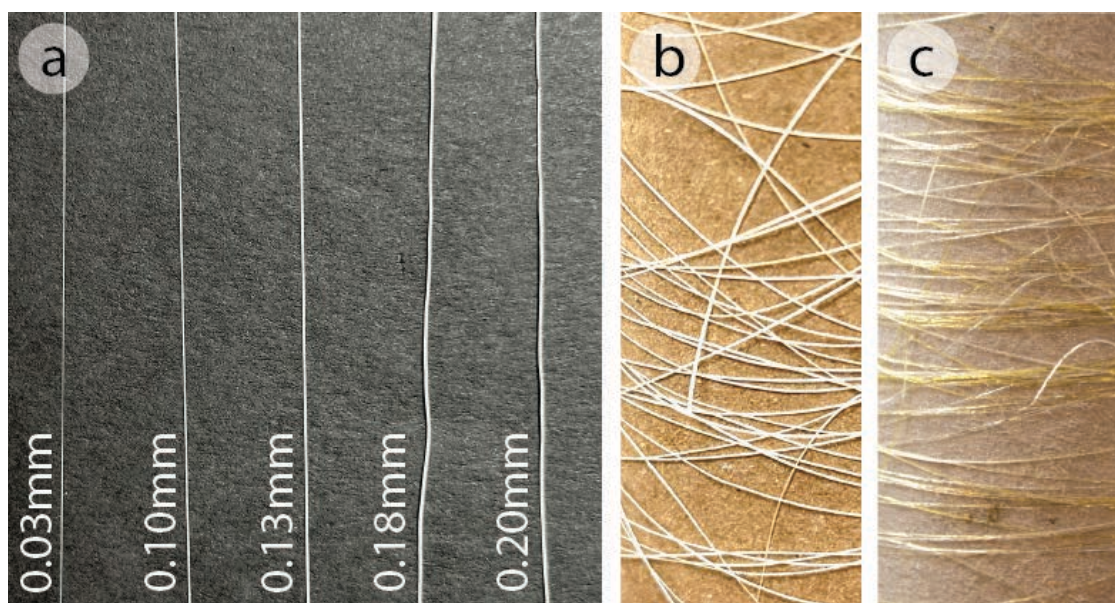


FIGURE 5.12: Material Explorations: (a) adjusting fiber diameter (thickness) via collector speed, (b) natural color of biofibers, (c) and yellow biofibers resulting from post-production food-coloring dye.

To maintain a consistent fiber diameter at the same collector speed across different spinning solutions, we adjust the extrusion temperature based on the specific solution's viscosity. For instance, with the gelatin and genipin spinning solution (Fig. 5.9e), we increase the extrusion temperature due to its higher viscosity compared to pure gelatin. Importantly, the diameter of the fiber affects

its properties. The thinnest gelatin fibers (0.03 mm) can easily dissolve with moisture from hands, while the thickest ones (0.20 mm) are more resilient and feel stiffer to the touch. The medium-thickness fibers (0.10 mm to 0.13 mm) are notably softer, more flexible, and easier to handle. Consequently, we primarily used biofibers of this diameter for our example applications in Section 5.5.

5.4.3 Adjusting Coagulation Bath for Enhanced Flexibility and Elasticity

In our initial coagulation bath formulation (Fig. 5.9a), we used off-the-shelf isopropanol (90% concentration) to precipitate pure gelatin biofibers. To enhance the flexibility of the resulting fibers, we experimented by introducing vegetable glycerine (Fig. 5.9b) as a plasticizer in various drying stages. For instance, we mixed vegetable glycerine (5% concentration) with isopropanol (85% concentration) and added this mixture to the second multipurpose bath. By varying the drying time before exposing the fibers to the second bath, we tested different immersion timings: immediately after leaving the coagulation bath while still wet; after 15 minutes while semi-dry; and after 30 minutes when fully dry. Immersing the fibers immediately (fully wet) resulted in elastic but less robust biofibers. Waiting 30 minutes for drying before immersion resulted in less malleable biofibers, likely due to insufficient moisture for glycerine bonding. Submerging semi-dry biofibers (after 15 minutes) yielded the best results in terms of tactile flexibility.

We also evaluated the impact of the first coagulation bath of 90% isopropanol concentration on the biofibers' flexibility. We removed this first bath from the process and precipitated the biofibers directly into the second bath of isopropanol (85% concentration) and glycerine (5% concentration). The produced biofibers exhibited similar tactile qualities and flexibility as those

produced using the two-bath setup. Thus, for simplicity and consistent results, we opted to use the formulation containing isopropanol and glycerine as our first coagulation bath. We also explored the elasticity of the biofibers by submerging them into a *non-solvent* solution after they were completely dried. In this context, a non-solvent solution refers to a solution that doesn't chemically interact with or disintegrate the biofibers. For example, we wet crosslinked gelatin fibers in a 70% isopropanol solution, resulting in elastic fibers while wet and a permanent color change due to genipin crosslinking. This unique quality is showcased in one of our example applications in Section 5.5.

5.4.4 Implementing Treatment Processes for Color and Coatings

Building on insights from earlier experiments, we adopted isopropanol (85%) with glycerine (5%) as our preferred first coagulation bath and used the second bath for treatments involving color solutions and coating pastes. For the yellow color treatment, we diluted 3–4 drops of food coloring in off-the-shelf isopropanol (85%) with glycerine (5%). After stirring to ensure even dispersion, we poured this mixture into the second multipurpose bath. This method produced flexible, yellow-colored pure gelatin fibers, as shown in (Fig. 5.12c).

Shifting our focus to coatings, we explored applying a photochromic²³ paste (UV-sensitive) onto dry biofibers (Fig. 5.13). We found that the paste adhered well to the fiber surface, transforming basic gelatin fibers into UV-sensitive ones. Because photochromic pigments are not biobased, we limited this line of exploration, though we see opportunities for future work using biobased alternatives to achieve similar sensing capabilities.

²³Photochromic Pigment (Pink–Blue): <https://www.amazon.com/dp/B0735BQQ7P>

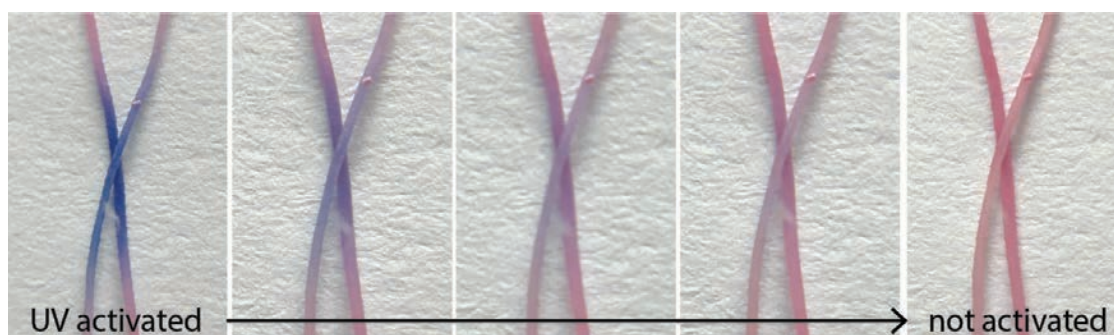


FIGURE 5.13: Biofibers coated with a photochromic paste.

5.5 Example Applications

To demonstrate the incorporation of biofibers into textiles, this section features applications in smart and shape-changing textiles for HCI. Our examples use dissolving as a feature, serving as a trigger for interaction while promoting sustainability through material recycling or reharvesting.

In our initial experiments, we attempted integration through plying, braiding, knitting, and crocheting, but these processes imposed forces that the gelatin biofibers couldn't withstand. Specifically, the high curvature and tensions of knitting and crochet caused fiber breakage. Hand weaving emerged as a suitable integration method that met the material requirements of gelatin biofibers, leveraging our familiarity with the process.

Unlike other techniques, hand weaving doesn't subject inserted weft yarns to tension during insertion, minimizing curving stress on the materials. Additionally, weaving allows for the integration of multiple materials within the same textile structure. By incorporating gelatin biofibers into woven assemblies, we explored how the interplay of diverse materials generates various interactive effects. The swatches presented in this section were designed using AdaCAD [46, 66], an open-source web-based weaving software.

5.5.1 Dissolving for Recycling and Reharvesting

Smart textiles pose a significant recycling challenge as they combine various materials (e.g., conductors, electronics) within a single fabric that are difficult to separate. For example, single-use electronic sensors (e.g., RFID tags in clothing) can significantly contribute to electronic waste concerns. We integrated gelatin biofibers into textile sensors to enable convenient recycling and reharvesting through dissolution [122] and disassembly [215]. To illustrate this concept, we developed two single-use woven sensors: a moisture sensor (Fig. 5.14a) and a pressure sensor (Fig. 5.14b).



FIGURE 5.14: Woven textile sensors with biofibers integrated into the cloth: a. moisture sensor and b. pressure sensor.

In the moisture sensor, wetting the gelatin biofibers creates an electrical pathway between two embedded silver threads. At the same time, it begins to dissolve the biofibers. In the force sensor, the dimensionality of its "waffle" woven structure separates the conductive yarns. When pressure is applied, the traces touch and shorten the electrical path leading to a lower resistance. When the sensors are no longer needed, they can be submerged in hot water to dissolve out the biofibers. Dissolving the biofibers loosens the structure, enabling the conductive yarns to be easily reharvested (Fig. 5.15).

This approach enables us to reuse the conductive yarn and recycle the cotton yarn when the sensor reaches its end of life. While these tests are small-scale

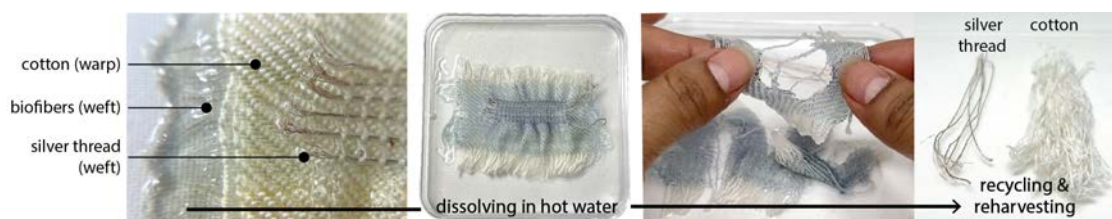


FIGURE 5.15: Dissolving biofibers in our woven moisture sensor enables reharvesting of conductive and non-conductive threads at the end of the sensor’s life. This process also applies to our pressure sensor. The biofibers’ change in color is due to the result of genipin (a crosslinker) in its composition.

and simple, they point to the potential sustainability impact of biofibers for dissolvable smart textiles, and more broadly single-use electronics. In future work, we would like to examine increasing the strength of our biofibers by further tuning the spinning solution formula. Higher strength would facilitate including these fibers into the warp during weaving, eliminating, for instance, our use of cotton.

5.5.2 Dissolving and Swelling to Trigger Interaction

Drawing inspiration from prior projects like bioLogic [218] where a cloth reacts to external stimulus, we contemplated how the unique dissolving properties of biofibers coupled with an appropriate weave structure could facilitate shape-changing interactions. We conceptualized a butterfly-shaped swatch with a 2-layer weave structure (Fig. 5.16a). The top layer of the cloth is made using a readily available moisture-reactive elastic yarn. The bottom layer uses a brightly colored synthetic yarn with no elastic properties. The two layers are bound together in the middle (along the body of the butterfly). They are also bound by gelatin biofibers woven around the edges of the wings.

The premise is that when the swatch becomes moist, the biofibers along its edges dissolve. This causes the layered wings to separate and the elastic material

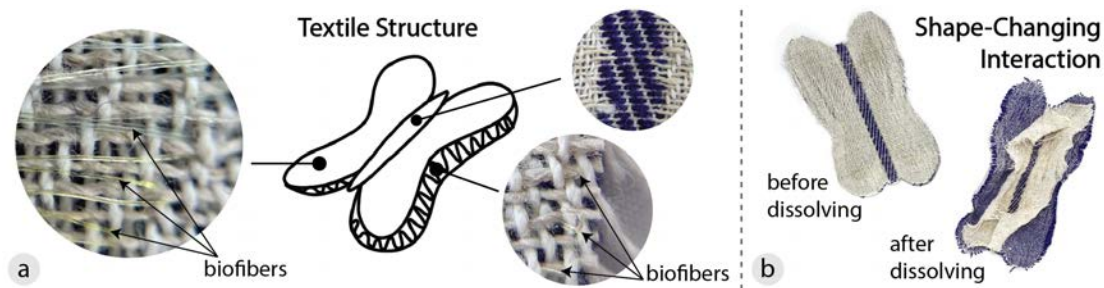


FIGURE 5.16: Dissolving as interaction: (a) woven butterfly that (b) unravels its wings when wet with water.

to contract along the weft, allowing the butterfly's wings to unfurl (Fig. 5.16b).

While dissolving is a distinctive feature of biofibers, we observed varying degrees of this behavior. For example, when gelatin biofibers are moistened with a 70% isopropanol and 30% water solution, they do not dissolve but instead swell, enabling stretch. We explored this controlled-swelling interaction by constraining biofibers within twill and crepe woven structures, both of which are known to produce textured surfaces when made with elastic yarns. When the swatch is dampened and the exposed biofibers absorb the solution, it shifts from inelastic to elastic (Fig. 5.17). Notably, this swelling is reversible—once the biofibers dry, the swatch returns to its original state.

We envision this behavior being useful in applications such as reactive clothing and weather-responsive structures. For example, a garment could vent



FIGURE 5.17: Swelling as an interaction: a woven structure that experiences color- and shape-change due to swelling when exposed to isopropanol.

open to cool an individual as they exercise (as in bioLogic [218]). Similarly, a fabric awning could be designed with responsive slits such that some light can pass through in dry sunny weather, while rain causes the slits to close, protecting individuals from any downpour.

5.5.3 "Etching" Flexible Circuits

We explored using the biofibers to create fabrics that can be "etched" similar to the conductive traces on a printed circuit board (Fig. 5.18). Specifically, the top layer of the cloth is created with gelatin biofiber and the bottom with a conductive yarn. Using a 2-layer structure, these layers become isolated and layered on top of each other. Because the biofiber dissolves, one may "etch" a

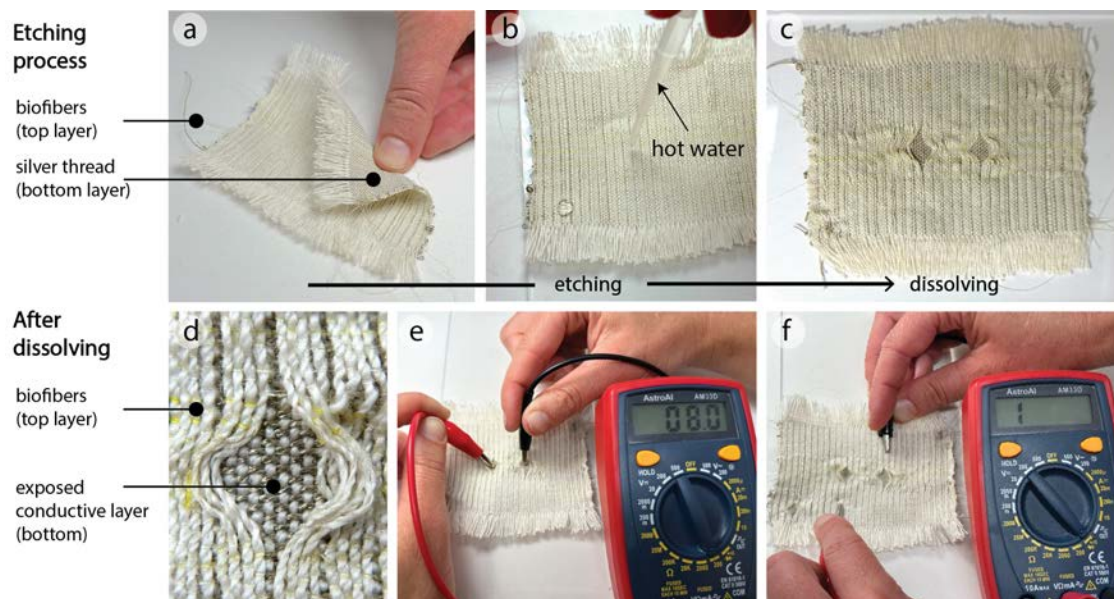


FIGURE 5.18: Example application for etching flexible woven circuits. The etching process consists of (a) a 2-layer cloth woven with the biofibers on the weft of the top layer and stainless steel on the back; (b) drops of hot water are selectively added to the top layer of the cloth; (c) areas in contact with the water are dissolved; (d) the bottom conductive layer becomes exposed conductive after dissolving; (e) testing the dissolved and exposed area shows that it is conductive; (f) testing undissolved areas are not conductive.

trace in the fabric by dotting it with hot water, exposing the conductive cloth on the bottom layer. This application could potentially enable on-body etching of flexible surfaces when prototyping a circuit in a cloth. Often, designers are unsure which areas of cloth would be best to have an electrical connection or soldering. Using biofibers to make a soluble top layer in cloth could facilitate enabling on-body etching of tracings and support the prototyping process of smart textile innovators. This approach could help minimize the amount of waste generated during the trial-and-error process.

5.5.4 Summary

These applications serve as proof-of-concepts demonstrating what can be achieved with gelatin biofibers produced using our machine. With continued development of both the machine and the spinning solutions, we envision a much broader design space. For example, solutions that yield stronger biofibers (not necessarily gelatin-based) could support additional textile techniques such as knitting or crocheting. While our demonstrations are small, they highlight the fine structures these biofibers can integrate into and the distinctive aesthetics—luster, color, and texture—they bring to cloth.

With increasing smart textile development happening at the level of yarn [28, 43, 44, 193], we envision this machine being integrated into conventional fabrication workflows to develop customized biofibers. These biofibers can act as a support material for different textile structures or to leverage cloth structure to support sensing. Biofibers can also enable potential sustainable approaches to emerging applications, including "single-use smart textiles", which we anticipate will be a growing waste stream as companies integrate sensing and actuation into fashion products.

5.6 Discussion

Our journey in fiber spinning has challenged our prior knowledge of textiles and biodesign. Despite the steep learning curve, the experience we gained at ITA and while developing the Desktop Biofibers Spinning Machine has yielded valuable insights worth sharing. In this section, we discuss the lessons we learned from working across disciplines, the unexpected aesthetics achieved when integrating biofibers into cloth, and our approach toward sustainable smart textile design.

5.6.1 Lessons Learned From Working Across Disciplines

Despite our prior experience with biodesign applied in HCI contexts, the space of fiber spinning with biobased materials felt unfamiliar. Collaborating with ITA researchers revealed challenges in establishing a common vocabulary, and our initial assumptions regarding the universal spinnability of biobased liquid solutions turned out to be overly optimistic. From our experience, we offer several key lessons for HCI designers and researchers interested in further exploring this fiber design space.

Each polymer is its own world: While materials scientists in fiber spinning inherently understand the importance of the spinnable solution at the polymeric level, our learning curve highlights the need for a nuanced grasp of this knowledge. Recognizing the specificity of creating spinnable solutions for different polymers or biopolymers is crucial—what works for gelatin (protein) may not apply to agar-agar (polysaccharide). Even within the same polymer category, variations in molecular structure demand distinct solvents, concentrations, and processing conditions for spinning solutions. Although

delving into intricate materials science details may seem overwhelming, possessing a fundamental understanding, as emphasized in Section 5.3, can greatly facilitate more effective interdisciplinary collaboration.

Where to seek for support: Initially, our assumption that consulting a materials scientist would provide the right mix of ingredients for our gelatin spinning solution proved overly simplistic. We realized that knowledge within the materials science field is highly specialized; expertise in one area, such as acrylic fibers, does not necessarily equate to proficiency in another, like sugar fibers. The key takeaway is to connect with materials scientists who specialize in the specific material relevant to your work, be it protein, carbohydrate, sugar, etc., rather than solely focusing on fiber expertise. Furthermore, our experience emphasizes the significance of actively seeking feedback and ideas beyond our immediate domain. Engaging with experts outside the realm of fiber spinning brought fresh inspiration and ideas. For instance, in a conversation with a chemist specializing in bio-compatible materials for tattoos, we learned about genipin as a natural crosslinker derived from a fruit. This led us to explore genipin as a way to increase the strength of our gelatin biofibers.

Prototyping at different scales: Our experience at ITA highlighted a significant contrast in prototyping workflows between our domain and lab-scale environments. While our skills in hacking and rapid prototyping were instrumental, we recognized the detailed planning, precise engineering, and contingency plans required in large-scale machine modification. Understanding the workflow disparity made us think that it stems from the cost and size of the equipment employed. This realization prompted reflection on the existing gap between fiber spinning in a materials science lab scale and an HCI lab, bringing awareness to the potential intimidation HCI designers and researchers might

face exploring new materials outside the HCI space. While our prototyping skills proved to be useful in modifying ITA's machinery and became pivotal in our independent development efforts, it also highlighted the interdisciplinary contributions HCI researchers can make in bridging the gap between materials science and practical applications in HCI.

5.6.2 The Aesthetics of Biofibers

We would like to bring attention to the aesthetics of the biofibers that we have produced. When compared with other materials, gelatin biofibers closely resemble synthetic nylon monofilament (e.g., fishing line). Many textile artists have leveraged nylon monofilament to create iridescent forms and structures [94, 134]. We believe that continued material development with a focus on strength has the potential to make biofibers a sustainable material alternative that could be considered by fiber artists. Some other aesthetic qualities, like luster (i.e., shine) and smoothness were intrinsic to the material and unpredictably arose during production. We find these unexpected qualities to be a way in which the material communicates its potential, a concept often referred to when discussing material agency [112, 186].

The gelatin biofibers show a high degree of luster (Fig. 5.19a), which became more apparent when integrated into cloth (e.g., Fig. 5.17). Surprisingly, we did not observe a correlation between color and level of shine, meaning that regardless of the biofiber's color, the level of shine appeared to be the same. However, we believe it is worth conducting a systematic test to confirm this. In addition, it is worth exploring the shape and texture (Fig. 5.19b) of the biofibers, particularly along their cross-section, as this has been associated with changes in the luster of other fibers [187].

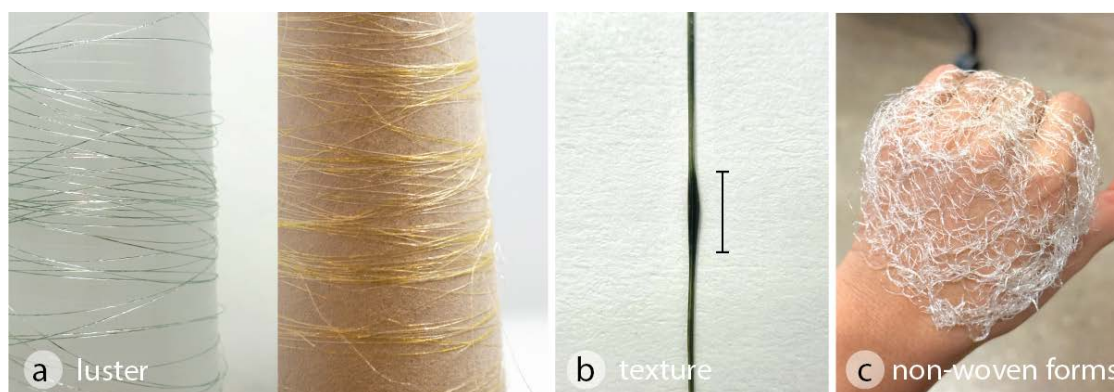


FIGURE 5.19: Qualities and forms of biofibers to further explore: (a) luster, (b) variable texture, and (c) non-woven structures.

We noticed that color gradients emerged naturally from the different additives and treatments used in biofiber production (e.g., Fig. 5.13a), creating visually pleasing effects in cloth (Fig. 5.17). Even "failed" samples that absorbed less color than expected added subtle tonality to our swatches. We also observed a texture change when biofibers were exposed to a non-solvent like isopropanol, which made them rough and stiff after drying; this effect could be further explored by varying non-solvent concentrations. Lastly, we found the biofibers' ability to swell and hold a shape after drying—especially when constrained within a woven structure (see Fig. 5.17)—particularly compelling. Although we only tested one degree of swelling, we see potential for using this property for aesthetic applications requiring shape change.

5.6.3 Towards Sustainable Smart Textile Design

In discussing sustainable smart textile design, we focus on two key phases of the electronic textile life cycle. First, we aim to expand the range of raw materials by enabling the fabrication of biofibers. Second, we propose an alternative end-of-life strategy through the dissolution of biofibers, supporting

easy disassembly and reuse of electronic components. Our machine is designed to facilitate the prototyping and exploration of these materials, with gelatin biofibers serving as one example of the possibilities in this space. The ability of gelatin biofibers to dissolve in hot water offers potential for recycling smart textiles, but also presents limitations for consumer applications due to their sensitivity to moisture and heat. This contrast underscores the need to investigate biofibers derived from other biobased materials that may provide greater resilience. We view our low-cost, open-source machine as a critical tool for examining this space and supporting smart textile innovators in moving toward more sustainable design practices.

5.7 Limitations and Future Work

Developing new materials requires significant time. Our exploration of material formulations and the specific qualities of gelatin biofibers for smart textiles spanned more than two years. A steep learning curve in fiber spinning led us to recalibrate our scope: while we initially envisioned experimenting with multiple biobased spinning solutions, practical constraints pushed us to focus exclusively on gelatin. This narrower focus yielded valuable insights but remains a limitation. At the same time, our machine is designed to handle a range of biobased solutions—particularly those requiring heat—opening opportunities to explore materials such as agar-agar [15] in future work. Our goal in creating an open-source desktop biofiber-spinning machine was to support prototyping and exploration of biofibers for sustainable smart textiles. In its current iteration, the machine offers several directions for future development, and we hope the broader community will continue advancing this work.

A Streamlined User-Interface. In its current iteration, we control the machine using G-code commands sent through a 3D printing host controller software. While this was sufficient for our material exploration, we recognize the potential barrier this may pose for smart textile innovators eager to engage in immediate material exploration. Developing a custom interface for our machine in close collaboration with smart textile innovators stands as a top priority for future work. We also intend to explore the correlation between different machine parameters and fiber characteristics, as observed with collector speed influencing fiber diameter (Fig. 5.12a). Integrating such high-level fiber specifications into our interface could also streamline exploration of the fiber design space.

Enhancing Fiber Customization. Our machine currently requires manual adjustment to change the air-gap distance between the nozzle and the collector, which can slow prototyping and limit biofiber customizability. Adding an adjustable Z-axis in the next iteration would speed up prototyping and allow fine-tuning of the air-gap distance—a critical parameter for materials that benefit from pre-curing. A movable Z-axis would also allow switching from dry-jet wet spinning to wet spinning by lowering the nozzle or spinneret directly into the coagulation bath. This adaptability is important because curing processes vary across polymers. For example, nanomaterials research shows that both dry-jet wet spinning and wet spinning have been used to process different protein-based materials into fibers [41]. We therefore see an adjustable Z-axis as a valuable asset for future material exploration.

Customized Nozzles for Innovative Fiber Design. The opportunity to customize the nozzle with multiple holes or different shapes is another exciting space to explore. This could enable experimentation of fiber-level texture.

Currently, our biofibers have a smooth surface, but with customized nozzles, we can envision spinning textured fibers (Fig. 5.19b) that provide enhanced grip when spun into yarns—a challenge often encountered with smooth-surfaced fibers. Additionally, texture customization opens the door to tuning fiber luster. This in turn could lead to variable color reflections along a single biofiber when integrated into textiles, thus eliminating the need for different dyes.

Customized Collectors for Fiber Production. Our machine’s ability to add collectors according to user needs opens an opportunity for further exploration in fiber production and post-production processes. For instance, it enables us to subject fibers to various concentrations of washing baths and other treatments using multipurpose baths. Downsizing the collectors and utilizing them as stretching rollers offers a space for exploring biobased fibers that benefit from this process. Furthermore, we see the potential of modifying the collector assemblies to support other fiber production techniques—for example, integrating a metal collector could enable melt electrospinning (as in [167]) of biofibers and support creating custom non-woven forms (Fig. 5.19c).

5.8 Conclusion

The development of the Open-source Biofiber Spinning Machine demonstrated how fiber-level fabrication can serve as both a technical and conceptual bridge for integrating biomaterials into interactive textiles. While the machine itself did not directly embed biomaterials into textile structures, it expanded the design space by making fiber production accessible, tunable, and adaptable for designers, HCI researchers, and textile innovators. This aligns with the

dissertation's broader commitment to material-led design as a means to embed sustainability into practice.

Within the context of **RQ3**, the project addressed enabling conditions for biomaterial–textile integration by lowering technical barriers, supporting open-source dissemination, and encouraging experimentation beyond lab-scale or industrial material science settings. At the same time, the project revealed that access to tools is only one part of the equation; tacit knowledge, disciplinary vocabularies, and baseline skills remain critical for effective use. These reflections connect directly to the dissertation's broader argument that moving toward sustainable interactive textiles requires attention not only to materials and tools, but also to the infrastructures of knowledge and collaboration that sustain their use. In doing so, the Biofiber Spinning Machine extends the dissertation's trajectory from working with gelatin in object- and textile-scale prototypes to creating tools that scaffold future material–textile integrations. It reinforces the view of biomaterials not as passive substitutions but as dynamic media whose properties, behaviors, and production methods can actively shape the possibilities for sustainable interactive textile design.

Chapter 6

Discussion, Implications, and Future Work



This chapter discusses the findings from the projects—"Biofoam for Tangible Interaction" (Chapter 3), "Dissolving Wearables" (Chapter 4), and the "Biofiber Spinning Machine" (Chapter 5)—and relates them to the research questions introduced in Chapter 1. It begins with a summary Table 6.1, outlining each project's focus, contributions, forms of interactivity, and methodological role, illustrating how they build on one another to advance the dissertation's material-led, biodesign-oriented approach to sustainability in interactive textiles.

Building on this summary, the following sections reflect on each research question in turn: Section 6.1 revisits **RQ1** by considering the role of biomaterials in expanding interactive textiles; Section 6.2 discusses **RQ2** in relation to how biomaterial properties inform aesthetics and functionality; and Section 6.3 examines **RQ3** through considerations of knowledge transfer, power dynamics, and systemic factors in biomaterials development. The chapter then reflects on the limitations of this dissertation in Section 6.4, and concludes with directions for future work in Section 6.5.

6.1 The Role of Biomaterials in Expanding Interactive Textiles

This section reflects on **RQ1**: *What unique opportunities for sustainable design emerge when engaging with gelatin in designing interactive systems?*

It considers how gelatin-based biomaterials can expand the design space of interactive textiles, and how these opportunities relate to **RO1**, which aims to investigate how biodesign practices grounded in material exploration influence the design of interactive systems, and **RO2**, which aims to examine how working with gelatin-based biomaterials shapes form, interaction, and

functionality in these systems. In doing so, it highlights how the biomaterial formulation process became a site for designing interaction, complementing and sometimes replacing electronics-first approaches.

TABLE 6.1: Summary of Contributions of Core Chapters

Aspect	Chapter 3: Biofoam as Interactive Material	Chapter 4: Designing Dissolving Wearables	Chapter 5: Open-Source Biofibers Machine
Focus	Developing biofoam as a new biomaterial and exploring its tunability through MDD	Applying biofoam in the context of wearable technology, transitioning into interactive textile design	Developing a tool to enable fiber-level biofabrication, in response to a material-led practical challenge in sustainable textile design
Main Contribution	Establishing biofoam's properties (e.g. dissolvability, density) and developing various interactive prototypes (e.g. pressure sensors, accessories)	Designing three dissolvable garments to demonstrate interaction through dissolution as a form of textile interaction	Creating an open-source desktop machine that contributes technically to HCI and serves as a proof-of-concept to expand design possibilities through hands-on fiber prototyping
Type of Interactivity	Interactivity via embedded elements (e.g. thermochromic pigments, embedded sensors)	Interactivity defined through material transformation, garments that dissolve over time, use, environmental exposure	Indirect: enables interactivity by allowing material customization at the fiber level for integration into future interactive textiles
Methodological Emphasis	Strong emphasis on MDD, exploring the material in depth	Continuation of material-led work, now focusing on craft integration and designing for temporality through textile techniques	Combines material-led design with Technical HCI methods, focusing on accessibility, adaptability, and biofabrication workflows
Narrative Role	Sets up gelatin/biofoam as a promising, tunable material	Advances the conceptual framing of interaction: moving from reactive sensing to ephemeral, lifecycle-based interaction	Demonstrates how tools can scaffold new material engagements and support embedding sustainability as a design value through fiber-based experimentation
Biodesign Orientation	Implicit in material exploration and values	More pronounced: embraces lifecycle and impermanence in design as sustainability values	Evident in the tool's orientation toward accessible material experimentation, lifecycle thinking, and support for sustainable prototyping practices

6.1.1 Biodesign Practices Grounded in Material-led Exploration

Reflecting on **RO1**, in this research, biodesign shaped decisions from the outset—foregrounding lifecycle thinking, circularity, local or by-product sourcing, low-tech fabrication, transformation and end-of-life as design drivers. In practice, however, these values were rarely applied in isolation. They were deeply entangled with my material-led approach and the collaborative, exploratory culture of the HCI community in which this PhD was situated. As such, the research outcomes cannot be attributed solely to "biodesign" or to "material-led exploration" in a clean, linear way. Instead, this entanglement expanded the space of possibilities, producing proofs-of-concept that integrated material affordances, lifecycle values, and system-level thinking in ways that may not have emerged from a more conventional, technology-led approach.

In *Biofoam for Tangible Interaction*, the biofoam's compressibility and dissolution properties, combined with a commitment to circularity, guided the development of pressure sensors designed for disassembly. While conductive fibers and electronics were eventually integrated to measure resistance changes, the decision to create a pressure sensor in the first place stemmed from recognizing compressibility as a defining affordance during early material tinkering. Here, lifecycle thinking intersected with interaction design: dissolution not only offered a functional reset for conductive fibers reuse but also suggested a broader design principle—interactive components that are meant to come apart.

In *Dissolving Wearables*, impermanence was treated as a sustainability value in its own right, influencing both material and textile-structure decisions. The project explored how biofoam yarn could be integrated into garments so that

exposure to water would trigger controlled unfolding. The construction method determined how and where dissolution unfolded, revealing opportunities for selective exposure and structural reconfiguration as forms of interaction operating on slower, and more tangible temporal scales. This suggests an alternative perspective on interactivity in HCI beyond digital input-output relationships, resonating with interactive designers Tsaknaki and Fernaeus' exploration of impermanence and material qualities as active elements in interaction design [189], where temporal material properties become central to the user experience rather than peripheral considerations [145, 191]. This outcome reflected the entanglement of biodesign values (designing for transformation and end-of-life) with material-led exploration at the textile level.

The *Biofiber Spinning Machine* project illustrates how the practice extended beyond the material itself into the tools that support its use. The idea emerged from trying to make gelatin-based fibers in a lab-scale machine not intended for biomaterials, where the spinning solution required specific parameters and the machine, ad-hoc adjustments to produce viable gelatin fibers. While this experience played a role in the design of the open-source Biofibers Spinning Machine, its development also depended on the skillset of the collaborative team, shared sustainability values, and the recognition—shared in biodesign's systems thinking—that accessible tools could broaden experimentation for both the HCI and biodesign communities. This example highlights how material-led design research in this space is shaped as much by community and context as by the material affordances themselves.

Taken together, these cases suggest that the influence of biodesign practice grounded in material-led exploration lies less in producing singular, replicable methods and more in expanding the range of what can be considered when

designing interactive systems. A material-led approach offers a different perspective on where and when interaction is considered in the design process. Unlike many traditional interactive textiles where interaction is often addressed at the user-experience stage with completed artifacts, biomaterials enable engagement at the earlier material formulation phase. This approach allows designers to consider interactive qualities before fabric structure is determined, shifting focus from post-production electronic integration to material development as a form of interaction design.

By embedding lifecycle values into material development, integrating transformation into interaction, and adapting tools to accommodate new material categories, this work demonstrates that interactive textiles can be approached from starting points other than electronics integration. While it would be reductive to claim that biodesign and material-led exploration alone transformed the field, the entanglement of these approaches has generated alternative pathways—ones that invite further exploration of hybrid practices, distributed making, and lifecycle-driven design in HCI.

6.1.2 Attuning to Biomaterial Affordances in Interactive Textile Design

Reflecting on **RO2**, this subsection examines how engagement with biomaterials shaped design decisions by attuning to the affordances that emerged from their properties, and how form, interaction, and functionality developed through these engagements. Attuning to biomaterial affordances reframed design as a negotiation with material tendencies, where properties both enable and delimit interaction possibilities. Iterative engagement with biomaterials turned observation into discovery: affordances surfaced through practice and began to guide decisions about form, interaction, and function. These engagements

highlight that interactivity in biodesign is not only an end-user concern but also emerges through the design process itself.

Figure 6.1 synthesizes the range of biomaterial affordances that I observed across the three research projects of this dissertation. It maps the diverse sensory and functional affordances I encountered when working with gelatin-based biomaterials. The affordances are grouped into categories, including **kinesthetic** (e.g., compression, flexibility, resistance), **tactile** (e.g., texture, sensory feedback), **visual** (e.g., translucency, color carrier), **auditory** (e.g., tone modification, sound diffusion), and **responsive** (e.g., swelling, solubility, natural biodegradability).

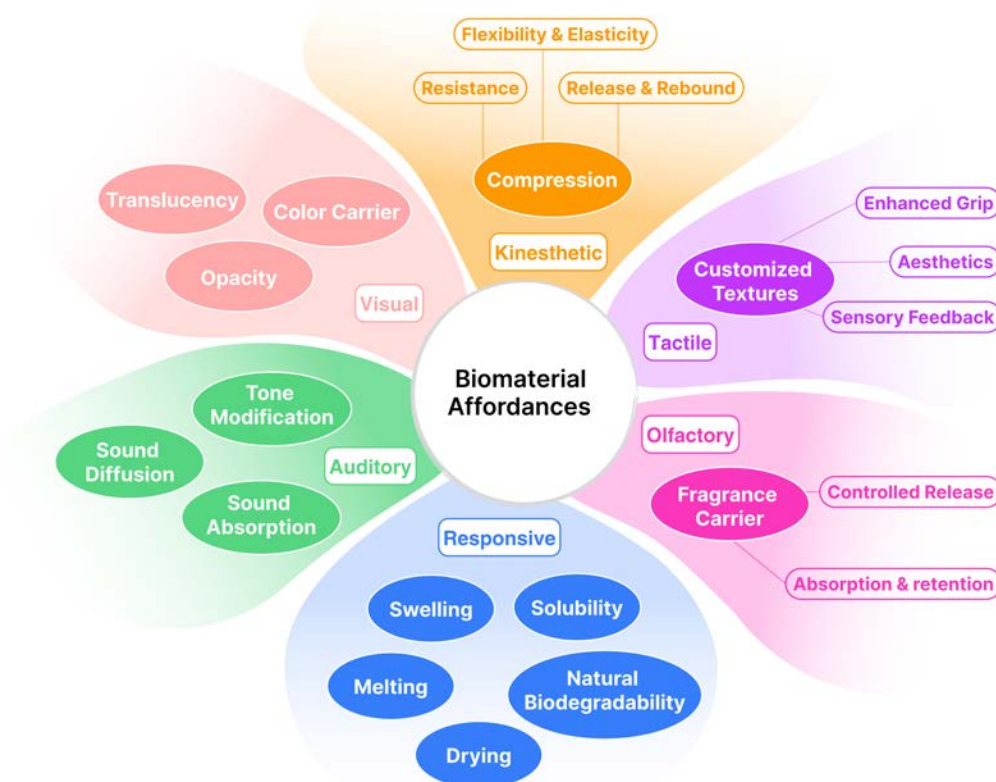


FIGURE 6.1: Synthesis of observed biomaterial affordances across my dissertation research projects. Illustration by Kunstin Xu.

sound absorption), **olfactory** (e.g., fragrance carrier, controlled release), and **responsive** (e.g., swelling, solubility, melting, drying). These categories were named retrospectively, after noticing recurring patterns in how biomaterial properties offered design possibilities across the projects. Using this figure 6.1, I will discuss the entanglements among affordances and my reflections on how attending to them informed design decisions, particularly in shaping form, function, and interaction in interactive textile design.

In *Chameleon Accessories* (Chapter 3), incorporating thermochromic and photochromic pigments into the biofoam revealed the color carrier affordance, while the biofoam's malleability allowed it to be molded into textured surfaces, highlighting a tactile response affordance. Recognizing these affordances guided design decisions that combined expressive color changes with tactile qualities in the final accessories. Coupling pigment responsiveness with the biofoam's thermal remeltability enabled circular design: the accessories could be melted and reshaped into new pieces at the end of their life without losing color or the thermochromic and photochromic properties conferred by the pigments. This example illustrates how leveraging multiple affordances simultaneously can integrate expressive and functional outcomes in interactive artifacts.

In *Biofoam for Tangible Interaction* (Chapter 3), kinesthetic properties such as compressibility and rebound revealed affordances for tactile and temporal interaction. Adjusting ingredient ratios allowed tuning of density and spring-back timing of the biofoam, which directly shaped the tactile behavior of pressure sensors. Even incidental observations, such as the pleasant scent introduced by walnut powder, became part of the wider repertoire of designer-material engagements, where sensory qualities might inform future design considerations.

Attuning to the malleability property of the biofoam, introduced another chain of affordances related to form factor and textile construction. Certain biofoam formulations could be extruded into yarn, enabling new biomaterial-textile integration possibilities. In *Dissolving Wearables* (Chapter 4), for instance, this affordance supported integration of biofoam yarns into garments that unfolded upon exposure to water, combining textile transformation with aesthetic change. Here, dissolution and malleability were recognized and leveraged together to produce slow-scale temporal interactions, illustrating how multiple affordances can inform both functional and expressive design simultaneously. This sequence shows how affordances can chain—where one property (malleability) conditions new fabrication logics (yarn extrusion) that, in turn, make temporal interaction (dissolution-driven unfolding) designable.

Across these projects, the material formulation stage was not merely preparatory work for later electronics integration but a primary site where form, function, and interactivity were negotiated through designer–material engagements, shifting design effort from specifying outcomes to embracing material behavior. By starting from the properties and behaviors of biomaterials, this work expands the design space of interactive textiles to include interactions grounded in material transformation and intrinsic responsiveness. This perspective complements electronics-first approaches by positioning material behavior as both a functional and expressive design resource, and invites hybrid systems that merge material-driven and electronic interactivity, broadening interaction logics beyond sensing and actuation to include material transformation as interaction. In doing so, it supports lifecycle-driven design strategies that embed transformation and reusability

into interaction from the outset, and calls for continued exploration of forms of interactivity that emerge not from computation alone but from the dynamic behaviors of the materials themselves.

Overall, working with gelatin-based biomaterials enabled interaction design possibilities grounded in the materials' properties and behaviors, through attunement to their affordances. In doing so, this work meets the aim of **RO2** by demonstrating how affordance-led design can shape form, function, and interactivity in interactive textile contexts, while building on practices discussed in **RO1**, where biodesign and material-led exploration established the conditions for these affordances to surface and be integrated into design.

Although this subsection highlights the range of affordances that informed different design decisions, solubility emerged as a particularly significant one across the research projects. While other affordances informed localized choices, the intentional activation of solubility led to working with **dissolution**, which shaped broader considerations related to interaction, lifecycle, and sustainability. Given its centrality, the next subsection examines how solubility was activated as dissolution in practice and discusses dissolution as a deliberate design strategy in this research.

6.1.3 Dissolution as a Design Strategy for Interaction and Sustainability

This subsection discusses *dissolution* as a design strategy that emerged in practice through the making and material exploration carried out in this research. While solubility was a key material property of the gelatin-based biomaterials I worked with, it became an affordance for dissolution when intentionally activated in design practice. It became a way to position temporality, transformation, and decay as central dimensions of interaction and

sustainability. Across the projects, dissolution revealed how interaction and sustainability can be understood through material change: the lifecycle of an interactive object does not end when the artifact is fabricated or first used; it continues as the material transforms, dissolves, or is reused, extending design and interaction into the processes of material transformation that unfold beyond the artifact's initial making or use.

Dissolution also carries interactional and experiential significance when enacted through wearables that respond to environmental or bodily conditions. In the *Designing Dissolving Wearables* project, dissolution became a performative and intentional transformation: when water contacted the garments, the biofoam-based yarns softened, released, or unfolded, revealing new patterns or shapes. These scenarios positioned the wearer as an active participant in triggering material change, transforming dissolution into a sensory and temporal interaction. Through such designs, dissolving operates not as a failure or decay but as a designed event that makes transformation itself a mode of engagement and expression. This experiential perspective also extends to sustainability, as these acts of transformation foreground end-of-life not as a point of termination but as part of the design's lifecycle, linking material change with questions of recovery and reuse.

The approach I developed in this research, centered on dissolving biomaterials, has been cited by other researchers as an example of how material breakdown can support new interaction possibilities and end-of-life considerations, for instance, in reimagining active end-of-life stages in materials [129] and in reviews of responsive-textile methods [29]. This engagement forms part of a growing conversation within the HCI and design research communities about lifecycle as a site of interaction. Across recent work,

researchers are exploring how dissolving [35, 69, 79], disassembling [212], or transforming materials [205, 209] can embed temporality, reflection, and renewal into interactive systems.

Through the core research projects, dissolution extends lifecycle thinking and positions end-of-life as an interactive stage. This perspective ties dissolution to the broader Sustainable HCI discourse, establishing it as a complementary approach to other strategies such as repairability, modularity, or longevity. The material recovery enabled through dissolution, exemplified by the reharvesting of conductive fibers and the re-forming of biofoam batches, illustrates how transformation can be integrated into sustainable design practice. Dissolution demonstrates practical value by connecting processes of decay with opportunities for reuse and renewal. Through dissolution, the end-of-life stage becomes part of the designed experience, a site for further material transformation rather than a point of termination.

Recent engagements with this research show how the ideas developed here resonate with a growing interest in HCI and design research in material transformation, decay, and reuse. Scholars have taken up the notion of material breakdown and dissolution to explore new interaction possibilities and end-of-life considerations [29, 129]. This growing attention to dissolving [69, 79, 212], disassembling [35, 212], and transforming materials [205, 209] signals an expanding interest in temporality, reflection, and reuse as integral to interactive systems.

Broadening to theoretical reflection, dissolution also contributes to discussions on material agency and posthumanist design, where materials are recognized as active parts of the design process that guide and shape outcomes. Dissolution can be seen as both a critical and speculative design stance, as

well as a counter-strategy to prevailing smart-textile values that prioritize stability, repeatability, and performance durability. In contrast, dissolving materials foreground fragility, adaptation, and the designed potential to end. This orientation connects with ongoing debates in HCI around control and unpredictability, inviting an epistemic shift toward attending to how materials act and transform rather than how they can be stabilized. Furthermore, while dissolution was the main design strategy that emerged in this research, the approach can be extrapolated to other biomaterial affordances—such as drying, swelling, or opacity—which may similarly open new possibilities not only for interaction and sustainability but also for social, aesthetic, and speculative dimensions of design.

Dissolution also serves as a conceptual link across the different strands of this dissertation. It ties together the material explorations that foreground temporality and transformation, the fabrication practices that translate those insights into accessible tools and methods, and the sustainability considerations that frame material change as part of design practice. Seen through dissolution, these elements form a coherent perspective on the role of biomaterials in interactive textile design, where making, transforming, and unmaking materials become interconnected modes of inquiry. Dissolution situates interaction and sustainability within the material processes through which design takes place, where making, transforming, and dissolving materials are integral to how design unfolds. These insights together suggest that dissolution is more than a functional feature; it offers a conceptual and methodological stance for how designers can engage with material transformation and sustainability.

Working with dissolving materials also produced methodological insight. Because their behavior could not be fully predicted or controlled, designing

required balancing control with acceptance of material transformation. This negotiation became a way of learning through material processes, an iterative dialogue between designer intention and material response. This stance aligns with material-led and Research-through-Design epistemologies, where knowledge emerges through making, reflection, and attunement to materials as active participants in inquiry. Seen in this light, designing with dissolution points toward a way of working that negotiates control and openness, where design unfolds through attentive engagement with material change.

6.2 Providing Additional Narratives in Material Agency and Material Design

This section reflects on the findings of my research in relation to **RQ2: *How might the specific properties of gelatin-based biomaterials inform the aesthetics and functionality of interactive textiles?*** The objectives guiding this inquiry were: **RO3**, to explore how the agency of gelatin, expressed through its properties and behaviours, influences the aesthetic and functional design of interactive textiles, and **RO4**, to explore how material responsiveness (e.g., shape change, dissolution) mediates interaction and user experience.

Here, responsiveness is approached as part of material agency—the ways in which the material itself participates in the design process, sometimes enabling, sometimes resisting, and often redirecting the work in unexpected ways. In doing so, the discussion moves from considering how designers attune to a material's affordances and work with them, to examining how the material's own agency mediated interaction, influenced user experience, and shaped both aesthetic expression and functional design possibilities in interactive textiles.

Drawing on examples from the core projects of the dissertation, it highlights how material agency becomes an active design parameter in material-led work with biomaterials, with the following subsections addressing its implications for design practice, material temporality, and sustainability.

6.2.1 Engaging and Reflecting on Material Agency and Material-led Design

Rather than treating biomaterials as passive substrates, my work engaged with them as materials with distinct properties that shape both design possibilities and interaction dynamics. This approach aligns with material-led design, where the properties and behaviors of materials inform the design process. My research primarily follows a material-led approach and methods such as material-driven design, allowing biomaterials to guide design choices while incorporating values such as sustainability, replicability, and accessibility. The iterative nature of working with biomaterials means that interaction is not only embedded in the final artifact but often emerges throughout the material formulation and exploration phases.

This material agency was evident in the biofoam project, where the process of cooking and modifying the recipe revealed unexpected design considerations. For instance, when attempting to integrate conductive elements into the biofoam, the material resisted standard incorporation techniques like whisking and felting, as the stainless steel fibers would clump around the whisk or distribute unevenly in the foam. This resistance led us to develop an alternative "folding" technique borrowed from baking practices to successfully incorporate the conductive elements. This material resistance was not simply a technical hurdle but a moment where the material's properties actively shaped

the fabrication process, illustrating what interaction designers Fernaeus and Sundström [58] describe as "materials speaking back to the designer."

This recognition of the material as an active participant in the design process aligns with perspectives from other domains including biodesign, and resonates with how I approached gelatin in my own work. Synthetic biologists Davies and Levin [40] describe *agential matter* as matter endowed with agency, contrasting it with inert matter whose behaviour is predictable. Biodesign researcher and synthetic biology scholar Dade-Robertson [37, 38] applies this concept in biotechnology to living cells in architecture that make decisions and solve problems, requiring designers to work with, rather than over, their intrinsic behaviors [7]. While my work engages with non-living biomaterials, a similar principle applies: design becomes a negotiation between intention and the material's own capacities, resistances, and tendencies.

For example, when developing gelatin biofibers at the Institute of Advanced Textiles (ITA), RWTH Aachen, the material's heat-sensitive nature directly shaped fabrication possibilities. Its narrow processing parameters, including the need for precise temperature control, required modifications to standard wet-spinning equipment. These included adding heating wires around the nozzle area and adjusting the coagulation bath to use two different isopropanol concentrations, all to accommodate gelatin's behavior. This was a clear case where the material's properties dictated specific technological requirements, as standard equipment designed for synthetic fibers wasn't suitable for biobased liquid solutions. These material constraints led directly to design decisions in our Desktop Biofibers Spinning Machine, such as incorporating a heated syringe and temperature-controlled nozzle—adaptations that wouldn't have been necessary with traditional synthetic polymers but were essential for

working with biomaterials like gelatin.

Instead of applying a predefined function to these materials, the research process was shaped by the material responses themselves. For example, during the biofiber spinning process, we discovered that gelatin's temperature-dependent viscosity required maintaining the spinning solution at precisely 31°C at the nozzle, while keeping the syringe wrap at a higher temperature of 52°C. These specific material requirements informed the design of our desktop machine with distinct heating zones and temperature sensors. Similarly, when testing the coagulation bath for the gelatin fibers, we found that using 90% isopropanol near the nozzle prevented clogging, but required a transition to 80-90% concentration for the main bath. This led to our adoption of a dry-jet wet spinning approach with an air gap, simplifying the process while accommodating the material's specific needs. These experiences exemplify what Parisi et al. [156] call "material tinkering," where the unpredictable behaviors of materials become generative elements that guide the development of both processes and equipment. This inverse approach—starting with the material itself and adapting tools and processes accordingly—is particularly relevant for emerging biomaterials that are not yet tied to specific fabrication methods, creating space for experimentation and invention.

In HCI, where discussions of materiality and design increasingly acknowledge *material agency*, my work with biomaterials offers three key insights. First, it demonstrates how working with "unoptimized" natural materials can reveal constraints that prompt innovative design solutions, challenging the field's tendency to work primarily with engineered materials. Second, it illustrates that material agency is not merely a conceptual framework but a practical reality that necessitates specific methodological

adaptations—such as the modifications required for both lab equipment and our custom machine. Finally, it shows how material-led approaches can bridge traditionally separate domains (textile design, material science, and interactive systems), generating research outcomes that might not emerge through technology-led or user-centered approaches. Together, these insights suggest that further exploration of material agency with additional biomaterials could continue to expand design possibilities while fostering more sustainable approaches in HCI.

6.2.2 Negotiating the Tension Between Ephemerality and Utility in Material-led Design

My research deliberately engages with the tension between designing for dissolution and transformation on one hand, and meeting practical, utilitarian expectations on the other. This tension is not merely a technical hurdle but a deeper design condition—one that exposes the ways interaction design has historically privileged permanence, reliability, and predictability. In my work, temporality becomes a central part of this negotiation: materials are conceived not as fixed, stable substrates but as dynamic systems whose properties and behaviors can shift over time. Designing with this temporal dimension in mind requires reframing the role of materials from passive carriers of form to active participants in shaping interaction, the lifecycle of artifacts, and user experience.

The *Dissolving Wearables* project provided a concrete site for exploring this negotiation. The placement of biofoam yarn within knitted and crocheted garments was not arbitrary but decided through a back-and-forth between aesthetic intent, structural considerations of the textile, and the material's own qualities—such as strength, elasticity, and diameter. Textile integration

introduced its own parameters. Climate and environment influenced how the yarn behaved during garment making: in dry Boulder, Colorado, the biofoam yarns let them be handled smoothly; in humid New York, they stretched and adhered to the knitting needles, slowing the knitter's pace of work. These sensitivities while could have been seen as inconveniences, the designers framed them as active design constraints that shaped where and how the making of the garments took place and set the cadence of production.

Working with dissolution as a feature rather than a flaw required navigating perceptual barriers of permanence. For instance, when developing the biofoam yarns, we encountered persistent questions about how to "fix" or "prevent" dissolution, revealing deep-seated assumptions about material permanence as a universal good. By instead treating controlled dissolution as a legitimate design parameter, this work brings disposal and transformation into the design space of interactive textiles—echoing Blevis's [24] call for connecting "invention" with "disposal" in sustainable interaction design. Here, our approach extends his principles to textiles by deliberately designing for material transformation and end-of-life as integral aspects of the interaction experience itself.

The *Biofiber Spinning Machine* project revealed additional trade-offs between temporal design and functional requirements. When we attempted to use gelatin biofibers for weaving sensors, their fragility limited feasibility, as the fibers tended to break during the weaving process. Through iterative material formulation, we introduced a crosslinker to improve strength, which made weaving possible. However, this adjustment came with a temporal cost: the added crosslinker slowed the fibers' dissolution time. The trade-off, then, lay between producing fibers robust enough for textile fabrication and preserving the immediacy of their transformation. This balancing act between material

composition, fabrication feasibility, and dissolution dynamics illustrates how constraints often framed as limitations can instead become generative design parameters when approached through a material-led perspective.

Across these projects, the emphasis on ephemerality and transformation challenges dominant cultural narratives around technology that equate progress with permanence, durability, and accumulated functionality. By designing explicitly for dissolution and material transformation, my work engages with what Ingold [92, 93] calls the "morphogenetic approach," where form emerges through material processes rather than being imposed on passive matter. The proof-of-concept objects we created as part of this dissertation exemplify this approach: they were conceived to transform or to eventually disappear, foregrounding temporality as part of their function, questioning fashion's paradoxical reliance on both rapid replacement and material permanence.

6.2.3 Rethinking Sustainability in HCI Through Material Engagement

Sustainability is often treated as a constraint in design, yet in my research it became a creative driver—opening space for approaches that work with, rather than against, the specific behaviors of materials. Here, it operated as a site of decision-making made visible through material engagement, where values in my practice, shaped by biodesign and material-led design, informed not only the choice of materials but also how they are shaped, placed, and used over time. Sustainability in this sense was grounded in a lifecycle perspective: raw material sourcing, fabrication, transformation, use, and end-of-life are considered not as isolated phases, but as interconnected opportunities for design intervention.

This orientation was present across all the dissertation projects, even as each foregrounded different moments in the lifecycle. For instance, the

Biofoam as Interactive Material project traced material sourcing, fabrication, and transformation across the entire life of the interactive artifacts; *Dissolving Wearables* zoomed in on end-of-life as a site for interaction through dissolution; and the *Biofiber Spinning Machine* engaged the fabrication phase as a point of intervention. Across these projects, tacit, hands-on work with materials turned sustainability from an abstract principle into a set of generative constraints that shaped aesthetics, performance, and interaction, and foregrounded how lifecycle transitions could themselves become part of the design space.

This perspective required nuancing what we meant by "sustainability" beyond broad claims toward specific environmental considerations. Working closely with gelatin-based biomaterials surfaced concrete sustainability trade-offs grounded in practice. Prioritizing local, accessible sourcing led us to buy gelatin from a butcher shop rather than a laboratory supplier. Batch-to-batch variation in bloom strength then produced noticeable differences in fiber stability; we routinely recalibrated formulation and processing to achieve comparable results. In contrast, gelatin fibers spun from lab-grade gelatin (e.g., Sigma-Aldrich) were more consistent across batches, but we accepted the variability to uphold values of accessibility and affordability. These differences were not abstract, they emerged through hands-on engagement (plying and hand-spinning), where stability changes became immediately apparent.

A second decision point concerned crosslinking. To achieve fibers strong enough for weaving, we selected a biobased crosslinker rather than conventional, non-biobased options. This choice aligned with our biodegradability goals but required longer research and iteration, and—once implemented—introduced a temporal cost, which was an increase in dissolution

time. Together, these cases show sustainability operating as a site of decision-making made visible through material engagement, where values such as local sourcing, affordability, biodegradability, are negotiated alongside performance and process. These trade-offs are not merely technical challenges but represent fundamental tensions within sustainable design that this research actively engages with rather than glosses over. By documenting these trade-offs across the core projects, the work makes visible how environmental values are negotiated through sourcing, formulation, and fabrication choices; and how those choices condition interaction and end-of-life downstream.

By approaching biomaterials as more than replacements for synthetic materials, my research contributed to sustainable HCI by expanding the design space for interactive systems. This work also invites to rethink sustainability at a systems level within interaction paradigms. For example, working with gelatin biofibers presented an alternative end-of-life strategy for interactive textiles, allowing disassembly and material recovery—addressing what Sung et al. (2019) identify as the "unsustainable paradox" of electronic textiles that combine non-biodegradable fabrics with electronics. The *Dissolving Wearables* project highlighted how garments could be designed with intentional ephemerality, using material degradation as a form of expression and interaction. In this project, the ability of biofoam to dissolve and reform, challenged traditional notions of material disposal, encouraging new ways of thinking about circularity and material regeneration. These examples illustrated how material-led sustainability can inspire new forms of interaction and engagement, aligning with Wakkary et al.'s [208] notion of "material speculation," where materials become sites for reimagining not only products but the values and assumptions that underpin them.

6.3 Beyond Access: Knowledge, Tools, and Systems in Biomaterials Development

This section reflects on **RQ3**: *How might we enable biomaterial–textile integration?* The objectives guiding this inquiry were: **RO5**, to explore biomaterial–textile integration through the design and development of a fabrication tool, and **RO6**, to examine how an open-source tool can support access, experimentation, and knowledge-sharing around integrating biomaterials into interactive textiles.

The discussion situates my work within broader efforts to democratize biomaterial research, highlighting how the development of the biofiber spinning machine and related projects engaged accessible, low-tech fabrication methods while addressing knowledge barriers that persist beyond access to production tools. It examines how tacit, embodied understanding shapes the uptake of biomaterial techniques, and how open-source dissemination intersects with questions of who actually gets to use them effectively and under what conditions. Finally, it extends the discussion toward a systemic perspective, moving beyond material substitution to consider how biomaterial–textile integration can prompt shifts in interaction design and sustainability frameworks. The following subsections address these themes in turn, drawing on examples from the three core projects of the dissertation.

6.3.1 Enabling Fiber-Level Customization for Biomaterial–Textile Integration

This discussion relates to **RO5** by reflecting on what the development of the *Biofiber Spinning Machine* revealed about making fiber-level work with

biomaterials possible in the first place. Before this work, accessible fabrication processes for biomaterial fibers were almost entirely manual, often relying on craft-based methods such as extruding biofoam yarns from a piping bag (Chapter 4). These approaches offered minimal scope for customization and were difficult to reproduce with precision. The machine shifted this situation by making it possible to control parameters such as color, elasticity, and diameter at the earliest stage of textile design. This positioned fiber-making as a site for design intervention, where choices made at the fiber level could inform subsequent stages of yarn production and textile structure, opening up a new scale of possibilities for biomaterial–textile integration.

Working with the machine also demonstrated how fiber-level customization can alter the aesthetic and functional qualities available to textile designers. Some properties, such as luster and smoothness, were intrinsic to the spun gelatin and became especially pronounced when integrated into woven cloth. Other qualities, such as color gradients, changes in texture, or the ability of fibers to swell and retain a shaped form, emerged from variations in additives and processing conditions. These outcomes were not only functional parameters to be tuned but also material expressions that could be intentionally designed for. In this way, the machine created conditions for interaction between material behavior and textile construction, allowing for both predictable and unexpected qualities to influence integration possibilities.

The development process also revealed that enabling integration at the fiber level depends on interdisciplinary knowledge, particularly in understanding the polymer-specific requirements for spinning solutions. Successful fiber production required identifying the right expertise—such as materials scientists with protein-specific knowledge—and translating between

disciplinary vocabularies. While the machine itself provided the means for spinning, its use made visible the tacit and scientific knowledge needed to produce fibers suitable for textile integration.

In the context of HCI and interactive textile design, the machine expanded the palette of available form factors beyond sheets, molded forms, 3D printed shapes, or extruded yarn-like biomaterials. Its modular, open-source design aimed to support adaptation to other biomaterials, such as algae- or casein-based fibers, and could be repurposed for applications beyond interactive textiles. Since the paper publication [120], and with ongoing support from the research team through our Discord channel [183], practitioners in different regions have replicated the machine for their own varied purposes. These replications point to its potential not only as a fabrication tool but also as an artifact that can spark broader discussions about sustainability, access to technology, and the roles of designers as material inventors and fabricators. While this work opened the door to fiber-level biomaterial–textile integration, the full scope of what is possible will depend on how others take up, adapt, and extend the machine in diverse contexts.

6.3.2 Addressing Knowledge Barriers in Open-Source Biomaterials

This discussion relates to **RO6** by examining how the development and dissemination of the *Biofiber Spinning Machine* revealed forms of knowledge that shape access to biomaterial–textile experimentation. While access to production tools was an important step toward material democratization, my research showed that tools alone were insufficient to achieve true accessibility. The development of the Biofiber Spinning Machine highlighted specific forms of knowledge and expertise that remained barriers despite the availability of

open-source fabrication tools. For instance, understanding polymer rheology, how liquid biomaterials flow and solidify, emerged as a critical knowledge domain that was rarely addressed in democratization efforts. This gap became evident when early users of the spinning machine struggled to adapt material formulations despite having full access to the hardware and documentation.

My approach extended previous democratization efforts (such as those by Camere and Karana [30], or Attias et al. [12]) by explicitly addressing what I call the "tacit knowledge problem"—a term I use to describe the embodied, sensory expertise that arises through material engagement and remains difficult to document or share. While tacit knowledge has long been acknowledged in design and craft literature (e.g., Polanyi's work on tacit knowing [159], and studies of tacit skills in craft practices [171]), here I operationalize it in the context of biomaterial fabrication, where such embodied understanding can be a significant barrier even when open-source tools are available. The biofoam project attempted to address this through detailed documentation of sensory cues (e.g., describing the "right" consistency as "coating the back of a spoon like thick cream") rather than relying solely on quantitative measurements. This emphasis on tacit knowledge offers a complementary perspective to democratization approaches that have historically emphasized hardware access over knowledge transfer.

Nevertheless, unexpected challenges arose even with these efforts. When teaching biofoam workshops, I observed that participants with previous cooking experience adapted more quickly to the material processes than those without, revealing how democratization intersected with unexamined assumptions about baseline skills. This finding aligned with Rosner's [174] observations about the hidden labor and knowledge embedded in seemingly

"accessible" craft processes and suggested that true democratization required attention to diverse knowledge backgrounds rather than assuming universal baseline capabilities.

6.3.3 Conditions Shaping Access in Open-source Biomaterials

This discussion further addresses **RO6** by reflecting on the conditions that mediate access and participation in open-source biomaterial design. It examines how communication style, documentation practices, and community infrastructures such as online channels supported knowledge-sharing and experimentation, while also revealing the limits of accessibility across different practitioner backgrounds.

The open-source approach to biomaterial development presented both opportunities and challenges for democratization. While the *Biofiber Spinning Machine* was designed to be modifiable and replicable with widely available components, reflection on its use suggested that differences in educational background, access to basic equipment, technical literacy, and time resources might influence who could work with open-source biomaterial approaches, despite efforts to minimize these barriers.

In one example, documentation for the machine was initially written using technical terminology familiar to engineers but potentially alienating to textile practitioners. After recognizing this barrier, we created separate posts on our personal and lab websites describing the project in more accessible, plain language. We also established a Discord channel [183] where practitioners could ask questions, share progress on replicating the machine, and receive guidance, providing a more interactive complement to static documentation [120]. These

steps were intended to reduce the kinds of knowledge hierarchies that can persist even within open-source communities [172].

The dissolving wearables project further illustrated that perceptions of material origin could also shape engagement. Because the project used gelatin biofoam yarns, some practitioners who encountered the work after publication assumed that gelatin was exclusively animal-based and therefore unsuitable for their own contexts. These practitioners reached out to request alternative biomaterials, at which point we explained that gelatin can also be derived from plant-based sources. In such cases, substituting one biomaterial for another would require adjustments to formulations and processing, as each material's composition demands different handling.

Collectively, these examples illustrate that enabling access to open-source biomaterial tools involves more than distributing hardware designs or publishing technical instructions. Access is mediated by how knowledge is communicated, by the technical assumptions embedded in documentation, and by the fit between those assumptions and practitioners' skills and resources. These conditions, while not unique to biomaterials, take on particular significance in this space because of the interplay between specialized technical requirements and the goal of lowering barriers to participation. Attending to these factors is therefore essential when aiming to broaden engagement in biomaterial–textile integration.

6.3.4 Biomaterial–Textile Integration as a Catalyst for Systemic Thinking

As stated in Chapter 2, my research moved beyond the paradigm of simple material substitution toward a more systemic approach to sustainability in HCI. The material-led exploration of biomaterial–textile integration — from

early non-woven biofoam pressure sensors, to yarn-like biofoam extrusions for knitting and crocheting, to fine woven gelatin biofibers — highlighted how working with biomaterials at multiple textile scales could influence not only production methods but also underlying design assumptions, prompting a rethinking of what interactive textiles are and how they might participate in sustainable futures. This process made visible how the properties and affordances of gelatin-based biomaterials could guide design decisions. It not only foregrounded material transformation and temporality as part of the interaction, but also revealed gaps in the surrounding system: in accessible fabrication methods, in knowledge transfer, and in the availability of tools suited to designers and researchers outside specialist material science contexts.

In the biofiber work, fiber properties directly informed new approaches to textile structure and electronic integration, highlighting how material qualities could become active design parameters in the creation of interactive textiles. Attuning to these systemic conditions influenced the development of the Biofiber Spinning Machine itself. The recognition that accessible, modifiable tools for producing biomaterial fibers did not exist for textile designers, HCI researchers, or other material innovators became a key driver for creating a tool that could both enable and expand integration possibilities. By making fiber-level customization accessible — in properties such as color, elasticity, and diameter — the machine positioned fiber production as a design space in its own right, rather than a fixed upstream process.

Seen from this perspective, biomaterial–textile integration acted as a catalyst: prompting not only new artifact forms, but also interventions in the larger ecosystem that shapes sustainable design practice. The collective insights from the biofoam, dissolving wearables, and biofiber projects aligned with design

researcher Terry Irwin's [95, 96] concept of "transition design" — approaches that address sustainability through rethinking systems. Here, rethinking involved expanding the palette of biomaterial form factors available to interactive textile designers, embedding knowledge-sharing practices alongside fabrication, and enabling material transformation to become an intentional part of the interaction lifecycle. This systemic approach also revealed specific gaps in existing sustainable design frameworks in HCI. Current frameworks like Bleviss's Sustainable Interaction Design [24] primarily address digital artifacts with physical components rather than materials with inherently transformative properties. My work extends these frameworks by demonstrating how material temporality creates new possibilities for sustainable design that go beyond reduced resource consumption or improved recyclability toward intentional material transformation and regeneration as interaction modalities.

6.4 Limitations

Challenges remain in making biomaterial fabrication truly replicable and adaptable across different contexts. One limitation is the lack of dedicated prototyping tools for biomaterial-based interactive textiles, which makes standardization difficult. While the Biofiber Spinning Machine addresses some of these gaps, ensuring that fabrication methods remain both adaptable and usable by diverse practitioners requires ongoing iteration.

A second limitation lies in the tension between standardization and adaptation. Standardization can facilitate replication and knowledge sharing, but it also risks constraining the open-ended material exploration that has been central to this work. This is particularly relevant when working with

biomaterials whose properties are highly sensitive to local conditions, making direct replication across regions challenging.

Scalability is another open question. Small-scale, localized production aligns with the values of sustainability and accessibility that underpin this research, yet it raises questions about how biomaterial approaches might also respond to broader manufacturing needs without losing their adaptability.

Finally, while this research engaged deeply with gelatin-based biomaterials, findings may not directly transfer to other biobased materials without further experimentation. Each material's chemistry, processing requirements, and affordances can differ substantially, which means that insights into integration, aesthetics, or interaction design cannot be assumed to apply universally.

6.5 Future Work

6.5.1 Expanding Biomaterial Affordances Exploration

Building on the range of biomaterial affordances identified throughout this dissertation and synthesized in Fig. 6.1, short-term future work could extend the biodesign orientation developed here by deepening engagement with these affordances as entry points for interaction design. Each affordance, such as dissolution, swelling, absorption, permeability, or reversible deformation, offers distinct implications for interactivity, temporality, and sustainability. They also provide accessible starting points for students and early-stage researchers exploring the intersection of biomaterial and interaction design, where material behavior itself becomes a site of discovery and inquiry.

Exploring these affordances systematically could reveal how transformation and decay become central to interaction—how materials can not only sense or

respond but also shift, erode, or renew as part of their designed expression. Combining multiple affordances within a single biomaterial, for instance by integrating soft dissolvable foams with more rigid bioplastic counterparts, might enable mono-material interactive systems that express complexity without relying on composite structures. These inquiries would expand how interaction is understood when it emerges from the material's own dynamics rather than computational augmentation.

Building on my recent explorations of fluid-responsive and shape-changing bioplastics, such as Bioactuated Textiles [202], Bio-e-Nails [201], and Designing for the Leaky Body (under review), future work could continue to examine how absorption, permeability, and reversible deformation can become interaction modalities in themselves. These projects extend the dissertation's material-led and life-cycle-oriented approach into other contexts of body-material interaction, where temporality, attachment, and care unfold through material change. These directions invite reconsideration of where and how interaction occurs—whether within materials, bodies, or environments—and encourage diverse forms of engagement beyond traditional user-technology paradigms. Further studies could also explore how users engage with biomaterials in everyday situations, how they maintain or adapt them over time, and how such experiences inform design decisions about durability, reusability, and transformation.

6.5.2 Building Infrastructures for Shared and Situated Knowledge

At a mid-term horizon, future work could extend this dissertation's focus on accessibility and tacit knowledge by examining how biomaterial practices circulate and evolve within collaborative contexts. The dissertation identified

knowledge transfer as a persistent barrier to participation in open-source biomaterial research. Building on this insight, subsequent investigations could explore how interdisciplinary teams translate between scientific, craft-based, and design vocabularies, and how these translations shape both material outcomes and collaborative dynamics. Developing shared yet adaptable frameworks for communicating material knowledge would help sustain the open, situated character of biodesign while lowering entry barriers for new practitioners. Concretely, this could include multimodal "recipe" formats that pair quantitative parameters with sensory cues; small, searchable repositories where practitioners annotate formulations with performance notes; and shared patterns for reporting failures and variations. The aim is portability without uniformity: practices that support reproducibility while leaving room for local adaptation and ongoing experimentation.

Emerging collaborative efforts in design research already point toward such possibilities. Recently, I have co-authored a paper that examines how stories, artifacts, and documentation practices make tacit, experiential knowledge more legible across communities [22]. Extending these approaches to biomaterial-textile contexts could support collective reflection on fabrication practices and lead to multimodal documentation strategies that integrate narrative, visual, and procedural forms of knowing. These directions would deepen the dissertation's articulation of the "tacit knowledge problem," expanding it from an individual design challenge to a distributed, community-driven inquiry.

In parallel, open-source tools such as the *Biofiber Spinning Machine* could evolve into living infrastructures for experimentation, enabling practitioners to document variation, compare outcomes, and refine formulations collectively.

Extending this notion of infrastructure beyond tools to include the social and collaborative systems that sustain them, recent explorations I have contributed to—such as studies of reversible actuation in casein-based textiles [202] and the Stories and Artifacts workshop (CHI 2026, under review)—illustrate how material-led research can couple technological development with shared reflection. These initiatives point toward infrastructures of practice, where experimentation, documentation, and storytelling together support the collective articulation of tacit, embodied knowledge across disciplines. Future work could build on these directions by developing lightweight, open frameworks for interdisciplinary collaboration—spaces where material recipes, design narratives, and failures are documented in parallel, and where shared vocabularies evolve through collective making. In doing so, the goal extends beyond improving biomaterial performance or fabrication tools, toward cultivating the social and epistemic infrastructures that allow material knowledge to be shared, questioned, and reimaged across communities. Such efforts would carry forward this dissertation’s concern with accessibility and knowledge transfer, translating it into durable, community-based modes of practice.

6.5.3 Toward Material Ecologies of Biodesign

In the long term, the implications of this work point toward reimagining how interaction design engages with materials, time, and sustainability. The dissertation framed dissolution and material transformation as design strategies that position temporality as integral to interaction. Extending this stance, future research could investigate how life-cycle-oriented approaches, those that embed transformation, reuse, or decay into material systems, might inform emerging

paradigms of circular and regenerative design in HCI. Rather than treating sustainability as an external goal, this orientation situates it within the material's own processes of transformation and reuse.

Long-term inquiry could also explore how material-led interaction design contributes to broader epistemic shifts in technology development. The attunement practices and open, collaborative infrastructures envisioned here suggest an alternative model of innovation: one grounded in care, maintenance, and situated experimentation rather than optimization or scale. This perspective resonates with ongoing conversations in posthumanist and feminist HCI, where knowledge is seen as distributed among humans, materials, and environments. Investigating how such distributed forms of making can sustain long-term stewardship of biomaterial practices offers an important challenge and opportunity for the field.

Finally, as biomaterial research increasingly enters public and educational contexts, future work could address how pedagogical models, open-access repositories, and institutional partnerships might support continuity between research, teaching, and community engagement. This could include designing curricula that foreground material ethics, temporality, and transformation as core competencies in interaction design education. In this way, the dissertation's insights on attunement to biomaterial affordances, and accessibility may evolve into a broader framework for cultivating sustainable design cultures—where making, unmaking, and remaking are understood as interconnected modes of inquiry and care.

Chapter 7

Conclusion



This dissertation investigated sustainability as a design opportunity through material-led work with biomaterials in interactive textiles. Working across biodesign, interactive textiles, and Sustainable HCI, it focused on gelatin as a central biomaterial and examined how its properties and behaviours shaped form, interaction, and design practice. It addressed three research questions: RQ1: What unique opportunities for sustainable design emerge when working with gelatin in the design of interactive systems? RQ2: How might the specific material properties of gelatin inform the aesthetics and functionality of interactive textiles? RQ3: How might we enable biomaterial-textile integration? Across three core projects—Biofoam for Tangible Interaction, Dissolving Wearables, and the Open-source Biofiber Spinning Machine—the dissertation offered a material-led account of how sustainability could be embedded as a design value, not only considered as an outcome. Throughout this process, dissolution emerged as a design strategy for engaging material change as part of interaction and sustainability. It shifted attention from stability and permanence toward the ways materials behave, transform, and break down over time, and how these changes can be intentionally designed for.

Taken together, these projects generated three main contributions: First, the development of new biomaterial formulations and low-tech fabrication techniques for gelatin-based biofoams and biofibers, demonstrating how a material-driven approach could tune properties relevant to interactive textiles. Second, the development of proof-of-concept interactive objects such as pressure sensors, dissolving garments, accessories, and woven sensors with biofibers that foregrounded transformation, impermanence, and end-of-life as part of interaction. Here, dissolution as a design strategy was expressed through the deliberate use of material impermanence to reimagine interaction as a process of

change and disappearance rather than endurance. Third, the development of an open-source machine to fabricate fibers from biomaterials, enabling fiber-level experimentation as a foundation for future textile integration. Together, these contributions showed how incorporating sustainability as a design value oriented the design process itself, shaping practices and decisions through the properties and behaviors of biomaterials.

Reflecting on RQ1, the research showed that working with gelatin opened opportunities to design for lifecycle, temporality, and transformation as part of interaction. Material formulation, making, and decay became sites where interaction could be shaped, complementing and at times replacing electronics-first approaches. As gelatin biofoam and biofibers were tuned for density, color, strength, water resistance, elasticity, or dissolution, opportunities emerged to prototype interactive objects whose behaviors were materially grounded. This reframed interactivity as residing not only in circuits or code but also in the evolving properties of the material itself. Working with dissolution reframed interaction as something that unfolds through material change, where the visible transitions of a material—softening, dissolving, or reforming—become part of how interaction is experienced and understood. In that sense, sustainability functioned as a design driver: material sourcing, low-tech fabrication, re-use, and end-of-life recovery informed design decisions from the outset. For RQ2, the work examined how gelatin biomaterials' properties and behaviours informed both aesthetic expression and functionality in interactive textiles. Material agency, expressed in part through responsiveness such as shape change, swelling, and dissolution, influenced the design process by enabling, resisting, or redirecting decisions. The prototypes demonstrated how visual qualities like luster and color change, and functional

qualities like degree of compression and moisture responsiveness, could be considered as design parameters. The dissertation also reflected on the tension between ephemerality and utility. Designing for transformation and disassembly introduced new aesthetic possibilities while asking how durability, maintenance, and use would be negotiated in practice. In this tension, dissolution became a site of aesthetic negotiation—one that invited new forms of care, attention, and letting go as part of the design experience. These reflections situated material temporality as integral to interaction rather than a constraint to be minimized. In response to RQ3, the discussion focused on enabling conditions for biomaterial–textile integration. The development of the *Open-source Biofiber Spinning Machine* made fiber-level customization possible within an interactive textiles context, allowing control over properties such as color, elasticity, and diameter. While the machine did not integrate biomaterials into textiles by itself, it created the conditions for textile designers to do so by positioning fiber production as a design space. The capacity of biomaterials to be dissolved, reformulated, and re-spun further extended this notion of integration—suggesting that design could circulate through continuous material transformation rather than fixed assembly.

Through the process of developing and sharing the Biofibers Spinning Machine, my collaborators and I came to recognize that access to tools was not sufficient on its own. From our experience, tacit knowledge, disciplinary vocabularies, and baseline skills all influenced who could make effective use of open-source approaches and under what conditions. To address these knowledge barriers, we created a community support channel for the ones interested in replicating our machine. Further reflections pointed toward a systemic perspective in which materials, tools, practices, and communities

co-shape what integration can become. In this broader system, dissolution also acted as a metaphor for openness—where boundaries between materials, disciplines, and expertise became porous, fostering shared experimentation and situated learning.

These reflections on access, skills, and community infrastructures connect directly to the dissertation's broader argument: that moving toward sustainable interactive textiles requires shifting from material substitution toward systemic thinking in SHCI. Working through nonwoven artifacts, yarn-like extrusions, and fiber-level weaving made visible how material properties guided design decisions and how infrastructures of knowledge, tooling, and collaboration mattered for adoption. In that sense, the work aligned with transition-oriented perspectives by connecting material-led practice to questions of access, replication, and community. It treated biomaterials as active participants in design and situated interactivity across formulation, making, use, and end-of-life. By articulating dissolution as a design strategy, this work reframed sustainability not as a fixed goal but as an evolving relationship—material, temporal, and participatory.

These insights suggested directions for future work that were outlined in Section 6.5. Developing flexible standards for sharing and adapting biomaterial practices, exploring a broader palette of biomaterials at the fiber level, and strengthening interdisciplinary collaboration and translation practices could extend the dissertation's trajectory. Open-source approaches that lower technical barriers and support knowledge transfer may broaden participation in biomaterial-textile integration while keeping sustainability central as a design value. Future explorations of dissolution in other biomaterial contexts could deepen this approach, expanding how designers engage transformation and

temporality as integral to sustainability.

In closing, the dissertation contributed a material-led account of sustainability in interactive textiles that treated biomaterials not as passive substitutes but as dynamic media that shape interactions and practices. By positioning dissolution as a design strategy, it showed how transformation, decay, and renewal could be woven into design as forms of interaction and care. By bringing biodesign into conversation with interactive textiles and SHCI, it offered conceptual and practical means to design with lifecycle, temporality, and transformation. These outcomes are intended as resources for designers and researchers who wish to work with and through materials to reimagine what interactive textiles can be and how sustainability can be enacted in design.

Bibliography

- [1] Acaroglu L. *A Guide to Life Cycle Thinking*. en. Mar. 2018. URL: <https://medium.com/disruptive-design/a-guide-to-life-cycle-thinking-b762ab49bce3> (visited on 02/28/2024).
- [2] Aldrich S. *Gelatin from porcine skin CAS No.9000-70-8 Sigma*. en. 2023. URL: <https://www.sigmaaldrich.com/US/en/product/sigma/g2500> (visited on 08/24/2023).
- [3] Alistar M. and Pevere M. "Semina Aeternitatis: Using Bacteria for Tangible Interaction with Data". In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI EA '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–13. ISBN: 9781450368193. DOI: 10.1145/3334480.3381817. URL: <https://doi.org/10.1145/3334480.3381817>.
- [4] Alix S. et al. "Biocomposite materials from flax plants: Preparation and properties". In: *Composites Part A: Applied Science and Manufacturing* 39.12 (2008), pp. 1793–1801. ISSN: 1359-835X. DOI: <https://doi.org/10.1016/j.compositesa.2008.08.008>. URL: <https://www.sciencedirect.com/science/article/pii/S1359835X08002169>.
- [5] Antle A. N., Marshall P., and Hoven E. van den. "Embodied interaction: Theory and practice in HCI". In: *Proc. CHI*. Vol. 11. 2011.
- [6] Arantes L. M. "Unraveling Knitting: Form Creation, Relationality, and the Temporality of Materials". In: *The Journal of American Folklore* 133.528 (2020),

-
- pp. 193–204. ISSN: 00218715, 15351882. URL: <https://www.jstor.org/stable/10.5406/jamerfolk.133.528.0193>.
- [7] Arnardottir T. et al. “Bacterial Choreography: Designing Interactions through Biological Induced Mineralisation”. In: *1st International Conference on Microbial Biotechnology in Construction Materials and Geotechnical Engineering*. Newcastle University. 2020.
 - [8] Arnardottir T. and Dade-Robertson M. “Exploring the Interplay of Biological Science, Sensory Engagement, and Material Probing.” In: *Cambridge University Press* (2024).
 - [9] Arnardottir T. H. “Bacterial Sculpting: a processual approach to forming with unruly matter”. PhD thesis. Newcastle University, 2024.
 - [10] Arora N. et al. “SATURN: A thin and flexible self-powered microphone leveraging triboelectric nanogenerator”. In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2.2 (2018), pp. 1–28.
 - [11] Arora N. et al. “Mars: Nano-power battery-free wireless interfaces for touch, swipe and speech input”. In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. 2021, pp. 1305–1325.
 - [12] Attias N. et al. “Implementing bio-design tools to develop mycelium-based products”. In: *The Design Journal* 22.sup1 (2019), pp. 1647–1657.
 - [13] Bae S. S. and West M. E. “Cyborg Crafts: Second SKIN (Soft Keen INteraction)”. In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '21. Salzburg, Austria: Association for Computing Machinery, 2021. ISBN: 9781450382137. DOI: 10.1145/3430524.3444705. URL: <https://doi.org/10.1145/3430524.3444705>.

-
- [14] BDC. *Biodesign Challenge*. en-US. URL: <https://www.biodesignchallenge.org> (visited on 08/02/2025).
- [15] Bell F. and Alistar M. "Designing with Alganyl: A Hands-on Exploration of Biodegradable Plastics". In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '22. Daejeon, Republic of Korea: Association for Computing Machinery, 2022. ISBN: 9781450391474. DOI: 10.1145/3490149.3503669. URL: <https://doi.org/10.1145/3490149.3503669>.
- [16] Bell F., Coffie J., and Alistar M. "Bio-Digital Calendar: Attuning to Nonhuman Temporalities for Multispecies Understanding". In: *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '24. Cork, Ireland: Association for Computing Machinery, 2024. ISBN: 9798400704024. DOI: 10.1145/3623509.3633386. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3623509.3633386>.
- [17] Bell F., Friedman-Gerlicz C., and Buechley L. "Biomaterial Recipes for 3D Printing: A Cookbook of Sustainable and Extrudable Bio-Pastes". In: *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '25. Association for Computing Machinery, 2025. ISBN: 9798400711978. DOI: 10.1145/3689050.3704427. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3689050.3704427>.
- [18] Bell F., Ofer N., and Alistar M. "ReClaym our Compost: Biodegradable Clay for Intimate Making". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491102.3517711. URL: <https://doi.org/10.1145/3491102.3517711>.
- [19] Bell F. et al. "SCOBY BREASTPLATE: SLOWLY GROWING A MICROBIAL INTERFACE". In: *Proceedings of the Seventeenth International Conference on*

-
- Tangible, Embedded, and Embodied Interaction*. TEI '23. Warsaw, Poland: Association for Computing Machinery, 2023. ISBN: 9781450399777. DOI: 10.1145/3569009.3572805. URL: <https://doi.org/10.1145/3569009.3572805>.
- [20] Bell F. et al. "µMe: Exploring the Human Microbiome as an Intimate Material for Living Interfaces". In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS '23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 2019–2033. ISBN: 9781450398930. DOI: 10.1145/3563657.3596133. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3563657.3596133>.
- [21] Bell F. et al. "3D Printing Eggshells: Exploring Eco-Socio-Technical Relations through Biomaterial Design". In: *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. CHI '25. Association for Computing Machinery, 2025. ISBN: 9798400713941. DOI: 10.1145/3706598.3714290. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3706598.3714290>.
- [22] Benabdallah G. et al. "'Chaotic, Exciting, Impactful': Stories of Material-led Designers in Interdisciplinary Collaboration". In: *Proceedings of the 2025 ACM Designing Interactive Systems Conference*. 2025, pp. 1313–1327.
- [23] Besana N. et al. "Expanding the Concept of Sustainable Interaction Design: A Systematic Review". In: *Sustainability* 16.17 (2024), p. 7486.
- [24] Blevis E. "Sustainable Interaction Design: Invention & Disposal, Renewal & Reuse". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '07. San Jose, California, USA: Association for Computing Machinery, 2007, pp. 503–512. ISBN: 9781595935939. DOI: 10.1145/1240624.1240705. URL: <https://doi.org/10.1145/1240624.1240705>.
- [25] Bornes L. "A Methodology and a Tool to Support the Sustainable Design of Interactive Systems: Adapting systemic design tools to model complexity in interaction design". In: *Extended Abstracts of the 2023 CHI Conference on Human*

-
- Factors in Computing Systems*. CHI EA '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394222. DOI: 10.1145 / 3544549.3577055. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3544549.3577055>.
- [26] Bremer C., Knowles B., and Friday A. "Have We Taken On Too Much?: A Critical Review of the Sustainable HCI Landscape". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517609. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3491102.3517609>.
- [27] Buechley L. and Ta R. "3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145/3544548.3580813. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3544548.3580813>.
- [28] Buso A. et al. "Weaving Textile-form Interfaces: A Material-Driven Design Journey". In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS '23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 608–622. ISBN: 9781450398930. DOI: 10.1145 / 3563657.3596086. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3563657.3596086>.
- [29] Buso A. et al. "AnimaTo: Designing a Multimorphic Textile Artefact for Performativity". In: *Proceedings of the 2024 ACM Designing Interactive Systems Conference*. DIS '24. Copenhagen, Denmark: Association for Computing Machinery, 2024, pp. 20–34. ISBN: 9798400705830. DOI: 10.1145/3643834.3660738. URL: <https://doi.org/10.1145/3643834.3660738>.

-
- [30] Camere S. and Karana E. "Fabricating materials from living organisms: An emerging design practice". In: *Journal of Cleaner Production* 186 (2018), pp. 570–584.
- [31] Campo Woytuk N. et al. "Tactful Feminist Sensing: Designing for Touching Vaginal Fluids". In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS '23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 2642–2656. ISBN: 9781450398930. DOI: 10.1145/3563657.3595966. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3563657.3595966>.
- [32] Chaochai T. et al. "Preparation and properties of gelatin fibers fabricated by dry spinning". In: *Fibers* 4.1 (2016), p. 2.
- [33] Chaochai T. et al. "Preparation and properties of gelatin fibers fabricated by dry spinning". In: *Fibers* 4.1 (2016), p. 2.
- [34] Chapman J. *Emotionally durable design: objects, experiences and empathy*. Routledge, 2012.
- [35] Cheng T. et al. "Functional Destruction: Utilizing Sustainable Materials' Physical Transiency for Electronics Applications". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145/3544548.3580811. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3544548.3580811>.
- [36] Cochrane K. A. et al. "Adaptive soft switches: co-designing fabric adaptive switches with occupational therapists for children and adolescents with acquired brain injury". In: *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction*. 2023, pp. 1–14.

-
- [37] Dade-Robertson M., Levin M., and Davies J. "How do we design with materials that have their own agency?" In: *Research Directions: Biotechnology Design* 1 (2023), e7. DOI: 10.1017/btd.2023.1.
 - [38] Dade-Robertson M. and Zhang M. "Theory and design in the biotechnical age: A schematic understanding of bio design and synthetic biology practice". In: *The Design Journal* 27.5 (2024), pp. 800–822.
 - [39] Das R. et al. "Multifunctional carbon nanotubes in water treatment: the present, past and future". In: *Desalination* 354 (2014), pp. 160–179.
 - [40] Davies J. and Levin M. "Synthetic morphology via active and agential matter". In: *OSF Preprints [Epub Ahead of Print]* (2022).
 - [41] DeFrates K. G. et al. "Protein-Based Fiber Materials in Medicine: A Review". In: *Nanomaterials* 8.7 (2018). ISSN: 2079-4991. DOI: 10.3390/nano8070457. URL: <https://www.mdpi.com/2079-4991/8/7/457>.
 - [42] Dementyev A., Vega Gálvez T., and Olwal A. "SensorSnaps: Integrating wireless sensor nodes into fabric snap fasteners for textile interfaces". In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 2019, pp. 17–28.
 - [43] Devendorf L. and Di Lauro C. "Adapting Double Weaving and Yarn Plying Techniques for Smart Textiles Applications". In: *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '19. Tempe, Arizona, USA: Association for Computing Machinery, 2019, pp. 77–85. ISBN: 9781450361965. DOI: 10.1145/3294109.3295625. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3294109.3295625>.
 - [44] Devendorf L., Koninck S. de, and Sandry E. "An Introduction to Weave Structure for HCI: A How-to and Reflection on Modes of Exchange". In: *Proceedings of*

-
- the 2022 ACM Designing Interactive Systems Conference*. DIS '22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 629–642. ISBN: 9781450393584. DOI: 10.1145/3532106.3534567. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3532106.3534567>.
- [45] Devendorf L. and Ryokai K. “Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, 2015, pp. 2477–2486. ISBN: 9781450331456. DOI: 10.1145/2702123.2702547. URL: <https://doi.org/10.1145/2702123.2702547>.
- [46] Devendorf L. et al. “AdaCAD: Parametric Design as a New Form of Notation for Complex Weaving”. In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145/3544548.3581571. URL: <https://doi.org/10.1145/3544548.3581571>.
- [47] Devendorf L. K. “Strange and unstable fabrication”. PhD thesis. UC Berkeley, 2016.
- [48] Dew K. N. and Rosner D. K. “Lessons from the Woodshop: Cultivating Design with Living Materials”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3174159. URL: <https://doi.org/10.1145/3173574.3174159>.
- [49] DiSalvo C., Sengers P., and Brynjarsdóttir H. “Mapping the Landscape of Sustainable HCI”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery,

-
- 2010, pp. 1975–1984. ISBN: 9781605589299. URL: <https://doi.org/10.1145/1753326.1753625>.
- [50] DIYBio. *An Institution for the Do-It-Yourself Biologist*. 2020. URL: <https://diybio.org>.
- [51] Dourish P. “Embodied interaction: Exploring the foundations of a new approach to HCI”. In: *Work* 1.1 (1999), pp. 1–16.
- [52] Dulal M. et al. “Toward Sustainable Wearable Electronic Textiles”. In: *ACS Nano* 16.12 (Dec. 2022). Publisher: American Chemical Society, pp. 19755–19788. ISSN: 1936-0851. DOI: 10.1021/acs.nano.2c07723. URL: <https://doi.org/10.1021/acs.nano.2c07723> (visited on 07/31/2023).
- [53] Dulal M. et al. “Toward sustainable wearable electronic textiles”. In: *ACS nano* 16.12 (2022), pp. 19755–19788.
- [54] Dunne L. E. et al. “Garment-Based Body Sensing Using Foam Sensors”. In: *Proceedings of the 7th Australasian User Interface Conference - Volume 50*. AUIC '06. Hobart, Australia: Australian Computer Society, Inc., 2006, pp. 165–171. ISBN: 1920682325.
- [55] Dunne M. *The Bioplastics Cookbook: A Catalogue of Bioplastics Recipes*. Barcelona: FabTextiles, 2018.
- [56] Egusa S. et al. “Multimaterial piezoelectric fibres”. In: *Nature materials* 9.8 (2010), pp. 643–648.
- [57] Fabricademy. *Textile & Technology Academy*. en. URL: <https://textile-academy.org/> (visited on 08/02/2025).
- [58] Fernaeus Y. and Sundström P. “The material move how materials matter in interaction design research”. In: *Proceedings of the Designing Interactive Systems Conference*. DIS '12. Newcastle Upon Tyne, United Kingdom: Association for

-
- Computing Machinery, 2012, pp. 486–495. ISBN: 9781450312103. DOI: 10.1145/2317956.2318029. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/2317956.2318029>.
- [59] Fletcher K. *Craft of use: Post-growth fashion*. Routledge, 2016.
- [60] *Force Sensing Resistor Integration and Evaluation Parts Catalog 400 Series Evaluation Parts with Suggested Electrical Interfaces*. 90-45632. Rev. D. Interlink Electronics.
- [61] Forman J. et al. “Modifiber: Two-way morphing soft thread actuators for tangible interaction”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019, pp. 1–11.
- [62] Forman J. et al. “Living Bits and Radical Aminos: A Workshop on Bio-Digital Interfaces for Human-Computer Interaction”. In: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI EA '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394222. DOI: 10.1145/3544549.3573813. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3544549.3573813>.
- [63] Forti V. et al. *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*. Report. United Nations University/United Nations Institute for Training and Research, 2020.
- [64] Foundation E. M. *A New Textiles Economy: Redesigning fashion's future*. URL: <https://www.ellenmacarthurfoundation.org/a-new-textiles-economy> (visited on 12/09/2022).
- [65] Frankjær R. and Dalsgaard P. “Understanding craft-based inquiry in HCI”. In: *Proceedings of the 2018 Designing Interactive Systems Conference*. 2018, pp. 473–484.
- [66] Friske M., Wu S., and Devendorf L. “AdaCAD: Crafting Software For Smart Textiles Design”. In: *Proceedings of the 2019 CHI Conference on Human Factors in*

-
- Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. ISBN: 9781450359702. DOI: 10.1145/3290605.3300575. URL: <https://doi.org/10.1145/3290605.3300575>.
- [67] Gaver B., Dunne T., and Pacenti E. “Design: cultural probes”. In: *interactions* 6.1 (1999), pp. 21–29.
- [68] Gaver W. “What should we expect from research through design?” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: Association for Computing Machinery, 2012, pp. 937–946. ISBN: 9781450310154. DOI: 10.1145/2207676.2208538. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/2207676.2208538>.
- [69] Ge G. et al. “BIOGEM: A Fully Biodegradable Gelatin-Based McKibben Actuator with Embedded Sensing”. In: *Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology*. UIST '25. Association for Computing Machinery, 2025. ISBN: 9798400720376. DOI: 10.1145/3746059.3747687. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3746059.3747687>.
- [70] Genç Ç., Launne E., and Häkkinen J. “Interactive Mycelium Composites: Material Exploration on Combining Mushroom with Off-the-shelf Electronic Components”. In: *Nordic Human-Computer Interaction Conference*. NordiCHI '22. Aarhus, Denmark: Association for Computing Machinery, 2022. ISBN: 9781450396998. DOI: 10.1145/3546155.3546689. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3546155.3546689>.
- [71] Giaccardi E. and Karana E. “Foundations of Materials Experience: An Approach for HCI”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, 2015, pp. 2447–2456. ISBN: 9781450331456. DOI: 10.1145/2702123.2702337. URL: <https://doi.org/10.1145/2702123.2702337>.

-
- [72] Godard P. et al. "Crystallization and melting of aqueous gelatin". In: *Journal of Polymer Science: Polymer Physics Edition* 16.10 (1978), pp. 1817–1828.
- [73] Gough P. et al. "Applying Bioaffordances through an Inquiry-Based Model: a literature review of interactive biodesign". In: *International Journal of Human–Computer Interaction* 37.17 (2021), pp. 1583–1597.
- [74] Gough P. et al. "Design, Mould, Grow!: A Fabrication Pipeline for Growing 3D Designs Using Myco-Materials". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145 / 3544548.3580958. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3544548.3580958>.
- [75] Goveia da Rocha B. and Andersen K. "Becoming Travelers: Enabling the Material Drift". In: *Companion Publication of the 2020 ACM Designing Interactive Systems Conference*. DIS' 20 Companion. Eindhoven, Netherlands: Association for Computing Machinery, 2020, pp. 215–219. ISBN: 9781450379878. DOI: 10.1145 / 3393914.3395881. URL: <https://doi.org/10.1145/3393914.3395881>.
- [76] Gross S., Bardzell J., and Bardzell S. "Structures, forms, and stuff: the materiality and medium of interaction". In: *Personal and Ubiquitous Computing* 18.3 (2014), pp. 637–649.
- [77] Groutars E. G. et al. "Flavorium: an exploration of flavobacteria's living aesthetics for living color interfaces". In: *Proceedings of the 2022 CHI conference on human factors in computing systems*. 2022, pp. 1–19.
- [78] Grushkin D. *What is biodesign?* Oct. 2024. URL: <https://issues.org/biodesign-challenge-synthetic-biology-grushkin/>.
- [79] Guridi S. "Crafting Sustainable Interfaces: The Aesthetic Potential of Bio-based eTextiles". In: *Companion Publication of the 2025 ACM Designing Interactive Systems*

-
- Conference*. DIS '25 Companion. Association for Computing Machinery, 2025, pp. 446–451. ISBN: 9798400714863. DOI: 10.1145 / 3715668.3736340. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3715668.3736340>.
- [80] Guridi S. *Change of skin*. 2023. URL: <https://sofiaguridi.xyz/change-of-skin>.
- [81] Guridi S., Iannacchero M., and Pouta E. “Towards More Sustainable Interactive Textiles: A Literature Review on The Use of Biomaterials for eTextiles.” In: *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. 2024, pp. 1–19.
- [82] Guridi S. et al. “LIGHT TISSUE: Development of cellulose-based optical textile sensors”. In: *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '23. Warsaw, Poland: Association for Computing Machinery, 2023. ISBN: 9781450399777. DOI: 10.1145 / 3569009.3572798. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3569009.3572798>.
- [83] Guridi S. et al. “Sense and Degrade: Fully Bio-Based and Biodegradable eTextile Capacitive Sensor”. In: *2024 International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles (E-Textiles)*. IEEE. 2024, pp. 118–125.
- [84] Gurova O. et al. “Sustainable Solutions for Wearable Technologies: Mapping the Product Development Life Cycle”. In: *Sustainability* 12.20 (2020). ISSN: 2071-1050. DOI: 10.3390 / su12208444. URL: <https://www.mdpi.com/2071-1050/12/20/8444>.
- [85] Hamidi F. and Baljko M. “Rafigh: a living media interface for speech intervention”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014, pp. 1817–1820.

-
- [86] Hamidi F. et al. ““Turning the Invisible Visible”: Transdisciplinary Bioart Explorations in Human-DNA Interaction”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI '21. Yokohama, Japan: Association for Computing Machinery, 2021. ISBN: 9781450380966. DOI: 10.1145/3411764.3445408. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3411764.3445408>.
- [87] Hansson L. Å. E. J., Cerratto Pargman T., and Pargman D. S. “A Decade of Sustainable HCI: Connecting SHCI to the Sustainable Development Goals”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI '21. Yokohama, Japan: Association for Computing Machinery, 2021. ISBN: 9781450380966. DOI: 10.1145/3411764.3445069. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3411764.3445069>.
- [88] Hudson S. E. and Mankoff J. “Concepts, values, and methods for technical human–computer interaction research”. In: *Ways of Knowing in HCI*. Springer, 2014, pp. 69–93.
- [89] Ikemiya M. and Rosner D. K. “Broken Probes: Toward the Design of Worn Media”. In: *Personal Ubiquitous Comput.* 18.3 (Mar. 2014), pp. 671–683. ISSN: 1617-4909. DOI: 10.1007/s00779-013-0690-y. URL: <https://doi.org/10.1007/s00779-013-0690-y>.
- [90] Inc. T. F. S. *Crosslinker Selection Tool* | Thermo Fisher Scientific - US. 2023. URL: <https://www.thermofisher.com/us/en/home/life-science/protein-biology/protein-labeling-crosslinking/protein-crosslinking/crosslinker-selection-tool.html> (visited on 09/05/2023).
- [91] Ingold T. “The textility of making”. In: *Cambridge journal of economics* 34.1 (2010), pp. 91–102.

-
- [92] Ingold T. *Making*. Routledge, Apr. 2013. DOI: 10.4324/9780203559055. URL: <http://dx.doi.org/10.4324/9780203559055>.
 - [93] Ingold T., ed. *Redrawing Anthropology: Materials, Movements, Lines*. London: Routledge, Apr. 7, 2016. 216 pp. ISBN: 978-1-315-60418-3. DOI: 10.4324/9781315604183.
 - [94] Irwin B. *Weaving Iridescence: Color Play for the Handweaver*. en. Stackpole Books, 2017. ISBN: 978-0-8117-1628-4.
 - [95] Irwin T. "Transition design: A proposal for a new area of design practice, study, and research". In: *Design and culture* 7.2 (2015), pp. 229–246.
 - [96] Irwin T. and Kossoff G. "Transition Design: Wicked Problem Resolution as a Strategy for Catalyzing Positive, Systems-Level Change". In: *Routledge Handbook of Sustainable Design*. Routledge, 2024, pp. 472–492.
 - [97] Jackson S. J. and Kang L. "Breakdown, Obsolescence and Reuse: HCI and the Art of Repair". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 449–458. ISBN: 9781450324731. DOI: 10.1145/2556288.2557332. URL: <https://doi.org/10.1145/2556288.2557332>.
 - [98] Jiang M., Bhömer
bibinitperiod, and Liang
bibinitperiod. "Exploring the Design of Interactive Smart Textiles for Emotion Regulation". English. In: *HCI International 2020 – Late Breaking Papers*. Ed. by Stephanidis C. et al. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). Publisher Copyright: © 2020, Springer Nature Switzerland AG.; 22nd International Conference on Human-Computer Interaction, HCII 2020 ; Conference date: 19-07-2020 Through 24-07-2020. Germany: Springer

-
- Science and Business Media Deutschland GmbH, 2020, pp. 298–315. ISBN: 9783030599867. DOI: 10.1007/978-3-030-59987-4_22.
- [99] Jones L. “The E-darning Sampler: Exploring E-textile Repair with Darning Looms”. In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '21. Salzburg, Austria: Association for Computing Machinery, 2021. ISBN: 9781450382137. DOI: 10.1145/3430524.3444700. URL: <https://doi.org/10.1145/3430524.3444700>.
- [100] Jones L. et al. “Punch-Sketching E-textiles: Exploring Punch Needle as a Technique for Sustainable, Accessible, and Iterative Physical Prototyping with E-textiles”. In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '21. Salzburg, Austria: Association for Computing Machinery, 2021. ISBN: 9781450382137. DOI: 10.1145/3430524.3440640. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3430524.3440640>.
- [101] Kääriäinen P. et al. *The CHEMARTS cookbook*. Aalto ARTS Books, 2020.
- [102] Karana E., Barati B., and Giaccardi E. “Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts.” In: *International Journal of Design* 14.3 (2020).
- [103] Karana E. et al. “Material driven design (MDD): A method to design for material experiences”. In: *International journal of design* 9.2 (2015), pp. 35–54.
- [104] Karana E. et al. “The Tuning of Materials: A Designer’s Journey”. In: *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. DIS '16. Brisbane, QLD, Australia: Association for Computing Machinery, 2016, pp. 619–631. ISBN: 9781450340311. DOI: 10.1145/2901790.2901909. URL: <https://doi.org/10.1145/2901790.2901909>.

-
- [105] Karana E. et al. "When the material grows: A case study on designing (with) mycelium-based materials". In: *International Journal of Design* 12.2 (2018).
- [106] Karastathi N., Salmane A. K., and Parker B. "pH-Responsive textile with anthocyanin-laden hydrogel yarns: a colorimetric and feasibility study". In: *Research Directions: Biotechnology Design* 2 (2024), e17.
- [107] Khan F. R. Aug. 2020. URL: <https://www.amazon.com/MyCo-Domicilia-Farjana-Ria-Khan/dp/B08H6RYKDJ>.
- [108] Kim R. et al. "A new mould rush: designing for a slow bio-digital game driven by living micro-organisms". In: *Proceedings of the 13th International Conference on the Foundations of Digital Games*. 2018, pp. 1–9.
- [109] Kim R. et al. "Microbe-HCI: Introduction and Directions for Growth". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–4.
- [110] Kim R. et al. "Surfacing livingness in microbial displays: A design taxonomy for HCI". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 2023, pp. 1–21.
- [111] King J. P. et al. "Design, Fabrication, and Evaluation of Tendon-Driven Multi-Fingered Foam Hands". In: *2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)*. 2018, pp. 1–9. DOI: 10.1109/HUMANOIDS.2018.8624997.
- [112] Knappett C. and Malafouris L. *Material agency: towards a non-anthropocentric approach*. Springer, 2008.
- [113] Knowles B., Bates O., and Håkansson M. "This Changes Sustainable HCI". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018,

-
- pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3174045. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3173574.3174045>.
- [114] Koelle M. et al. “Prototyping Soft Devices with Interactive Bioplastics”. In: *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 2022, pp. 1–16.
 - [115] Koninck S. de. *Knotting. knotted. knot.* 2020. URL: <https://studiosdk.net/Knotting-Knotted-Knot>.
 - [116] Lab M. E. *About Us - Materials Experience Lab* — materialsexperiencelab.com. <https://materialsexperiencelab.com/>. [Accessed 06-08-2025]. 2016.
 - [117] LabLineCompact D. *DIENES LabLineCompact Wet Spinning Line – DIENES Apparatebau GmbH*. URL: <https://www.dienes.net/blog/2016/03/08/dienes-lablinecompact-nassspinnanlage/?lang=en> (visited on 07/28/2025).
 - [118] Laput G., Chen X., and Harrison C. “3D printed hair: Fused deposition modeling of soft strands, fibers, and bristles”. In: *Proceedings of the 28th annual ACM symposium on user interface software & technology*. 2015, pp. 593–597.
 - [119] Laurell Thorslund M. and Leifler O. “Exploring Assumptions about Sustainability: Towards a Constructive Framework for Action in Sustainable HCI”. In: *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. CHI ’25. Association for Computing Machinery, 2025. ISBN: 9798400713941. DOI: 10.1145/3706598.3714001. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3706598.3714001>.
 - [120] Lazaro Vasquez E. S. et al. “Desktop biofibers spinning: An open-source machine for exploring biobased fibers and their application towards sustainable smart textile design”. In: *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. 2024, pp. 1–18.

-
- [121] Lazaro Vasquez E. S., Wang H.-C., and Vega K. "Introducing the Sustainable Prototyping Life Cycle for Digital Fabrication to Designers". In: *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1301–1312. ISBN: 9781450369749. URL: <https://doi.org/10.1145/3357236.3395510>.
- [122] Lazaro Vasquez E. S. et al. "Exploring Biofoam as a Material for Tangible Interaction". In: *Designing Interactive Systems Conference*. DIS '22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 1525–1539. ISBN: 9781450393584. DOI: 10.1145/3532106.3533494. URL: <https://doi.org/10.1145/3532106.3533494>.
- [123] Lazaro Vasquez E. S. et al. "Designing Dissolving Wearables". In: *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing*. UbiComp/ISWC '23 Adjunct. Cancun, Quintana Roo, Mexico: Association for Computing Machinery, 2023, pp. 286–290. ISBN: 9798400702006. DOI: 10.1145/3594739.3610781. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3594739.3610781>.
- [124] Lee S. *Grow your own clothes*. 2011. URL: https://www.ted.com/talks/suzanne_lee_grow_your_own_clothes?language=en.
- [125] Leitch L. *Chalayan spring 2016 ready-to-wear collection*. Oct. 2015. URL: <https://www.vogue.com/fashion-shows/spring-2016-ready-to-wear/chalayan>.
- [126] Leong J. et al. "proCover: sensory augmentation of prosthetic limbs using smart textile covers". In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 2016, pp. 335–346.
- [127] Liu S.-Y. (, Bardzell J., and Bardzell S. "Decomposition as Design: Co-Creating (with) Natureculture". In: *Proceedings of the Thirteenth International Conference*

-
- on Tangible, Embedded, and Embodied Interaction*. TEI '19. Tempe, Arizona, USA: Association for Computing Machinery, 2019, pp. 605–614. ISBN: 9781450361965. DOI: 10.1145/3294109.3295653. URL: <https://doi.org/10.1145/3294109.3295653>.
- [128] Lu J. and Lopes P. “Integrating Living Organisms in Devices to Implement Care-based Interactions”. In: *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. UIST '22. Bend, OR, USA: Association for Computing Machinery, 2022. ISBN: 9781450393201. DOI: 10.1145/3526113.3545629. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3526113.3545629>.
- [129] Lu Q. et al. “Degrade to Function: Towards Eco-friendly Morphing Devices that Function Through Programmed Sequential Degradation”. In: *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. UIST '24. Pittsburgh, PA, USA: Association for Computing Machinery, 2024. ISBN: 9798400706288. DOI: 10.1145/3654777.3676464. URL: <https://doi.org/10.1145/3654777.3676464>.
- [130] Lu Q. et al. “Ecological HCI: Reflection and Future”. In: *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. CHI EA '24. Honolulu, HI, USA: Association for Computing Machinery, 2024. ISBN: 9798400703317. DOI: 10.1145/3613905.3643985. URL: <https://doi.org/10.1145/3613905.3643985>.
- [131] Lücking M. et al. *The Wet Biofibre Spinner*. en. July 2025. URL: <https://www.instagram.com/designstudio.malu/> (visited on 08/02/2025).
- [132] Mankoff J. C. et al. “Environmental sustainability and interaction”. In: *CHI '07 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '07. San Jose, CA, USA: Association for Computing Machinery, 2007, pp. 2121–2124. ISBN: 9781595936424. DOI: 10.1145/1240866.1240963. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/1240866.1240963>.

-
- [133] Materiability Research Group. *Materiability*. 2012. URL: <https://materiability.com/> (visited on 08/06/2025).
- [134] MaterialDriven. *Looking inside a material—A new woven language from Rita Parniczky*. en-US. Jan. 2017. URL: <https://www.materialdriven.com/blog/2017/1/9/looking-inside-a-material-a-new-woven-language-from-rita-parniczky> (visited on 09/15/2023).
- [135] Materiom. *Materiom — materiom.org*. <https://www.materiom.org/>. [Accessed 06-08-2025]. 2017.
- [136] Meena Y. K. et al. “Self-sustainablechi: Self-powered sustainable interfaces and interactions”. In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–7.
- [137] Mencarini E. et al. “Imagining Sustainable Futures: Expanding the Discussion on Sustainable HCI”. In: *Interactions* 31.2 (Feb. 2024), pp. 39–43. ISSN: 1072-5520. DOI: 10.1145/3643493. URL: <https://doi.org/10.1145/3643493>.
- [138] Merritt T. et al. “Living media interfaces: a multi-perspective analysis of biological materials for interaction”. In: *Digital Creativity* 31.1 (2020), pp. 1–21.
- [139] Morais L. et al. “From Exploration to End of Life: Unpacking Sustainability in Physicalization Practices”. In: *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. CHI '24. Honolulu, HI, USA: Association for Computing Machinery, 2024. ISBN: 9798400703300. DOI: 10.1145/3613904.3642248. URL: <https://doi.org/10.1145/3613904.3642248>.
- [140] Myers W. and Antonelli P. “Bio design: Nature, science, creativity”. In: *(No Title)* (2018).
- [141] NEFFA. *MycoTEX*. 2016. URL: <https://neffa.nl/mycotex/>.

-
- [142] Neri-Numa I. A. et al. "Genipin: A natural blue pigment for food and health purposes". In: *Trends in food science & technology* 67 (2017), pp. 271–279.
- [143] Ng A. "Grown Microbial 3D Fiber Art, Ava: Fusion of Traditional Art with Technology". In: *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. ISWC '17. Maui, Hawaii: Association for Computing Machinery, 2017, pp. 209–214. ISBN: 9781450351881. DOI: 10.1145 / 3123021.3123069. URL: <https://doi.org/10.1145/3123021.3123069>.
- [144] Nguyen V. et al. "SOFTii: Soft Tangible Interface for Continuous Control of Virtual Objects with Pressure-Based Input". In: *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '15. Stanford, California, USA: Association for Computing Machinery, 2015, pp. 539–544. ISBN: 9781450333054. DOI: 10.1145 / 2677199.2687898. URL: <https://doi.org/10.1145/2677199.2687898>.
- [145] Núñez-Pacheco C. et al. "Designing [Im] Material Inventories of Nomadic Belongings". In: *Companion Publication of the 2024 ACM Designing Interactive Systems Conference*. 2024, pp. 401–404.
- [146] Ofer N. and Alistar M. "Felt Experiences with Kombucha Scoby: Exploring First-Person Perspectives with Living Matter". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145 / 3544548.3581276. URL: <https://doi.org/10.1145/3544548.3581276>.
- [147] Ofer N., Bell F., and Alistar M. "Designing Direct Interactions with Bioluminescent Algae". In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1230–1241. ISBN: 9781450384766. DOI: 10.1145 / 3461778.3462090. URL: <https://doi.org/10.1145/3461778.3462090>.

-
- [148] Oliva-Moreno E. E. and Encinas A. "Addition of Pine Rosin to Pectin bioplastic films for improved water resistance". In: *Materials Letters* 290 (2021), p. 129488. ISSN: 0167-577X. DOI: <https://doi.org/10.1016/j.matlet.2021.129488>. URL: <https://www.sciencedirect.com/science/article/pii/S0167577X21001841>.
- [149] Olwal A. et al. "I/O Braid: Scalable touch-sensitive lighted cords using spiraling, repeating sensing textiles and fiber optics". In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. 2018, pp. 485–497.
- [150] OpenAI. *ChatGPT*. Accessed: 2025-11-03. 2025. URL: <https://chatgpt.com/>.
- [151] others and. "DIY-Materials approach to design meaningful materials for the sustainability transition". In: *Education for Sustainability approaching SDG 4 and target 4.7*. Universidad Pontificia Bolivariana, 2022, pp. 37–66.
- [152] Ou J. et al. "Cilllia: 3D printed micro-pillar structures for surface texture, actuation and sensing". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2016, pp. 5753–5764.
- [153] Panigrahy S. N. et al. "ecSkin: Low-Cost Fabrication of Epidermal Electrochemical Sensors for Detecting Biomarkers in Sweat". In: *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. CHI '24. Honolulu, HI, USA: Association for Computing Machinery, 2024. ISBN: 9798400703300. DOI: 10.1145/3613904.3642232. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3613904.3642232>.
- [154] Parisi F. "Material Engagement and Mediation: Two Necessary Concepts". In: *Exploring Contextualism and Performativity: The Environment Matters*. Springer, 2022, pp. 105–114.
- [155] Parisi S., Ferraro V., and Rognoli V. "Interactive connected smart (ICS) materials experience: Collaborative embodied knowledge through material tinkering".

-
- In: *Craft and Design Practice from an Embodied Perspective*. Routledge, 2024, pp. 198–212.
- [156] Parisi S., Rognoli V., and Sonneveld M. “Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education”. In: *The Design Journal* 20.sup1 (2017), S1167–S1184. DOI: 10.1080 / 14606925.2017.1353059. eprint: <https://doi.org/10.1080/14606925.2017.1353059>. URL: <https://doi.org/10.1080/14606925.2017.1353059>.
- [157] Pataranutaporn P., Ingalls T., and Finn E. “Biological HCI: Towards Integrative Interfaces Between People, Computer, and Biological Materials”. In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–6. ISBN: 9781450356213. DOI: 10.1145/3170427.3188662. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3170427.3188662>.
- [158] Plastics B. *Beyond Plastics - Working To End Single-Use Plastic Pollution* — [beyondplastics.org](https://www.beyondplastics.org/). <https://www.beyondplastics.org/>. [Accessed 06-08-2025]. 2018.
- [159] Polanyi M. “Tacit knowing: Its bearing on some problems of philosophy”. In: *Reviews of modern physics* 34.4 (1962), p. 601.
- [160] Poupyrev I. et al. “Project Jacquard: interactive digital textiles at scale”. In: *Proceedings of the 2016 chi conference on human factors in computing systems*. 2016, pp. 4216–4227.
- [161] Prado N. S. et al. “Nanocomposite films based on flaxseed gum and cellulose nanocrystals”. In: *Materials Research* 21 (2018).
- [162] Programme U. N. E. *UN report: Time to seize opportunity, tackle challenge of e-waste*. en. Section: News and Stories. Jan. 2019. URL: <http://www.unep.org/news->

and-stories/press-release/un-report-time-seize-opportunity-tackle-challenge-e-waste (visited on 12/09/2022).

- [163] Project D. B. S. M. *utilityresearchlab/desktop-biofibers-spinning*. original-date: 2024-01-23T03:04:34Z. July 2025. URL: <https://github.com/utilityresearchlab/desktop-biofibers-spinning> (visited on 07/28/2025).
- [164] Pusch K., Hinton T. J., and Feinberg A. W. "Large volume syringe pump extruder for desktop 3D printers". In: *HardwareX* 3 (2018), pp. 49–61.
- [165] Ramos-de-la-Peña A. M. et al. "A review through recovery, purification and identification of genipin". In: *Phytochemistry Reviews* 15 (2016), pp. 37–49.
- [166] Regenstein J. and Zhou P. "13 - Collagen and gelatin from marine by-products". In: *Maximising the Value of Marine By-Products*. Ed. by Shahidi F. Woodhead Publishing Series in Food Science, Technology and Nutrition. Woodhead Publishing, 2007, pp. 279–303. ISBN: 978-1-84569-013-7. DOI: <https://doi.org/10.1533/9781845692087.2.279>. URL: <https://www.sciencedirect.com/science/article/pii/B9781845690137500132>.
- [167] Rivera M. L. and Hudson S. E. "Desktop electrospinning: a single extruder 3D printer for producing rigid plastic and electrospun textiles". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019, pp. 1–12.
- [168] Rivera M. L., Bae S. S., and Hudson S. E. "Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds". In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS '23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 294–311. ISBN: 9781450398930. DOI: 10.1145/3563657.3595983. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3563657.3595983>.

-
- [169] Roedl D., Bardzell S., and Bardzell J. "Sustainable Making? Balancing Optimism and Criticism in HCI Discourse". In: *ACM Trans. Comput.-Hum. Interact.* 22.3 (June 2015). ISSN: 1073-0516. DOI: 10.1145 / 2699742. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/2699742>.
- [170] Rognoli V., Salvia G., and Levi M. "The Aesthetic of Interaction with Materials for Design: The Bioplastics' Identity". In: *Proceedings of the 2011 Conference on Designing Pleasurable Products and Interfaces*. DPPI '11. Milano, Italy: Association for Computing Machinery, 2011. ISBN: 9781450312806. DOI: 10.1145 / 2347504. 2347540. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/2347504.2347540>.
- [171] Roosth H. S. "Crafting life: a sensory ethnography of fabricated biologies". PhD thesis. Massachusetts Institute of Technology, 2010.
- [172] Rosner D. K. and Fox S. E. "Legacies of craft and the centrality of failure in a mother-operated hackerspace". In: *new media & society* 18.4 (2016), pp. 558–580.
- [173] Rosner D. K. et al. "Designing with Traces". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. Paris, France: Association for Computing Machinery, 2013, pp. 1649–1658. ISBN: 9781450318990. DOI: 10.1145/2470654.2466218. URL: <https://doi.org/10.1145/2470654.2466218>.
- [174] Rosner D. K. et al. "Making Core Memory: Design Inquiry into Gendered Legacies of Engineering and Craftwork". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3174105. URL: <https://doi.org/10.1145/3173574.3174105>.
- [175] Schmid M., Rümelin S., and Richter H. "Empowering Materiality: Inspiring the Design of Tangible Interactions". In: *Proceedings of the 7th International Conference*

-
- on *Tangible, Embedded and Embodied Interaction*. TEI '13. Barcelona, Spain: Association for Computing Machinery, 2013, pp. 91–98. ISBN: 9781450318983. DOI: 10.1145/2460625.2460639. URL: <https://doi.org/10.1145/2460625.2460639>.
- [176] Silberman M. S. et al. “Next steps for sustainable HCI”. In: *Interactions* 21.5 (Sept. 2014), pp. 66–69. ISSN: 1072-5520. DOI: 10.1145/2651820. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/2651820>.
- [177] Soares da Costa F. et al. “Making Seafoam: An Autobiographical Design Journey Engaging Local Ecologies Through Making”. In: *Proceedings of the 2025 ACM Designing Interactive Systems Conference*. DIS '25. Association for Computing Machinery, 2025, pp. 2518–2533. ISBN: 9798400714856. DOI: 10.1145/3715336.3735413. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3715336.3735413>.
- [178] Søndergaard M. L. J. and Campo Woytuk N. “Feminist Posthumanist Design of Menstrual Care for More-than-Human Bodies”. In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN: 9781450394215. DOI: 10.1145/3544548.3581083. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3544548.3581083>.
- [179] Song K. W. and Paulos E. “Unmaking: Enabling and celebrating the creative material of failure, destruction, decay, and deformation”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–12.
- [180] Song K. W. et al. “Towards decomposable interactive systems: Design of a backyard-degradable wireless heating interface”. In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 2022, pp. 1–12.
- [181] Song K. W. et al. “Sustainable Unmaking: Designing for Biodegradation, Decay, and Disassembly”. In: *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. CHI EA '24. Honolulu, HI, USA: Association for Computing

-
- Machinery, 2024. ISBN: 9798400703317. DOI: 10.1145 / 3613905.3636300. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3613905.3636300>.
- [182] Song K. W. and Paulos E. “Vim: Customizable, decomposable electrical energy storage”. In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 2023, pp. 1–18.
- [183] Spinners B. M. B.
bibinitperiod. *Join the Biofibers Machine Builders & Spinners Discord Server!* en-US.
URL: <https://discord.com/invite/vDmk3t2FMX> (visited on 07/28/2025).
- [184] Stoessel P. R. et al. “Fibers mechanically similar to sheep wool obtained by wet spinning of gelatin and optional plasticizers”. In: *Macromolecular Materials and Engineering* 300.2 (2015), pp. 234–241.
- [185] Stoessel P. R. et al. “Porous, water-resistant multifilament yarn spun from gelatin”. In: *Biomacromolecules* 16.7 (2015), pp. 1997–2005.
- [186] Tholander J., Normark M., and Rossitto C. “Understanding Agency in Interaction Design Materials”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: Association for Computing Machinery, 2012, pp. 2499–2508. ISBN: 9781450310154. DOI: 10.1145/2207676.2208417. URL: <https://doi.org/10.1145/2207676.2208417>.
- [187] Tortora P. G. *Understanding Textiles*. 2nd ed. New York: Macmillan, 1982, p. 454. ISBN: 0024208701.
- [188] Tosif M. M. et al. “A Comprehensive Review on Plant-Derived Mucilage: Characterization, Functional Properties, Applications, and Its Utilization for Nanocarrier Fabrication”. In: *Polymers* 13.7 (2021). ISSN: 2073-4360. DOI: 10.3390/polym13071066. URL: <https://www.mdpi.com/2073-4360/13/7/1066>.

-
- [189] Tsaknaki V. and Fernaeus Y. "Expanding on Wabi-Sabi as a Design Resource in HCI". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: Association for Computing Machinery, 2016, pp. 5970–5983. ISBN: 9781450333627. DOI: 10.1145 / 2858036.2858459. URL: <https://doi.org/10.1145/2858036.2858459>.
- [190] Tsaknaki V., Fernaeus Y., and Schaub M. "Leather as a Material for Crafting Interactive and Physical Artifacts". In: *Proceedings of the 2014 Conference on Designing Interactive Systems*. DIS '14. Vancouver, BC, Canada: Association for Computing Machinery, 2014, pp. 5–14. ISBN: 9781450329026. DOI: 10.1145 / 2598510.2598574. URL: <https://doi.org/10.1145/2598510.2598574>.
- [191] Tsaknaki V. et al. "Things fall apart: unpacking the temporalities of impermanence for HCI". In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. 2016, pp. 1–3.
- [192] Tyler D. et al. "Wearable electronic textiles". In: *Textile Progress* 51.4 (2019), pp. 299–384.
- [193] Vallgård A. and Redström J. "Computational Composites". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '07. San Jose, California, USA: Association for Computing Machinery, 2007, pp. 513–522. ISBN: 9781595935939. DOI: 10.1145 / 1240624.1240706. URL: <https://doi.org/10.1145/1240624.1240706>.
- [194] Vanden Elsacker E. "Mycelium Matters - an Interdisciplinary Exploration of the Fabrication and Properties of Mycelium-Based Materials". PhD thesis. VUB Press, Apr. 20, 2021. ISBN: 9789461171689.
- [195] Vasquez E. S. L., Wang H.-C., and Vega K. "The Environmental Impact of Physical Prototyping: a Five-Year CHI Review". In: *Self-Sustainable CHI Workshop*. Vol. 1. 1. 2020, p. 8.

-
- [196] Vasquez E. S. L. et al. "Yupana: Understanding the Environmental Impact of Digital Fabrication Prototyping through a Life Cycle Impact Assessment". en. In: *International Journal of Academic Makerspaces and Making* (2025).
- [197] Vasquez E. S. L. *ACM DIS'23 Soft Robotics and Programmable Materials for Human-Computer Interaction Workshop. How to make soft biofoam strings*. en. July 2023. URL: <https://www.softrobotics.io/post/how-to-make-soft-biofoam-strings-exploring-an-affordable-and-accessible-fabrication-method> (visited on 07/30/2023).
- [198] Vasquez E. S. L. and Vega K. "From Plastic to Biomaterials: Prototyping DIY Electronics with Mycelium". In: *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*. UbiComp/ISWC '19 Adjunct. London, United Kingdom: Association for Computing Machinery, 2019, pp. 308–311. ISBN: 9781450368698. DOI: 10.1145/3341162.3343808. URL: <https://doi.org/10.1145/3341162.3343808>.
- [199] Vasquez E. S. L. and Vega K. "Myco-accessories: sustainable wearables with biodegradable materials". In: *Proceedings of the 2019 ACM International Symposium on Wearable Computers*. ISWC '19. London, United Kingdom: Association for Computing Machinery, 2019, pp. 306–311. ISBN: 9781450368704. DOI: 10.1145/3341163.3346938. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3341163.3346938>.
- [200] Vasquez E. S. L., Yetisen A. K., and Vega K. "BraceIO: biosensing through hydrogel dental ligatures". In: *Proceedings of the 2020 ACM International Symposium on Wearable Computers*. ISWC '20. Virtual Event, Mexico: Association for Computing Machinery, 2020, pp. 87–89. ISBN: 9781450380775. DOI: 10.1145/

-
- 3410531.3414290. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3410531.3414290>.
- [201] Vasquez E. S. L. et al. "Bio-e-Nails: a Sustainable Design Approach to Biobased Nail Interfaces". In: *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '25. New York, NY, USA: Association for Computing Machinery, 2025. ISBN: 9798400711978. DOI: 10.1145/3689050.3704426. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3689050.3704426>.
- [202] Vasquez E. S. L. et al. "Bioactuated Textiles: Exploring Reversible Actuation of Casein Bioplastic in Woven Textiles". In: *Companion of the 2025 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp Companion '25)*. Espoo, Finland: Association for Computing Machinery, 2025, pp. 1–6. DOI: 10.1145/3714394.3750704. URL: <https://doi.org/10.1145/3714394.3750704>.
- [203] Vijayakumar V. et al. "How do we grow a Biodesigner?" In: *Research Directions: Biotechnology Design 2* (2024), e2. DOI: 10.1017/btd.2024.1.
- [204] Vogl A. et al. "StretchEBand: Enabling Fabric-based Interactions through Rapid Fabrication of Textile Stretch Sensors." In: *CHI*. Vol. 17. 2017, pp. 2617–2627.
- [205] Voorwinden M. et al. "A Design Space for Animated Textile-forms through Shuttle Weaving: A Case of 3D Woven Trousers". In: *Proceedings of the 2025 ACM Designing Interactive Systems Conference*. DIS '25. Association for Computing Machinery, 2025, pp. 2465–2484. ISBN: 9798400714856. DOI: 10.1145/3715336.3735741. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3715336.3735741>.
- [206] Wakkary R. and Tanenbaum K. "A sustainable identity: the creativity of an everyday designer". In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2009, pp. 365–374.

-
- [207] Wakkary R. et al. "A sustainable design fiction: Green practices". In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 20.4 (2013), pp. 1–34.
- [208] Wakkary R. et al. "Material speculation: actual artifacts for critical inquiry". In: *Proceedings of The Fifth Decennial Aarhus Conference on Critical Alternatives*. CA '15. Aarhus, Denmark: Aarhus University Press, 2015, pp. 97–108. DOI: 10.7146/aahcc.v1i1.21299. URL: <https://doi.org/10.7146/aahcc.v1i1.21299>.
- [209] Walters K., Devendorf L., and Landahl K. "Animated Linen: Using High-twist Hygromorphic Yarn to Produce Interactive Woven Textiles". In: *Proceedings of the 2024 ACM Designing Interactive Systems Conference*. DIS '24. Copenhagen, Denmark: Association for Computing Machinery, 2024, pp. 1177–1191. ISBN: 9798400705830. DOI: 10.1145/3643834.3662146. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3643834.3662146>.
- [210] Wang G. et al. "X-Hair: 3D Printing Hair-like Structures with Multi-form, Multi-property and Multi-function". In: *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. 2024, pp. 1–14.
- [211] Weiler J. et al. "Mycelium Artifacts: Exploring Shapeable and Accessible Biofabrication". In: *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion*. DIS '19 Companion. San Diego, CA, USA: Association for Computing Machinery, 2019, pp. 69–72. ISBN: 9781450362702. DOI: 10.1145/3301019.3325156. URL: <https://doi.org/10.1145/3301019.3325156>.
- [212] Wen X., Bae S. S., and Rivera M. L. "Enabling Recycling of Multi-Material 3D Printed Objects through Computational Design and Disassembly by Dissolution". In: *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 2025, pp. 1–21.

-
- [213] Wiberg M. et al. "Materiality Matters—Experience Materials". In: *Interactions* 20.2 (Mar. 2013), pp. 54–57. ISSN: 1072-5520. DOI: 10.1145/2427076.2427087. URL: <https://doi.org/10.1145/2427076.2427087>.
- [214] Wicaksono I. and Paradiso J. "Fabrickeyboard: multimodal textile sensate media as an expressive and deformable musical interface". In: *Proceedings of the International Conference on New Interfaces for Musical Expression*. 2017, pp. 348–353.
- [215] Wu S. and Devendorf L. "Unfabricate: Designing Smart Textiles for Disassembly". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–14. ISBN: 9781450367080. DOI: 10.1145/3313831.3376227. URL: <https://doi.org/10.1145/3313831.3376227>.
- [216] Yan Z. et al. "Future Paradigms for Sustainable Making". In: *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. UIST '23 Adjunct. San Francisco, CA, USA: Association for Computing Machinery, 2023. ISBN: 9798400700965. DOI: 10.1145/3586182.3617433. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3586182.3617433>.
- [217] Yan Z. et al. "SolderlessPCB: Reusing Electronic Components in PCB Prototyping through Detachable 3D Printed Housings". In: *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. CHI '24. Honolulu, HI, USA: Association for Computing Machinery, 2024. ISBN: 9798400703300. DOI: 10.1145/3613904.3642765. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3613904.3642765>.
- [218] Yao L. et al. "BioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for

-
- Computing Machinery, 2015, pp. 1–10. ISBN: 9781450331456. DOI: 10.1145/2702123.2702611. URL: <https://doi.org/10.1145/2702123.2702611>.
- [219] Young-Ng M. et al. “Sweatcessory: a Wearable Necklace for Sensing Biological Data in Sweat”. In: *Adjunct Proceedings of the 2022 ACM International Joint Conference on Pervasive and Ubiquitous Computing and the 2022 ACM International Symposium on Wearable Computers*. UbiComp/ISWC ’22 Adjunct. Cambridge, United Kingdom: Association for Computing Machinery, 2023, pp. 141–143. ISBN: 9781450394239. DOI: 10.1145/3544793.3560342. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3544793.3560342>.
- [220] Zhai Y. et al. “Flexible and wearable carbon black/thermoplastic polyurethane foam with a pinnate-veined aligned porous structure for multifunctional piezoresistive sensors”. In: *Chemical Engineering Journal* 382 (2020), p. 122985. ISSN: 1385-8947. DOI: <https://doi.org/10.1016/j.cej.2019.122985>. URL: <https://www.sciencedirect.com/science/article/pii/S1385894719323952>.
- [221] Zhang Z. et al. “DeltaLCA: Comparative Life-Cycle Assessment for Electronics Design”. In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 8.1 (Mar. 2024). DOI: 10.1145/3643561. URL: <https://doi.org/10.1145/3643561>.
- [222] Zhou J. et al. “Cyano-chromic Interface: Aligning Human-Microbe Temporalities Towards Noticing and Attending to Living Artefacts”. In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS ’23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 820–838. ISBN: 9781450398930. DOI: 10.1145/3563657.3596132. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3563657.3596132>.
- [223] Zhou Y. et al. “MossWater: A Living Media Interface for Encouraging Office Workers’ Daily Water Intake”. In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI EA ’21. Yokohama, Japan: Association

-
- for Computing Machinery, 2021. ISBN: 9781450380959. DOI: 10.1145 / 3411763.3451648. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3411763.3451648>.
- [224] Zhu J., Winagle L., and Kao H.-L. (“EcoThreads: Prototyping Biodegradable E-textiles Through Thread-based Fabrication”. In: *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. CHI ’24. Honolulu, HI, USA: Association for Computing Machinery, 2024. ISBN: 9798400703300. DOI: 10.1145 / 3613904.3642718. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3613904.3642718>.
- [225] Zhu J. et al. “BioWeave: Weaving Thread-Based Sweat-Sensing On-Skin Interfaces”. In: *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. UIST ’23. San Francisco, CA, USA: Association for Computing Machinery, 2023. ISBN: 9798400701320. DOI: 10.1145 / 3586183.3606769. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3586183.3606769>.
- [226] Zhu J. et al. “Empowering Sustainable E-Textiles: DIY Biofiber Wet Spinning for Community Material Exploration”. In: *Proceedings of the 2025 ACM Designing Interactive Systems Conference*. DIS ’25. Association for Computing Machinery, 2025, pp. 2395–2409. ISBN: 9798400714856. DOI: 10.1145 / 3715336.3735409. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3715336.3735409>.
- [227] Zhu J. et al. “LivingLoom: Investigating Human-Plant Symbiosis Through Integrating Living Plants Into (E-)Textiles”. In: *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. CHI ’25. Association for Computing Machinery, 2025. ISBN: 9798400713941. DOI: 10.1145 / 3706598.3713156. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/3706598.3713156>.
- [228] Zhu J. et al. “Wearable Bio-HCI: Challenges & Opportunities”. In: *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. CHI EA ’25. Association for Computing Machinery, 2025. ISBN:

9798400713958. DOI: 10.1145/3706599.3716295. URL: <https://doi.org/10.1145/3706599.3716295>.

- [229] Zimmerman J., Forlizzi J., and Evenson S. “Research through design as a method for interaction design research in HCI”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '07. San Jose, California, USA: Association for Computing Machinery, 2007, pp. 493–502. ISBN: 9781595935939. DOI: 10.1145/1240624.1240704. URL: <https://doi-org.colorado.idm.oclc.org/10.1145/1240624.1240704>.